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CLIMATE POLICY WITHOUT TEARS:
CGE-BASED ANCILLARY BENEFITS
ESTIMATES FOR CHILE

by

Sébastien Dessus and David O'Connor

Research programme on:
Responding to the Challenge of Climate Change



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FOREWORD

What, if anything, should be done about climate change is a question on policy agendas worldwide. The issues are controversial because of disagreements about costs and benefits of alternative climate policies. Measures limiting the growth of greenhouse gas emissions are seen to impose near term economic costs in return for uncertain and distant benefits. While the experience with implementing the 1989 Montreal Protocol on Ozone Depleting Substances gives cause for optimism that costs of compliance with the Kyoto Protocol may prove lower than anticipated, the present study's contribution is to show that the *benefits* of climate policy may well have been underestimated, notably for developing countries. In finding that a middle-income developing country can have a significant interest in limiting the growth of its greenhouse gas emissions, the authors — Sébastien Dessus and David O'Connor, both of the OECD Development Centre — introduce a new perspective on this contentious policy debate.

Using a standard computable general equilibrium model of the Chilean economy, the authors estimate the effects of a carbon tax on emissions of local and regional air pollutants and, in turn, on human health in the capital city of Santiago. Transferring results from valuation studies on mortality and morbidity risk in other countries, then adjusting them for Chile, the health benefits are valued and compared with carbon dioxide abatement costs to determine the scope for “no regrets” abatement as well as a *quasi*-optimal abatement rate and carbon tax. This comparison assumes that policy makers do not consider the primary, but uncertain, benefits of avoiding climate change. Rather, they value only the ancillary benefits of reducing local pollutants whose emissions are closely correlated with those of carbon dioxide, thanks to their common origin in fossil fuel combustion.

The authors find that, for Chile, the health-related ancillary benefits *per se* would justify measures aimed at a significant reduction of carbon dioxide emissions below their baseline trajectory. Even under conservative assumptions about key parameters influencing costs and ancillary benefits, a reduction of 10 per cent in emissions for the year 2010 could be achieved with no welfare loss. This suggests that carbon dioxide abatement is in the short-run economic self interest of Chilean residents, once the health benefits of pollution reduction are properly accounted for.

Another important finding is that, in physical terms, the health benefits of climate policy are likely to be greater in developing than in developed countries. This follows from the fact that direct controls on local pollutants are generally less stringent in developing than in developed countries so that the potential for low-cost abatement is that much greater. Thus, each ton reduction in carbon resulting, for example, from a carbon tax achieves a larger reduction in other pollutants, with larger associated health impacts, than would be the case in a higher income country of the OECD. To compare costs and benefits properly, however, one should attach a price to the physical impacts.

In the case of Chile, assuming a continuation of its strong growth performance until 2010, its per capita income will converge rather quickly towards the 1992 US level (the usual point of reference), so that the welfare result will be preserved. In countries like China and India, starting with much lower per capita incomes than the OECD economies, valuation may yield smaller ancillary benefits of carbon reduction — though there too, rapid economic growth should raise the welfare gains from local environmental quality improvements.

This study of Chile's potential for reaping ancillary benefits from climate policy is part of the Development Centre's Activity on "Responding to the Challenge of Climate Change" under the 1999-2000 Programme of Work. Beyond Chile, the intention is to examine ancillary benefits potential in a few large developing countries as well. The results of this research will serve as an input into decision making by climate negotiators and policy makers in the developing world, as well as into the ongoing research effort under the auspices of the Intergovernmental Panel on Climate Change (IPCC) on the economic and social dimensions of climate change.

Jorge Braga de Macedo
President
OECD Development Centre
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RÉSUMÉ

Quel intérêt pourraient avoir les pays en développement à limiter leurs émissions de gaz à effet de serre ? De la réponse à cette question dépend en partie la poursuite des négociations internationales sur la question. Les gains attendus pour chaque pays d'une limitation des gaz à effet de serre restent en effet encore très hypothétiques, et d'horizon lointain. Les coûts, en revanche, sont immédiats.

Cette étude tente d'estimer, à l'aide d'un modèle d'équilibre général calculable pour le Chili, le bénéfice souvent négligé d'une politique de contrôle des émissions pour la qualité de l'air à Santiago du Chili, et ses effets associés sur la santé de ses habitants. Les pays adoptant ces politiques peuvent en retirer les bénéfices directement et à court terme. Une large analyse de sensibilité est menée, en raison des incertitudes qui pèsent sur la valeur de certains paramètres clés. Elle concerne notamment le montant que seraient prêts à payer les habitants de Santiago pour voir diminuer les risques de morbidité et de mortalité, ou encore les élasticités de substitution entre les différentes sources énergétiques et entre l'énergie et les autres intrants. Même si l'on retient les hypothèses les plus conservatrices à propos de ces paramètres, les résultats suggèrent que le Chili pourrait réduire sans coût ses émissions de CO₂ d'au moins 10 pour cent par rapport au niveau qu'il atteindrait en 2010 s'il ne prenait aucune mesure en ce sens (ce dernier cas définissant le scénario de référence). Si l'on retient des hypothèses plus réalistes à propos de ces mêmes paramètres, le taux optimal de réduction des émissions de CO₂ (sans tenir compte encore une fois des gains « primaires ») atteindrait alors environ 20 pour cent, et correspondrait à l'application d'une taxe environnementale comprise entre 115 et 130 dollars par tonne de carbone.

Les résultats obtenus pour le Chili sont cohérents avec ceux que donnent des modèles d'équilibre général pour les États-Unis et l'Europe. Les bénéfices secondaires par tonne de carbone éliminée au Chili se situent à l'extrémité supérieure de l'intervalle de confiance des estimations faites pour l'Europe. Cela provient principalement du fait que les scénarios de référence diffèrent grandement d'une région à l'autre, puisqu'au contraire du Chili, l'Europe a déjà mis en place des régulations strictes de contrôle des émissions de particules et de plomb, lesquelles contribuent majoritairement à la dégradation de la santé à Santiago. Une politique de réduction des émissions de CO₂ au Chili est donc susceptible de procurer des gains marginaux d'amélioration de la qualité de l'air plus importants qu'en Europe. Compte tenu des projections de croissance du revenu par habitant du Chili d'ici à 2010, les effets relativement importants de telles mesures sur la santé se traduisent par des gains de bien-être monétarisés élevés.

ABSTRACT

What interest do developing countries have in limiting the growth of their greenhouse gas (GHG) emissions? Answering this question is crucial to moving international climate policy negotiations forward. The primary benefits for individual countries of GHG abatement remain highly uncertain and, in any case, long-term in nature. The costs, on the other hand, are near-term.

Using an economy-wide model of Chile, this study examines a hitherto neglected set of benefits from climate policy, viz., the reduction in emissions of local and regional air pollutants and the “ancillary” health benefits, in this case for the people of Santiago, the capital city. These benefits are both near-term and readily captured by the country implementing the policy. Extensive sensitivity analysis is performed in recognition of the uncertainty surrounding certain key parameter and exogenous variable values — notably, Santiago residents’ willingness to pay (WTP) for reduced mortality and morbidity risk, and the substitution elasticities (σ) among energy sources and between energy and other inputs. Even with the most conservative assumptions about WTP and substitution possibilities, it is found that policy makers in Chile could safely aim to reduce CO₂ emissions by 10 per cent from their baseline 2010 level without any welfare loss. If one takes as most reliable the central estimates of WTP and σ , an “optimal” abatement rate (neglecting primary benefits) would be around 20 per cent and the corresponding carbon tax in the range of \$115-130/tC.

The results for Chile are consistent with findings from similar exercises using CGE models for the United States and Western Europe. The ancillary benefits per ton of carbon abated in Chile are at the upper end of the range of European and US estimates. This owes much to the different baseline conditions, with the latter countries having already implemented rather stringent direct controls on PM-10, lead and the other pollutants that are found to contribute most to health damages in Santiago. Thus, in Chile, the marginal contribution of climate policy to local air quality improvements is likely to be that much greater. Given Chile’s projected per capita income growth to 2010, the relatively large health impacts translate into large monetised welfare gains.

GLOSSARY

AB	Ancillary benefits
AEEI	Autonomous energy efficiency improvement
Annex 1	Annex to the United Nations Framework Convention on Climate Change (UNFCCC) containing list of countries, including most OECD countries (excluding Korea and Mexico) plus the European economies-in-transition and several former Soviet republics (most importantly, Russian Federation and Ukraine)
BAU	Business as usual
BIOAIR	Bioaccumulative emissions to air
C	Carbon
CES	Constant elasticity of substitution
CGE	Computable general equilibrium
CO	Carbon monoxide
CO₂	Carbon dioxide
COI	Cost of illness
COP	Conference of Parties to the UNFCCC
CV	Compensating variation
CVM	Contingent valuation method
ERV	Emergency room visit
GREEN	GeneRal Equilibrium ENvironmental Model
GHG	Greenhouse gas
HWM	Hedonic wage method
IAB	Incremental ancillary benefits
IAC	Incremental abatement costs
IPCC	Intergovernmental Panel on Climate Change
IPPS	Industrial Pollution Projection System
IQ	Intelligence quotient
KP	Kyoto Protocol

LRI	Lower respiratory infection
MAC	Marginal abatement costs
MRAD	Minor restricted activity day
NO_x	Nitrogen oxides
NO₂	Nitrogen dioxide
PART	Total particulates in air; equivalent to TSP
PM-10	Respirable particulates
ppm	parts per million
PPP	Purchasing power parity
RAD	Restricted activity day
RHA	Respiratory hospital admission
RRAD	Respiratory restricted activity day
SAM	Social accounting matrix
Sink	An activity or natural process that serves to remove or store carbon dioxide taken from the atmosphere, e.g., the process of photosynthesis in plants.
SO₂	Sulphur dioxide
tC	ton carbon
TSP	Total suspended particulates
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile organic compounds
VSL	Value of a statistical life
WTP	Willingness to pay

I. INTRODUCTION

What developing countries can and should do to limit their emissions of greenhouse gases (GHG) remains one of most contentious issues in international climate negotiations. In signing on to the Kyoto Protocol (KP), the Annex 1 countries (essentially most of the OECD plus the transitional economies of Europe, including Russia) have committed themselves to specific GHG emission targets during the first control period, from 2008 to 2012. For most OECD countries, this involves a reduction of the net combined emissions of five GHGs relative to a base year (normally 1990). Thus far, non-Annex 1 countries have set no quantitative emission targets. The arguments for the developed countries' taking the lead in climate policy are familiar. The existing atmospheric stock of GHGs is overwhelming the result of past releases by Annex 1 countries and these countries are on average far more economically developed than non-Annex 1 countries. Thus, they have both the responsibility and the means to take the lead in reducing GHG emissions. Hence the universal recognition of the principle of common but differentiated responsibilities for addressing the human causes of climate change.

Still, the voluntary commitment to limit GHG emissions by a couple of non-Annex 1 countries at the 4th Conference of the Parties to the KP (COP4, held at Buenos Aires in late 1998) poses the question anew of whether it may not be in the self-interest of many developing countries unilaterally to slow GHG emissions growth. At present, incentives for non-Annex 1 countries unilaterally to control their GHG emissions would appear to be weak. Remaining uncertainties about the rate of future global warming and associated climate change and damage costs (or perhaps even benefits) to be expected by a given country are large. Faced with more immediate and visible threats to popular well-being, policy makers may find precautionary GHG abatement measures difficult to justify, especially if they carry significant near-term costs. Views differ about the size of expected costs, with some arguing that a well-designed climate policy could reduce widespread inefficiencies in energy use, thereby yielding an economic payoff as well as an environmental one. Even if one assumes such inefficiencies to be minimal, however, up to a point GHG abatement could still yield ancillary benefits greater than the abatement costs. These might arise, for example, if the measures designed to reduce greenhouse gases also reduce local air pollutants and their associated health and other environmental damages. These ancillary benefits differ from the primary benefits from averting climate change in that they are *i)* nearer-term; and *ii)* more readily captured by the individual country implementing the policy. Thus, if these ancillary benefits should turn out to be substantial, they would make the political case for GHG abatement measures in both Annex 1 and non-Annex 1 countries that much more convincing.

A number of studies of climate policy have made reference to ancillary benefits (AB)¹ of GHG abatement, and several have estimated the magnitude of those benefits for the United States and Europe (see Burtraw and Toman, 1998, for a review of the former studies and Ekins, 1996, for a review of the latter). While the estimated ancillary benefits per ton of carbon abatement (AB/tC) vary widely, even the most conservative AB estimates suggest some scope for "no regrets" GHG abatement in major Annex 1 countries. To our knowledge, the present study is the first to use an economy-wide model to estimate the ancillary benefits and the "no regrets" level of GHG abatement in a developing country, in this case,

Chile². (Wang and Smith, 1999, propose a “bottom-up” methodology for assessing the health benefits of greenhouse gas reduction in the energy sector, with special reference to China; Markandya, 1998, also presents a methodology for assessing ancillary benefits/costs of climate policy, while Markandya and Boyd, 1999, apply that framework to assessing benefits of specific technologies in the case of Mauritius.)

The paper is organised as follows. Section II provides an overview of the theoretical framework employed for estimation of ancillary benefits, the net benefits/costs of climate policy, and the “optimal” and “no regrets” levels of abatement. Section III then describes the Chile model and data used for the analysis. Section IV deals with a number of methodological issues. Section V presents the main features of the baseline simulation, with particular attention to the modelling of energy use and pollution emissions. Section VI describes the basic policy scenario (involving successive percentage reductions in CO₂ from baseline projected emissions) and performs sensitivity analysis to account for uncertainty regarding values of certain key model parameters and exogenous variables. Section VII discusses policy implications and Section VIII concludes.

II. THEORETICAL FRAMEWORK

In the simplest terms, a country will choose to adopt a given climate policy only if the expected benefits are at least as great as the expected costs. The costs of GHG abatement have been widely discussed in the literature and can be thought of as the net reduction in national economic welfare resulting from the introduction of a constraint on a variable, GHG emissions, that would otherwise be unconstrained. What are the associated benefits? Potentially, there are both direct and indirect — primary and ancillary — benefits to any given country from GHG abatement measures. The primary benefits are conditional in the sense that a small country like Chile could not expect to reap any climate change mitigation benefits from unilateral GHG reduction if other countries continue along BAU emissions paths. As is well known, climate change mitigation requires a co-operative global solution involving at a minimum the major national contributors to GHG emissions. Even assuming global co-operation is effective, an individual country's primary benefits are highly uncertain and are, in any case, not likely to be immediate. Indeed, they are likely to occur only decades in the future.

For this reason, we focus here solely on potential ancillary benefits, which are in many cases immediate and highly localised, on the assumption that these are more likely to motivate a pro-active climate policy, at least in the near term. A broad definition of ABs would include, besides health improvements and reduced mortality, improvements in visibility, reduced materials and crop damage, and even reduced congestion from less intensive use of motor vehicles. Here we consider only the human health (morbidity and mortality) benefits of reduction in air pollution as a result of controls on CO₂ emissions.

If there are net social benefits to be realised from cleaner air, why has government not already taken steps to reap them, independently of climate policy? A major reason is that air pollution control policy cannot possibly rely on perfect information about costs and benefits. Moreover, even if environmental standards were in some sense “optimal”, governments have only limited enforcement capacity, usually more limited in developing countries than in developed ones. Thus, the assumption that the actual level of air pollution at any given time and place corresponds to a social optimum is an unrealistically strong one.

If there are ancillary benefits associated with climate policy, then it is possible that over some range of GHG abatement those benefits outweigh abatement costs, resulting in positive welfare gains even without accounting for any primary benefits. In that event, estimates of the magnitude of ancillary benefits at different abatement levels, combined with information on abatement costs, would yield a range of “no regrets” GHG reductions (i.e. those bearing negative or zero net cost). This information would also enable policy makers to calculate an appropriate carbon tax rate, whether the policy objective is to maximise net benefits or to exhaust all “no regrets” options.

Figures 1.a. and 1.b. illustrate the way in which ancillary benefits enter an analysis of optimal climate policy. The ‘gross costs’ curve refers to total CO₂ abatement costs, with the slope of that curve suggesting rising marginal costs. Ancillary benefits of CO₂ abatement increase at a constant rate, reflecting the assumed linearity of the dispersion and dose-response functions for the main pollutants of interest. The assumed linearity of the benefits function makes marginal ancillary benefits (MAB) equal to average ones.

Figure 1a. **Gross and Net Costs of CO₂ Abatement**

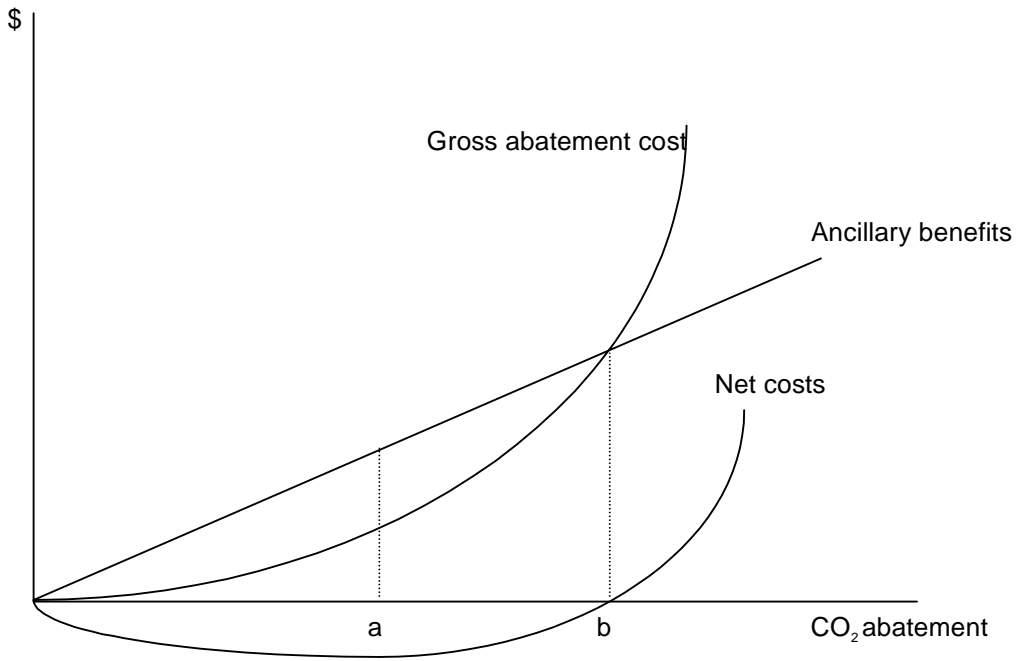
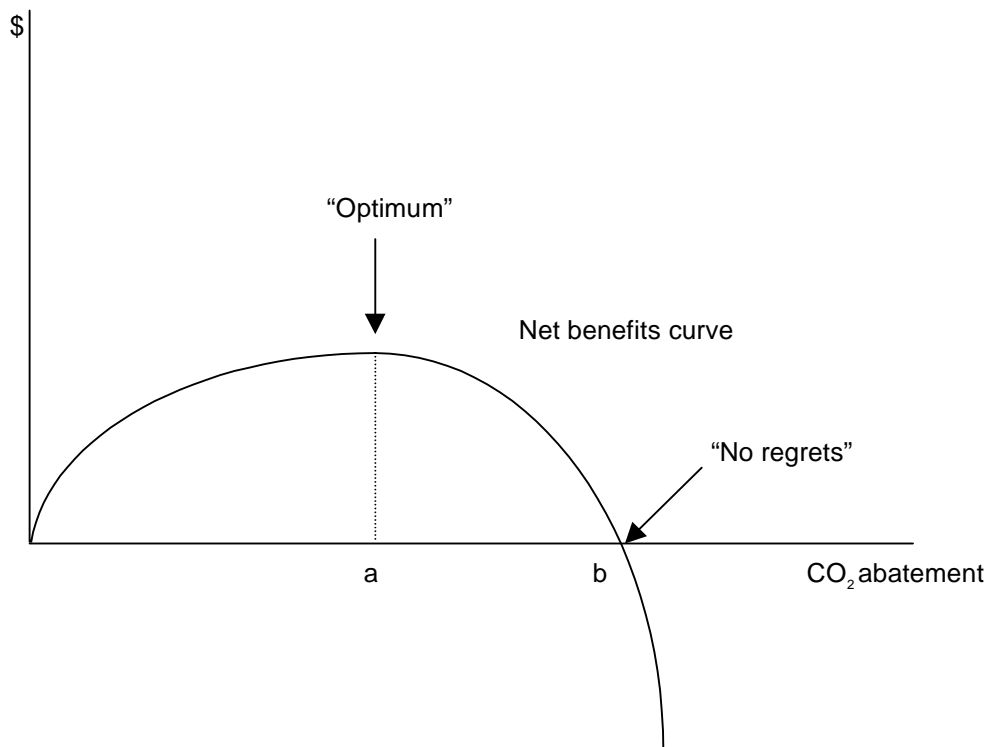


Figure 1b. **“Optimum” and “No Regrets” CO₂ Abatement**



(Note that this assumption could be relaxed without materially altering the analysis; if the marginal benefits decline with increasing abatement, then the benefits curve is convex to the origin.) The “net costs” curve is the vertical distance between abatement costs and ancillary benefits. Even before considering primary benefits, it is apparent that some CO₂ abatement would be better than none and, more specifically, that the net benefits are maximised (net costs minimised) at abatement level *a*, where the marginal costs of abatement are equal to the marginal ancillary benefits. (Assuming primary benefits are positive, then their inclusion would rotate up the benefits curve and shift the optimal abatement level to the right.) At any level of abatement up to *b*, there are negative net costs (i.e. “no regrets”), though beyond point *a* the size of net benefits is diminishing.

Point *a*, then, can be considered the *quasi*-optimal level of CO₂ control (*quasi* because only ancillary benefits are considered, not primary ones). It does not follow that the particular policies introduced to achieve that level of CO₂ control are the least-cost means of realising those ancillary benefits. If we suppose for simplicity that the benefits derive solely from reducing emissions of respirable suspended particulates (PM-10), then an efficient policy instrument (like an emissions tax targeted directly at PM-10 emissions) would very likely achieve a given particulate reduction at lower marginal cost than an instrument targeted at CO₂ emissions or the carbon content of fuels³. How good a substitute the one policy is for the other depends on how close the cross-elasticity of PM-10 emissions with respect to a carbon tax is to the own-price elasticity of PM-10 emissions.

The ancillary benefits curve in Figure 1.a. passes through the origin since we are concerned only with how CO₂ abatement affects emissions of other pollutants and associated damages, starting from wherever those emissions may have been prior to CO₂ control. In some countries, the pre-climate-policy levels (say of PM-10) may already reflect fairly stringent regulations, while in others such regulations may be either lenient or leniently enforced. In the former group, a large share of the benefits of PM-10 reduction have already been realised through direct controls, while in the latter climate policy has the potential to make a bigger contribution to realising those benefits. This should be reflected in the different particulate emission baselines from which further, climate-policy-linked reductions are measured.

III. THE CHILE DATA AND MODEL

Chile has a population of almost 15 million, one-third of whom live in the greater Santiago area. In 1997, its PPP GNP per capita was \$12 080, roughly on a par with Greece and Slovenia. Life expectancy at birth is 72 years for men, 78 for women — roughly the same as in Denmark. In 1997, the country ranked 34th in the world in terms of UNDP's "human development index" (the highest of any Latin American country). Still, like many other Latin American countries, Chile's income distribution remains rather skewed.

As in many newly industrialising economies, Chile's rapid economic growth has brought with it a worsening of certain environmental problems, notably air pollution from growing energy and motor vehicle use in urban agglomerations like metropolitan Santiago, even as other problems — like access to safe drinking water — have been largely solved. According to one comparison of total suspended particulate (TSP) concentrations in major cities, Santiago's annual average in the early 1990s was about the same as Bangkok's and 50 per cent higher than Bombay's — and more than twice the upper bound of WHO recommendations (World Bank, 1994, Table 1.2).

Chile has a below average per capita commercial energy consumption (just over one ton⁴ of oil equivalent — toe — in 1995, compared with a world average of 1.5 toe), and well below other countries with comparable per capita income. Also, since Chile has until now relied heavily for its electricity on its hydroelectric resources, its per capita CO₂ emissions are below the world average (3.1 *versus* 4.0 tons per capita in 1995) (World Bank, 1999). Total 1995 CO₂ emissions from fuel combustion were approximately 42 million tons (IEA, 1998), while a recent GHG inventory for Chile suggests that agriculture, forestry and land-use change are net carbon sinks (INIA, 1997). Ideally, a complete analysis of climate policy options for Chile would incorporate these sinks as well as sources, but here we must limit our focus to the latter.

The model employed is a dynamic computable general equilibrium (CGE) model of the Chilean economy with a basic structure similar to a number of others built at the OECD Development Centre and used in studies of optimal environmental policy in an open economy (see Beghin *et al.*, 1996 and Beghin *et al.*, 1994). Specific Chilean applications include an exploration of the potential for an environmental double dividend from substituting environmental taxes for trade taxes (Beghin and Dessus, 1999) and an estimation of the impact of trade liberalisation on environmental degradation and public health (Beghin *et al.*, 1999). While this is not the first use of an economy-wide model for assessing ancillary benefits of climate policy (see Boyd *et al.*, 1995, for a US application), it is to our knowledge the first use of such a model for this purpose in a developing country.

The CGE model (whether global, regional, or national) has become a standard tool for integrated assessment of climate change. The principal advantage of this approach lies in the ability to capture feedback effects and market interdependencies that may either mute or accentuate first-order effects, say, of a carbon tax. The disadvantages include a lack of technological detail and possible sensitivity of results to variation of certain key parameter values. Bottom-up models can provide a check on the realism of technology assumptions (see, for example, Burtraw and Toman, 1997, for a comparison of energy

sector specific models and CGE models in estimating ancillary benefits for the United States). In general, it is important to conduct sensitivity analysis on those parameters and assumptions thought to have a sizeable effect on the results.

The Chile model has been calibrated using a detailed social accounting matrix (SAM) for 1992. All markets are modelled as perfectly competitive, with flexible price adjustment. Thus, there is no scope for *x*-efficiency gains, though improvements in allocative efficiency are certainly possible — e.g. as a result of removal of price distortions like energy subsidies. Initial energy subsidies in Chile are relatively small in any case, with fuel and electricity prices reflecting marginal financial costs (World Bank, 1994).

The production technology exhibits constant returns to scale (CRS) and the production structure consists of a series of nested CES functions (see Appendix for a general description of the model). The model is dynamic recursive and is solved for the years 1992, 1995, 2000, 2005 and 2010. The labour force and productivity growth rates are exogenous, with the model solving endogenously for the savings and investment rate. Capital is of the putty-clay variety, with higher substitution elasticities applicable to new investment than to existing (already installed) stock.

For analysing the impacts of climate policy on pollution, two components of the model are particularly important: the energy bundle and the pollution coefficient matrix. We briefly describe how these have been modelled in Section V.

IV. METHODOLOGICAL ISSUES

Making estimates of ancillary benefits involves carefully following the chain linking a specific policy measure to changes in emissions levels to changes in ambient pollutant concentrations to changed human (or animal or plant or material) exposure to environmental/health effects and finally to monetised welfare changes. Each link in this chain involves difficult estimation problems (Figure 2).

Figure 2. **Links in Chain from Policy Measure to Welfare Change**

Policy change (e.g. pollution tax) \Rightarrow Emissions reduction \Rightarrow Lower ambient concentration
 \Rightarrow Reduced exposure \Rightarrow Improved health \Rightarrow Welfare gains

The link (1 \Rightarrow 2) from policy change to emissions reductions is the most tractable, as the effects of policy on emissions are determined by the structure of the CGE model itself — e.g. the relevant price and income elasticities.

To translate emissions reductions into changes in ambient concentration (2 \Rightarrow 3) requires a dispersion model for each pollutant linking location-specific emissions to location-specific concentrations. Given sufficiently rich data on actual emissions by location-specific source as well as on various determinants of pollutant transport (e.g. in the case of air, stack height, emissions velocity, temperature, humidity, precipitation, wind direction and speed), one can estimate the effect of a change in source emissions on ambient pollutant concentration levels at different locations. In the Chile case, there is no source-specific pollution inventory, but there is pollution monitoring data giving readings of ambient concentrations for various locations in the greater Santiago area. With these one can calculate average concentrations of various pollutants in a given period — in this case, yearly. Then, these data can be linked to sectoral emissions by taking the Santiago share of total sectoral output, assuming its pollution intensity is the same in Santiago as in rest of the country. This permits us to say, approximately, that if sector *a* contributes *x* % of total SO₂ emissions in the Santiago area it also accounts for *x* % of average ambient SO₂ concentrations. This assumed linearity in the relationship between emissions and concentrations means that a *y* % reduction in sector *a*'s emissions will also yield a *y* % reduction in ambient concentration, all else equal.

To link changed emissions to changed human exposure (3 \Rightarrow 4), it is necessary to have more than a “simple average” measure of ambient concentration, since actual exposure of individuals may differ significantly from that average. For example, an average Santiago-wide ambient TSP concentration of 100 µg/m³ may be the result of averaging three station readings of 50, 50 and 200. If, however, 80 per cent of the population lives near the 200 µg/m³ station and only 10 per cent near each of the other two stations, the simple average gives a very misleading picture of actual exposure (and potential health effects). Thus, in this study the individual station average concentrations are weighted by the proportion of the Santiago population living “near” each station; this weighted average should better approximate actual exposure levels. It is still a far from perfect measure of

actual exposure, however, as that depends also on the pattern of distribution of work in relation to residence, the proportion of time spent out-of-doors, various climatic factors, and measures taken by individuals to limit exposure.

The link between ambient concentrations (and, implicitly, exposure levels) and health effects (4⇒5) has been studied for a few air pollutants in Santiago, building on a large body of epidemiological evidence for cities in the United States and other countries. The epidemiological studies generally relate variations over time (and to a lesser extent space) in ambient pollutant levels to variations in morbidity and/or mortality. In general, the epidemiological evidence linking suspended particulates (specifically, respirable particulates measured as PM-10) to mortality and acute morbidity appears to be the strongest. In the case of Santiago, a statistically significant, positive relationship has been established between PM-10 and both health endpoints. Ostro *et al.* (1996) estimate that, from 1989 to 1991, a 10 µg/m³ decrease in daily PM-10 levels was associated with a 1.1 per cent decrease in mortality, a result consistent with findings of studies for several US cities (Schwartz, 1994). Applying this to the actual mortality rate in Santiago gives a reduction in deaths of 221 per year or, given the city's population of 4.7 million, roughly 4.7 fewer premature deaths per 100 000 inhabitants (World Bank, 1994). Similarly, Ostro *et al.* (1998) find a significant link between PM-10 and the incidence of respiratory illness in Santiago children, controlling for a range of confounding variables like temperature, season, month and day of the week.

With respect to other pollutants, the epidemiological evidence is somewhat less extensive and conclusive than for particulates. Nevertheless, Ostro (1994) summarises that evidence, suggesting the following relationships. In general, air pollution is most commonly associated with respiratory illnesses, though other illnesses are known to be linked to specific pollutants. For example, elevated blood lead is associated with cardiovascular illness (hypertension and heart attacks) in adults and impaired neurological development in children (measured as reduced IQ). Besides the evidence presented above on PM-10, elevated sulphate aerosol and ozone levels are associated with aggravation of asthma conditions in both children and adults; high ozone causes eye irritation and respiratory symptoms; long-term exposure to particulates, particularly in the form of sulphate and nitrate aerosols, can cause chronic bronchitis and reduced lung function; and elevated carbon monoxide (CO) levels are normally associated with higher incidence of headaches. For the most part, the dose-response studies for other pollutants than PM-10 have been conducted elsewhere than in Santiago, Chile, so coefficient (or function) transfer is necessary⁵. In using the "transfer method", the degree of comparability of sites in terms of those factors that may affect either exposure or health impacts of a given exposure (e.g. climate, occupational distribution of workforce, age and health profile of population) influences estimate reliability (see Desvousges *et al.*, 1998.)

Table 1 summarises the quantitative estimates of health effects associated with each of the main air pollutants examined here, based on available epidemiological evidence. In many cases, the studies provide a range of estimates with a central estimate and lower/upper bounds based on a probability distribution (often given by the central estimate ± one standard deviation). Here we report only the central estimate. Due to the unavailability of suitable dose-response functions, the health effects of exposure to air toxics like benzene, formaldehyde, acetaldehyde, and 1,3-butadiene are not considered⁶. The major effect is likely to be increased incidence of cancer in humans (and cancer-related mortality).

Table 1. Dose-Response Function Slopes (Central Estimates)

	PM-10 (10 µg/m ³)	SO ₂ (10 µg/m ³)	NO ₂ (pphm)	CO (ppm)	Ozone (O ₃) (pphm)	Lead (Pb) (µg/m ³)
Premature mortality/100 000 pop.	4.7				0.006	
Premature mortality/million males age 40-59						350
RHA/100,000	12				7.7	
ERV/100,000	235					
RAD/person	0.575					
MRAD/person					0.34	
Clinic visits for LRI/child age < 15	0.0028					
Respiratory symptoms/person	1.83				0.55	
Respiratory symptoms/adult			0.10			
Respiratory symptoms/1 000 children		0.18				
Asthma symptoms/asthmatic	0.33				0.68	
Chronic bronchitis/100 000 age > 25	44					
Chest discomfort/adult		0.10				
Eye irritation/adult					0.266	
Headache/person				0.013		
IQ point decrement/child age < 7						0.975
Hypertension/million males age > 20						72 600
Non-fatal heart attack/million males age 40-59						340

Note: For blank cells, there is no known significant relationship between the pollutant and health endpoint.

Sources: Ostro (1994); Ostro *et al.* (1998); World Bank (1994).

In estimating health benefits of pollution reductions, the shape of the dose-response function is important. Many of the epidemiological studies suggest that linearity may not be an unreasonable assumption and that is what is normally assumed here. There is, however, some conflicting evidence on this score (see Cropper *et al.*, 1997, for Delhi; Ostro *et al.*, 1996, for Santiago; Xu *et al.*, 1994, for Beijing). Ostro *et al.* (1996) find for Santiago that the incremental mortality impact of rising PM-10 concentrations declines at higher ambient concentrations. For instance, based on their Poisson model, a 10 µg/m³ increase in PM-10 results in a 1.4 per cent increase in mortality from a level of 50 µg/m³, a 0.7 per cent increase for a 10 µg/m³ increase from the mean level of 110 µg/m³, and a 0.4 per cent increase for the same PM-10 increase from 150 µg/m³. Thus, the assumption of linearity may or may not lead to a significantly biased estimate of mortality benefits, depending on how large a change in ambient PM-10 concentrations results from a given policy scenario. (In the MED,MED scenario discussed below, for a 20 per cent CO₂ reduction by 2010, the PM-10 concentration declines by around 15 µg/m³ from a baseline for Santiago of 135 µg/m³).

Health effects are measured in heterogeneous units, depending on health endpoint and pollutant. For instance, mortality effects are normally measured in increased incidence of premature death (e.g. per 100 000 population), while morbidity effects may be measured in terms of either increased frequency of specific symptoms (respiratory symptoms, asthma attack, headache, etc.), increased frequency of hospital admissions or emergency room/clinic visits for a specific condition, or increased number of days of restricted activity attributable to said condition.

Aggregation of these heterogeneous health impact measures requires a common metric, which for economists is usually money. This completes the chain with link (5⇒6), with the welfare change from reduced risk of death and illness measured in terms of individuals' "willingness to pay" (WTP) for these health improvements. The WTP measure is rooted in consumer demand theory, wherein income-constrained individuals choose among all the possible consumption bundles those that yield the highest level of satisfaction (utility). Then, assuming that individuals are maximising utility before some welfare-improving change in environmental quality, the welfare measure tells us how much that change is worth to those individuals in terms of income foregone — in other words, what is the most they would be willing to pay to secure that environmental improvement. The logic is that they would only be willing to pay up to the point where, weighing the income foregone against the environmental quality improvement, they would be no worse off than in the *status quo*. Aggregation of WTP across all individuals gives a measure of how much this environmental improvement is worth to society as a whole.

More specifically, peso (or dollar) values must be attached to changes in mortality risk and changes in incidence of morbidity. There is a vast valuation literature for the United States (see Viscusi, 1993, for a review), but no comparable literature for Chile (and precious little for other developing countries: exceptions are Simon *et al.*, 1999, for mortality risk in India, Liu *et al.*, 1997, for mortality risk in Taiwan, and Alberini *et al.*, 1997, for morbidity change in Taiwan). The absence of Chile-specific valuation studies necessitates a transfer of benefits estimates from studies done elsewhere, with appropriate adjustments for differences in living standards and other relevant variables. One possible approach is to select among the numerous studies the one(s) that pertain to a study site deemed to have relevant characteristics most like those of Chile. A second is to average estimates across the various studies to arrive at a mean value for a particular impact, without regard to site-specific characteristics. A third is to take a range of estimates from the various studies and to calculate a comparable range for Chile. A fourth is to conduct a meta-analysis of existing studies, so as to take advantage of the information on determinants of risk valuation contained in those studies.

Bowland and Beghin (1998) perform a meta-analysis on hedonic wage estimates of the value of a statistical life (VSL)⁷, which are in turn derived from estimates of the wage differentials paid to compensate individuals for assuming an increased risk of work-related fatality. They then apply their preferred model specification to the Chilean case, providing a range of VSL estimates (in 2010 under a business as usual — BAU — scenario) between \$518 656 and \$674 997 (at 1992 PPPs). The PPP per capita income adjustments made in that study, however, are based on Summers and Heston, while more recent World Bank adjustments suggest that Chilean PPP per capita income in 1992 was much higher relative to US per capita income, viz., about 38 per cent of the latter⁸. Given the GDP growth rates assumed in our baseline scenario (see below), Chile's PPP per capita income in 2010 should be roughly 80 per cent of the 1992 US level, so that the end-year VSL estimate for Chile needs to be adjusted upward accordingly. By just how much depends on the assumed income elasticity of VSL.

Since the VSL estimate for Chile is a transferred value based on studies done mostly in the United States, where PPP per capita income is more than twice that in Chile, the choice of income elasticity of VSL (or marginal WTP for reduced mortality risk) makes a difference to the Chilean VSL estimate. A number of morbidity risk studies find an income elasticity of WTP below unity (Loehman and De, 1982; Alberini *et al.*, 1997), while the

results of mortality risk studies are less consistent, with one meta-analysis of US studies yielding an elasticity estimate significantly greater than one⁹ (Bowland and Beghin, 1998) and another an estimate less than one (Liu *et al.*, 1997; see also Krupnick *et al.*, 1996). Since we have no *a priori* reason to prefer one hypothesis to the other, we initially assume an income elasticity of unity for the base case and perform sensitivity analysis around this value.

Similarly, we assume a base-case income elasticity of WTP for morbidity reductions equal to unity, then perform sensitivity analysis. In this case, the empirical findings from other studies are more consistent, so the assumption of elasticity < 1 seems more defensible than that of elasticity > 1. A further issue — but one not of central concern here — is whether we have reason to suppose that the elasticity for morbidity risk reduction is significantly different from that for mortality risk reduction.

Table 2 contains estimated monetary benefits associated with a unit change in each of the health endpoints enumerated in Table 1.

Table 2. Estimated Monetary Values of Unit Changes in Various Health Endpoints
(1992 PPP \$)

	Estimate for United States, 1992	Equivalent Estimate for Chile ^a , 2010	Units	Estimation Method
Value of a statistical life (VSL)	2.5	2.1	\$million/death avoided	Hedonic wage method (HWM), Contingent valuation method (CVM)
Respiratory hospital admission (RHA)	7 058	5 871	\$/event	Cost of illness(COI)
Emergency room visit (ERV)	199	166	\$/event	COI
Restricted activity day (RAD)	57.5	47.8	\$/day	Wages foregone
Minor restricted activity day (MRAD)	24.3	20.2	\$/day	CVM
Clinic visit for LRI in children	...	160	\$/visit	Medical costs
Chronic bronchitis in adults	237 604	197 633	\$/case	CVM
Asthma attack	33.4	27.8	\$/attack day	CVM
Respiratory symptom day	6.7	5.6	\$/day	CVM
Child respiratory symptom day	5.4	4.5	\$/day	CVM
Adult chest discomfort case	6.7	5.6	\$/event	CVM
Eye irritation	6.7	5.6	\$/event day	CVM
Headache episode (avg. of mild and severe)	27.2	22.6	\$/event day	CVM
IQ decrement	2 957	2 460	\$/point loss	Human capital
Hypertension in adult males	696	579	\$/case	COI
Non-fatal heart attack	53 040	44 117	\$/event	COI

Notes: ^a The conversion factor for the Chilean estimates is the ratio (2010 per capita GDP for Chile at 1992 PPPs/1992 per capita GDP for US at 1992 PPPs) = 0.83; this assumes an income elasticity of WTP for both mortality and morbidity benefits = 1. The 2010 Chilean per capita GDP figure is based on an annual growth rate of 4.5 per cent, the baseline growth assumption for the simulations in the next section.

Sources: Krupnick *et al.* (1996), U.S. EPA (1997), Beghin *et al.* (1999, appendix); communication with Jose Miguel Sanchez, Universidad de Chile.

V. THE BASELINE SIMULATION

The model simulations are designed to estimate the approximate size of potential ancillary benefits of climate policy in Chile, to calculate net welfare gains (losses) associated with different levels of CO₂ abatement, and to determine the “optimal”¹⁰ and “no regrets” levels of abatement. Since the initial commitment period for Annex 1 parties to the Kyoto Protocol (KP) begins only in 2008 (and is centred on 2010), it seems very unlikely that non-Annex 1 countries would make firm commitments to control their own GHG emissions earlier than that date. Thus, 2010 is chosen as the relevant end-year for the model simulations and calculation of potential welfare impacts of climate policy.

As a comparator for evaluating the effects of climate policy, we must first construct a baseline (or reference) scenario in which no climate policy is introduced in Chile but, as far as possible, other key developments in both the domestic and the international policy environment are adequately reflected. The welfare changes associated with various policy scenarios are then calculated relative to the baseline level of disposable income.

As explained in Section II, domestic environmental policy assumptions are crucial, since a failure to account for actions that are likely to be taken to control domestic pollution even in the absence of climate policy could bias estimates of the latter’s net benefits. Predicting what future emissions of specific pollutants would be in the absence of climate policy is very difficult; the best one can expect to do is to reflect the likely effects of government policies that are already being implemented or have a high probability of implementation (see below for assumptions about lead and PM-10 emissions in the baseline).

The baseline simulation assumes a Chilean per capita GDP growth rate of 4.5 per cent per annum to 2010, slightly lower than the 5 per cent per annum growth achieved over the decade 1987-97. Autonomous energy efficiency improvements (AEEI) are assumed to occur over time at a rate of 1 per cent per year. (Over the past quarter of a century, the energy intensity of GDP in Chile has declined by roughly 1 per cent per annum, so this seems a reasonable assumption.) The AEEI reflects exogenous technological advance and the historical experience of most countries that, once energy efficiency enhancing innovations have been introduced (perhaps initially in response to an energy price increase like the 1975 oil price shock), they persist even if energy prices subsequently decline. Naturally, the size of this coefficient has implications for the evolution of the energy intensity and, by implication, the CO₂ emissions intensity of GDP.

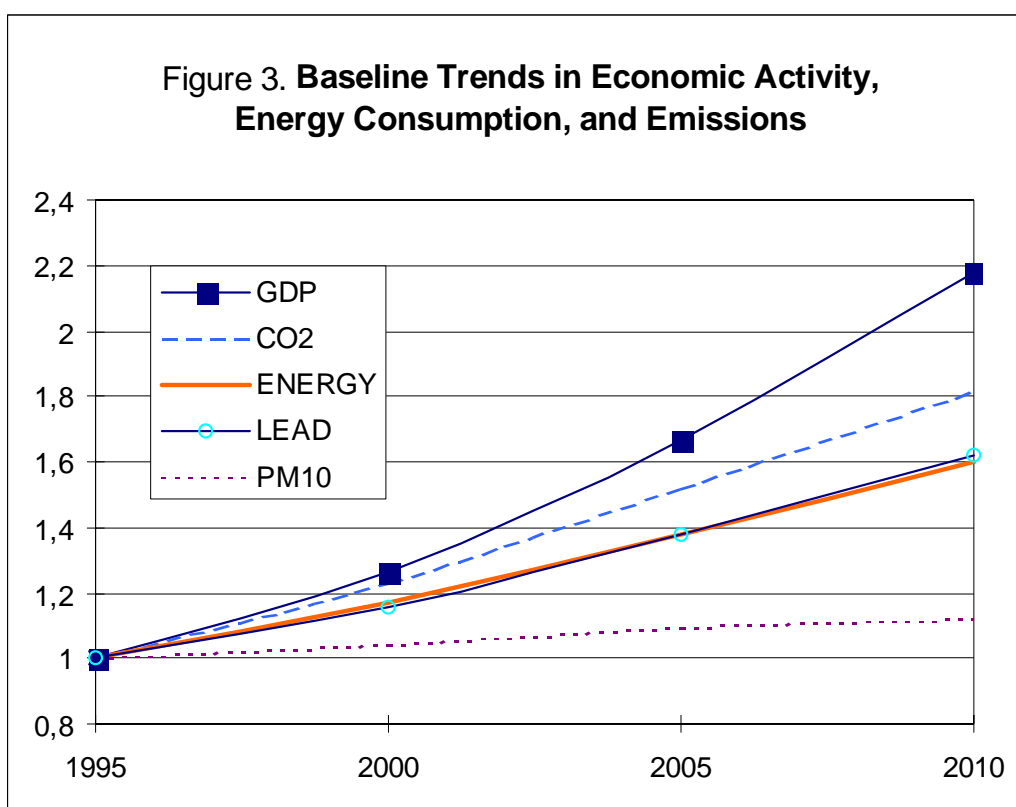
Table 3 summarises the key assumptions about parameter values used in the baseline simulation and also reports values of the main variables for the base-year and for 2010, as well as annual growth rates over the scenario period. Figure 3 shows the trends in these variables in the baseline. Largely because of the AEEI, GDP grows faster than energy demand but, because of assumed developments in the electricity sector (see discussion below), CO₂ emissions grow faster than energy consumption.

Two sets of modelling assumptions are particularly important for ancillary benefits assessment — those defining the evolution of the energy sector and those affecting the pollution intensity of economic activity.

Table 3. Key Exogenous Assumptions and Variable Values, Baseline Scenario

	Units	1992	2010	Growth rate p.a., 1992-2010 (%)
<i>Exogenous Assumptions</i>				
Labour force	Index	1	1.32	1.5
Productivity	Index	1	1.46	2.1
AEEI	Index	1	1.20	1.0
<i>Key Variables</i>				
GDP per capita	1992 PPP \$	7 834	17 354	4.5
Energy consumption	T.O.E.	15 698	29 943	3.6
CO ₂ emissions	Tons	33 450	78 026	4.8
PM-10 emissions	Tons	28 390	33 220	1.0
Lead emissions	Tons	329	675	4.1

Note: emissions are for Santiago only (except CO₂).
Source: CO₂ emissions data for 1992 are from IEA (1998).



V.1. The Energy Sector

Within any given sector, substitution is possible among four energy sources/types (coal, refined petroleum, gas, and electricity). The electricity sector can consume any of the first three, but at present (and in the base-year of the model) hydro power accounts for more than half of electricity generation. Due to both physical constraints and government policy, hydro is expected to grow very slowly in the future. The overwhelming share of incremental electricity demand will be met from other energy sources. The importance of gas is expected to grow upon completion of major projects currently underway, including a gas pipeline from fields in Argentina and an electricity distribution network for the import of gas-generated electricity from that country. We have therefore constrained growth of hydro capacity while at the same time ensuring reasonable growth in gas capacity through *a*) a base-line subsidy to gas consumption combined with *b*) a relatively high Armington elasticity for gas imports. On the one hand, the hydro capacity constraint should raise adjustment costs to a climate policy shock, while on the other a supply of relatively cheap gas should lower those costs. The net effect is not known *a priori* (but it is possible to test for the separate effects by solving the model sequentially, introducing a new constraint each time; in a linear model, the order in which the constraints are entered should not make a difference to the outcome).

Returning to Figure 3, the constraint on hydro capacity expansion explains why CO₂ emissions grow more rapidly than energy demand in the baseline. In short, over the next decade, even as electricity comes to account for a growing share of energy consumption, carbon-based fossil fuels are expected to supply a growing share of that electricity.

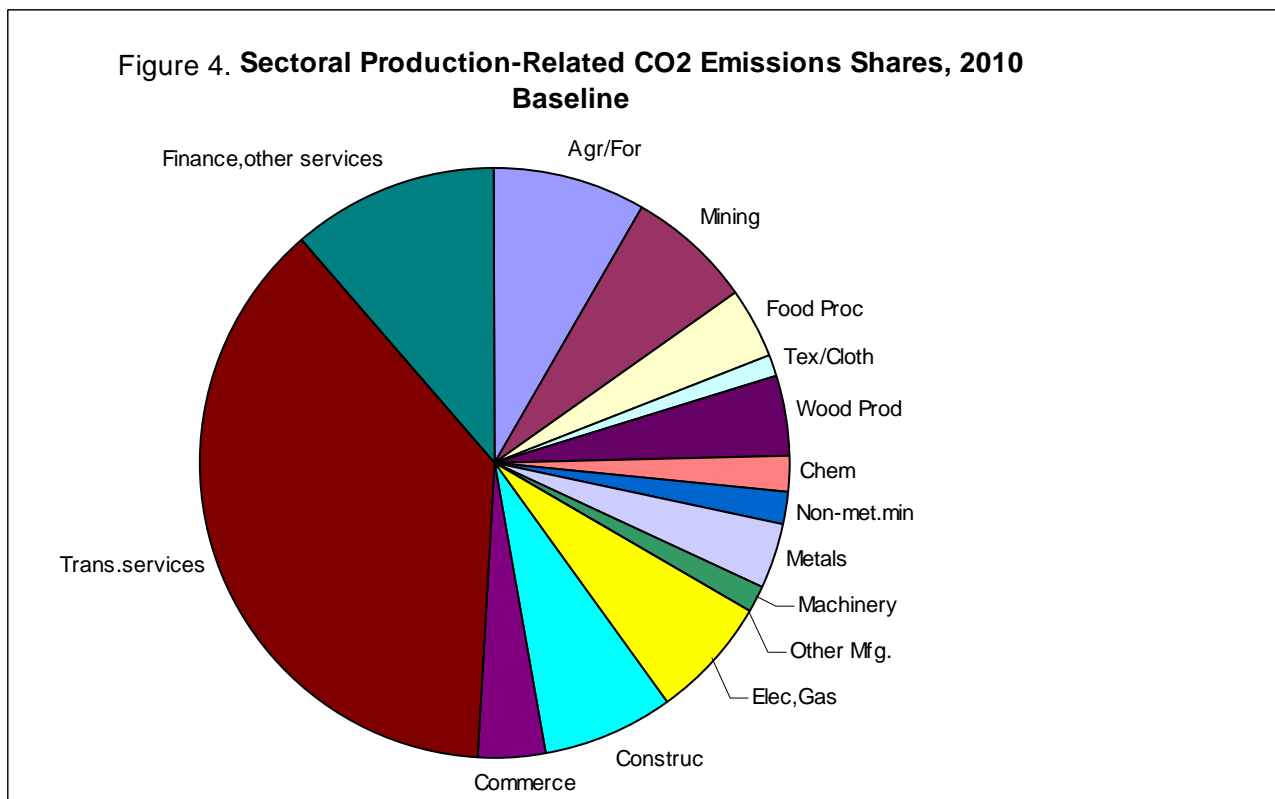
V.2. The Pollution Coefficients

The model includes a matrix of sectoral emission coefficients for seven air pollutant categories (including one composite category, bioaccumulative metals, which contains lead). In the first instance, pollution coefficients are derived from estimates for the United States of the World Bank's pioneering IPPS project (Hettige *et al.* 1995). The World Bank's pollution coefficients, which are output-based (e.g. kilograms of PM-10 per million dollars of output), have been transformed into input-based estimates by regressing them on intermediate inputs (including different energy sources) in the sectoral production functions (for a description of the methodology used see Dessus *et al.*, 1994). Adjustments to the US coefficients have been made to represent more nearly Chilean conditions, specifically in the cases of PM-10 and lead. Since reductions in these two air pollutants account for the overwhelming share of estimated health benefits for Santiago, we have taken special care to reflect government policies relating to these pollutants in our baseline assumptions, so as to minimise risk of upward bias in our ancillary benefits estimates.

In the case of PM-10, recent ambient concentration data for Santiago indicate significant reductions since the early 1990s. We therefore assume that policy will have a significant impact on particulate emissions over the scenario period, in particular, that the sectoral emission coefficients will decline at a rate of 3 per cent per annum to 2010. This is why Figure 3 shows a rather shallow PM-10 emissions gradient in the baseline (amounting to a little over a 15 per cent increase from 1995 to 2010).

In the case of lead, the transfer of US coefficient estimates to Chile is thought to be particularly problematic because of the success the United States has had in phasing out lead use in gasoline. Thus, we have applied the regulation on lead content of gasoline in Santiago (0.18 g/l effective from 1995) to base-year gasoline consumption to estimate motor vehicle-related lead emissions, then allocated the remainder of lead emissions in the base year to other sectors in accordance with the US coefficients, constraining total Santiago emissions to yield the average ambient concentration of 1.5 $\mu\text{g}/\text{m}^3$, given the dispersion function. Since, however, Chile has the intention to phase down leaded gasoline use over time (and appears, from recent World Bank data, to have made progress in this direction), we have incorporated a 75 per cent reduction in the transport sector emission coefficient for lead over the period to 2010. Despite this, lead emissions grow rather strongly in the baseline. This is largely because of the high income elasticity of demand for transport services, but also owes something to the growth of lead-emitting industrial sectors. The non-transport-sector emission coefficients are held at their base-year values, since we have no knowledge of policy initiatives relating to lead sources other than gasoline combustion.

Not in the World Bank's list of air pollutants, carbon dioxide (CO_2) — the principal greenhouse gas — has been incorporated in the pollutant matrix for the Chilean economy, linked to sectoral consumption of the different fossil fuels, and applying standard CO_2 emission factors to each fuel type. Figure 4 shows the sectoral composition of base-year production-related CO_2 emissions in Chile. While the transport sector is by some margin the largest sectoral source, emissions are fairly widely distributed across the economy¹¹.



VI. “OPTIMAL” AND “NO REGRETS” OUTCOMES

The policy simulations are designed to answer three questions:

- 1) how large a reduction in Chile’s 2010 CO₂ emissions relative to baseline emissions could be achieved with “no regrets” — i.e. with zero welfare loss (counting only the ancillary benefits of abatement, but not any primary ones from climate change averted)?
- 2) what is the “optimal” level of abatement in the sense of the one yielding the maximum net benefits — in other words, where marginal abatement costs equal marginal ancillary benefits? and
- 3) what carbon tax rates correspond to the: *i*) “optimum” and *ii*) “no-regrets” solutions?

VI.1. The Basic Policy Scenario

The basic policy scenario (designated MED,MED) assumes: *i*) medium (or central) values for WTP for reduced mortality and morbidity risk; *ii*) medium values of various elasticities of substitution; and *iii*) an elasticity of WTP with respect to income of unity. These assumptions are varied in Section VI.2.

The mortality benefits associated with pollution abatement are calculated outside the CGE model, as are all those morbidity benefits whose estimated values are not based solely on “cost of illness” (COI — see Table 2). Where COI is the basis of the estimate, the benefits are endogenised in the model by assuming that, with lower pollution levels, a smaller-sized outlay is required on health care expenditures to maintain a given incidence of morbidity (or health status of the population). Those reduced health-care expenditures free up equivalent resources to be spent on other goods and services. Mortality and morbidity benefits are summed to yield total ancillary benefits (narrowly defined as human health benefits) associated with a given climate policy. (Remember that these benefits are calculated only for greater Santiago.)

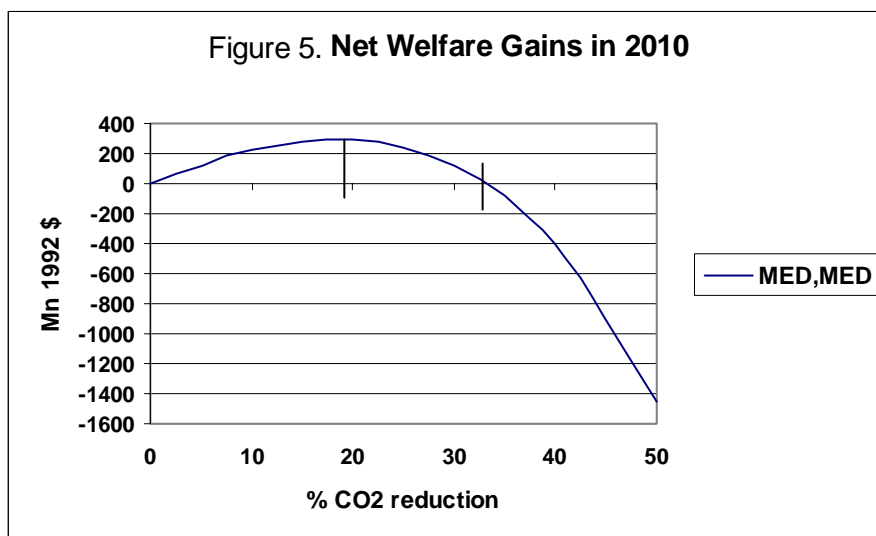
The calculation of mortality benefits outside the CGE modelling framework requires the imposition of separability conditions on both firms’ cost functions and individuals’ utility functions. In the former case, this implies that environmental costs are fixed, entering cost functions independently of own production levels. In the latter case, it implies that the utility of reduced mortality risk is independent of the consumption levels of various commodities.

To obtain net welfare changes, it is also necessary to calculate the effect on disposable income and ultimately consumption of having to commit a growing share of resources to CO₂ abatement. Faced with a policy shock (e.g. a carbon tax), a given productive sector can react by altering its output level, by changing the input mix, or some combination of the two. The sum of the additional costs incurred by all productive sectors in adjusting to the carbon constraint, relative to the (unconstrained) baseline, constitutes the aggregate abatement costs. Consumers ultimately bear these costs in terms of reduced real disposable income. In the model, abatement costs are calculated simply by setting all ancillary benefits equal to zero, then solving for the welfare changes (measured in this case by compensating variation) associated with different rates of CO₂ abatement.

The net social gains (losses) from a given rate of CO₂ abatement are given by *a*) the sum of ancillary benefits (positive) and *b*) abatement costs (negative) (equal to the change in households' disposable income in the “zero benefits” case). As long as *a*) exceeds *b*), the level of abatement is a “no regrets” one.

To answer the three questions posed above, the model is solved for successively higher CO₂ abatement rates (10 per cent, 20 per cent, 30 per cent, etc.). At each abatement rate, welfare gains/losses relative to the baseline scenario are calculated in 2010. These abatement rates and the corresponding welfare changes trace out a curve similar to that in Figure 1.b. Figure 5 plots the curve of welfare gains/losses at different abatement rates (up to 50 per cent) for the MED,MED case. This figure suggests that the “optimal” rate of CO₂ abatement (given the assumptions underlying the MED,MED scenario) is around 20 per cent of baseline 2010 emissions (or roughly 16 million tons of CO₂), while the “no regrets” abatement rate is over 30 per cent.

It is worth noting that over 95 per cent of the ancillary benefits from pollutant reductions in the MED,MED case are ascribable to reduced PM-10 and lead exposure. Of the total, mortality benefits constitute about one-fourth and benefits from avoided IQ loss in children under seven for about half. The remainder consists of benefits from reduced incidence of disease and pollution-related symptoms.



VI.2. Sensitivity Analyses

While the WTP values and substitution elasticity parameter values informing the basic policy scenario are thought to be the best available, given limited information, there remains considerable uncertainty about the “true” values for Santiago and Chile. Inevitably, climate policy will have to be made with limited information. For this reason, it is important to conduct sensitivity analysis on key assumptions to determine the range of possible outcomes. Clearly, to make such an exercise worthwhile, reasonable upper and lower bounds on the values taken by the relevant variables and parameters must be established. Given some distribution of estimates for a particular parameter value, confidence intervals around a central value can be defined. *A priori*, we expect that the simulation results would be especially sensitive to alternative assumptions concerning the following:

- a) For calculating ancillary benefits:
 - i) the estimates of WTP for changes in mortality and morbidity risk
 - ii) the elasticity of WTP with respect to income, and
- b) For calculating abatement costs:
 - j) substitution elasticities between energy and other inputs/factors, and among the various energy sources;
 - jj) the timing of abatement (whether immediate, gradual, or delayed).

We consider first a set of nine scenarios combining low, medium, and high WTP values [a)ii)] with low, medium, and high values of the elasticity of substitution [b)jj)]. Then we turn to income elasticities and timing issues.

Varying WTP Estimates and Substitution Elasticities

Table 4 presents the simulation results for 2010 of the nine policy scenarios obtained by varying both WTP and substitution elasticities (σ). The high and low values of WTP correspond, respectively, to the values at one standard deviation above and below the central WTP estimates for the various health endpoints. In the case of σ , the central values correspond to those in the OECD's GREEN model, while the high and low values represent a doubling and halving, respectively, of the central values. [Note that, in referring to these scenarios, the WTP assumption comes first, the σ assumption second: thus, LOW,HIGH refers to low assumed WTP and high assumed elasticity of substitution. Also note that HIGH σ translates into *low* abatement costs, and vice versa, since the greater the substitution possibilities are, the easier it is to reduce CO₂ emissions.]

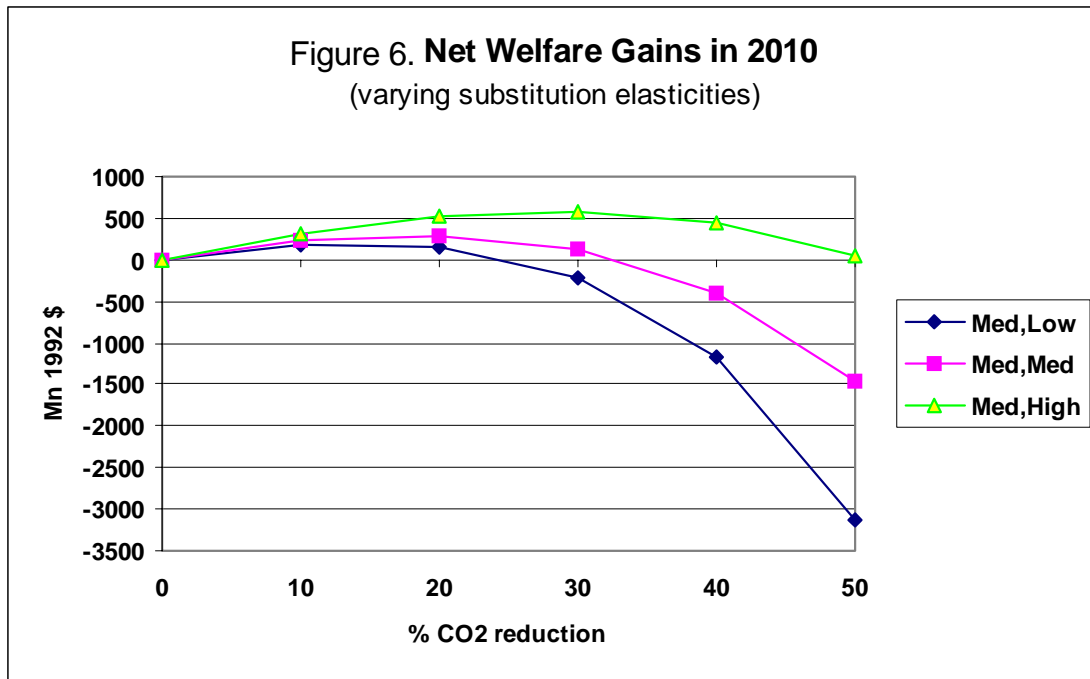
Table 4. Scenario Results for 2010 Varying WTP, Substitution and Income Elasticities

CO2 REDUCTION FROM BASELINE (%)		0	10	20	30	40	50	60
CO2 EMISSIONS 2010 (MT)								
	<i>SubElast</i>							
	LOW	74	66	59	52	44	37	29
	MED	78	70	62	55	47	39	31
	HIGH	90	81	72	63	54	45	36
ABATEMENT COSTS (Mn 1992 \$)								
	<i>SubElast</i>							
	LOW	0	275	780	1653	3127	5656	10333
	MED	0	262	697	1386	2424	4039	6683
	HIGH	0	242	603	1124	1821	2810	4275
ANCILLARY BENEFITS in 2010 (Mn 1992 \$)								
WTP	<i>SubElast</i>							
LOW	LOW	0	293	602	928	1281	1673	2115
LOW	MED	0	311	633	965	1309	1677	2086
LOW	HIGH	0	468	945	1432	1926	2441	2987
MED	LOW	0	455	929	1423	1950	2524	3166
MED	MED	0	488	989	1502	2027	2581	3182
MED	HIGH	0	563	1130	1702	2271	2851	3446
HIGH	LOW	0	588	1198	1832	2502	3226	4032
HIGH	MED	0	634	1283	1945	2620	3326	4085
HIGH	HIGH	0	736	1476	2221	2962	3715	4483
MED + LOW INC EL	MED	0	533	1079	1638	2210	2813	3469
MED + HIGH INC EL	MED	0	411	832	1264	1706	2172	2678
WELF GAINS IN 2010 (Mn 1992 \$)								
WTP	<i>SubElast</i>							
LOW	LOW	0	17	-178	-725	-1846	-3983	-8219
LOW	MED	0	49	-64	-421	-1116	-2362	-4597
LOW	HIGH	0	226	342	308	105	-368	-1288
MED	LOW	0	179	149	-229	-1177	-3131	-7168
MED	MED	0	227	292	117	-397	-1458	-3501
MED	HIGH	0	321	527	578	450	41	-830
HIGH	LOW	0	313	418	179	-625	-2430	-6302
HIGH	MED	0	373	586	560	196	-713	-2599
HIGH	HIGH	0	494	873	1097	1141	905	207
MED + LOW INC EL	MED	0	271	382	252	-214	-1225	-3214
MED + HIGH INC EL	MED	0	149	135	-121	-718	-1867	-4006

Note: Cells showing positive net welfare gains are shaded.

The climate policy maker faces four possible states of information: *i*) complete information about both WTP and σ values (say, the basic policy scenario assuming MED, MED represent the “correct” parameter values); *ii*) complete information about the former but limited information about the latter; *iii*) *vice versa*; and *iv*) limited information about both sets of values.

Taking *ii*) first, Figure 6 shows the options facing the risk-averse policy maker who is confident that WTP (MED) is accurate but much less confident about the flexibility with which the economy can substitute away from carbon-intensive technologies. In this case, a 15 per cent reduction in emissions would appear to be a “safe minimum”, maximising welfare gains in the event of low substitution possibilities. A “no regrets” minimum level of abatement would be approximately 25 per cent of baseline 2010 emissions.



Supposing (as in *iii*) that information on technological possibilities is good [with σ (MED) representing the “correct” elasticity values] but information on WTP is limited, the policy maker’s options are represented in Figure 7. In this case, if WTP turns out to be low, the welfare gains are quite modest. Nevertheless, they are still positive up to around a 15 per cent CO₂ reduction, peaking at just under 10 per cent. Thus, even with a rather low WTP, it is still sensible for government to aim at a moderate reduction in CO₂ emissions by 2010. Only beyond a 20 per cent reduction would welfare losses become significant.

To round off this discussion, let us assume a worst case (as in *iv*), viz. that policy makers have limited information on both the costs and the benefits side. As can be seen from Table 4, the worst possible scenario for welfare gains is represented by LOW,LOW — i.e. low willingness to pay for reduced health risk and low substitution elasticities (hence, high abatement costs). Conversely, the best possible scenario is represented by HIGH,HIGH. The welfare gains under these scenarios are shown in Figure 8 along with those in the MED,MED case. The points of intersection of the LOW, LOW and HIGH,HIGH curves with the horizontal axis define a range of possible “no regrets” CO₂ abatement rates — from a low of around 15 per cent to a high of 60 per cent. [It is worth noting that in a best-case (HIGH,HIGH) scenario — “best” that is for climate policy — the “no regrets” rate of CO₂ abatement for Chile would result in near stabilisation of emissions by 2010 at their 1992 level.] Clearly, the higher abatement rate would represent a “no regrets” outcome only if policy makers were certain that both WTP and substitution elasticities were at the high end of their ranges. In the event of significant uncertainty about those parameter values, a risk-averse policy maker might well opt for a level of abatement effort that minimises expected welfare losses. Up to 15 per cent abatement, assuming a worst case scenario, there would be essentially “no regrets”, while beyond 20 per cent regrets could mount very quickly.

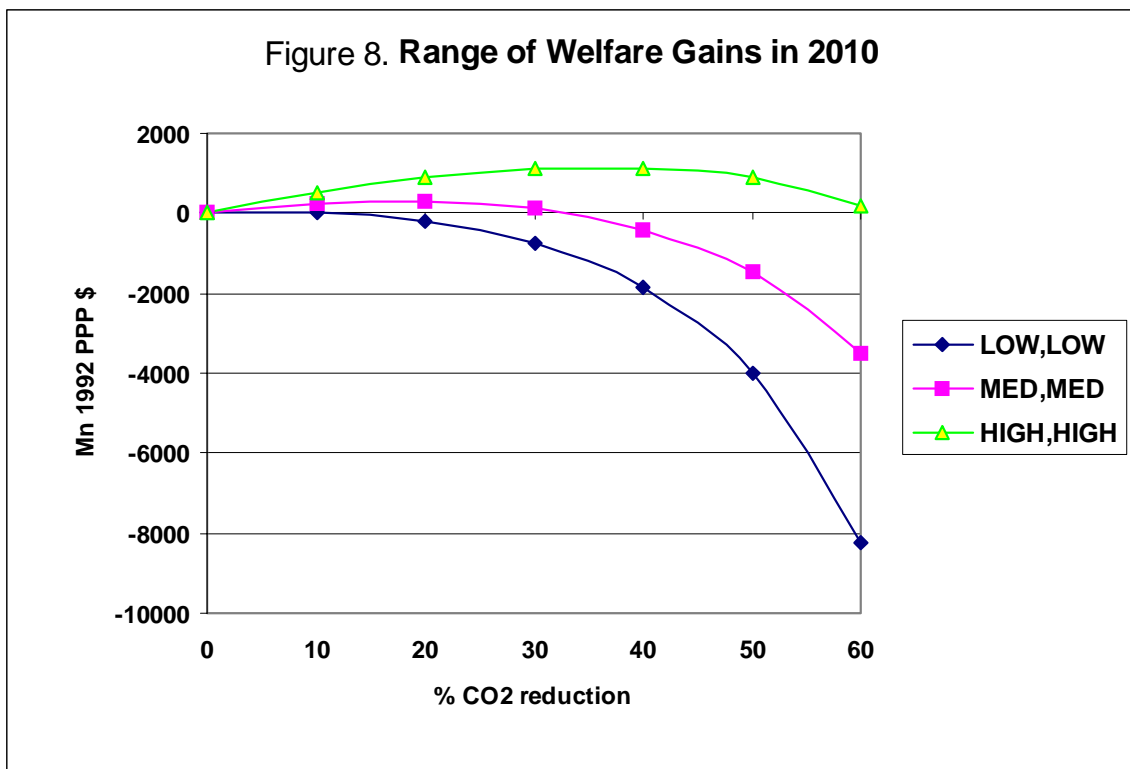
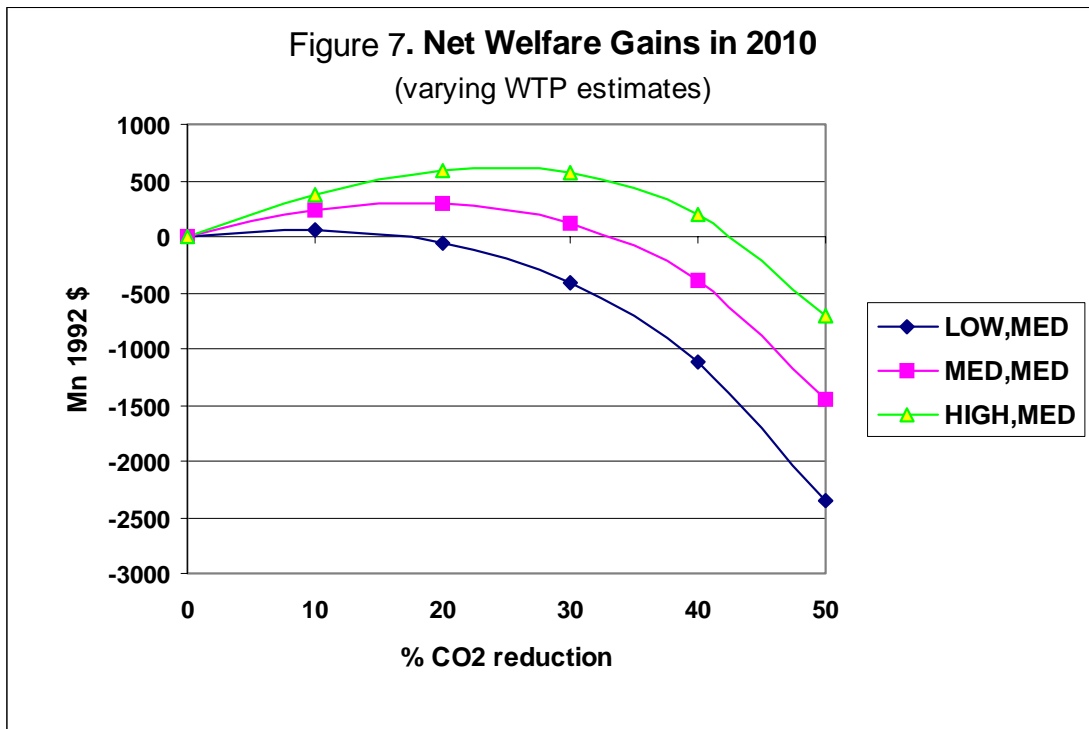
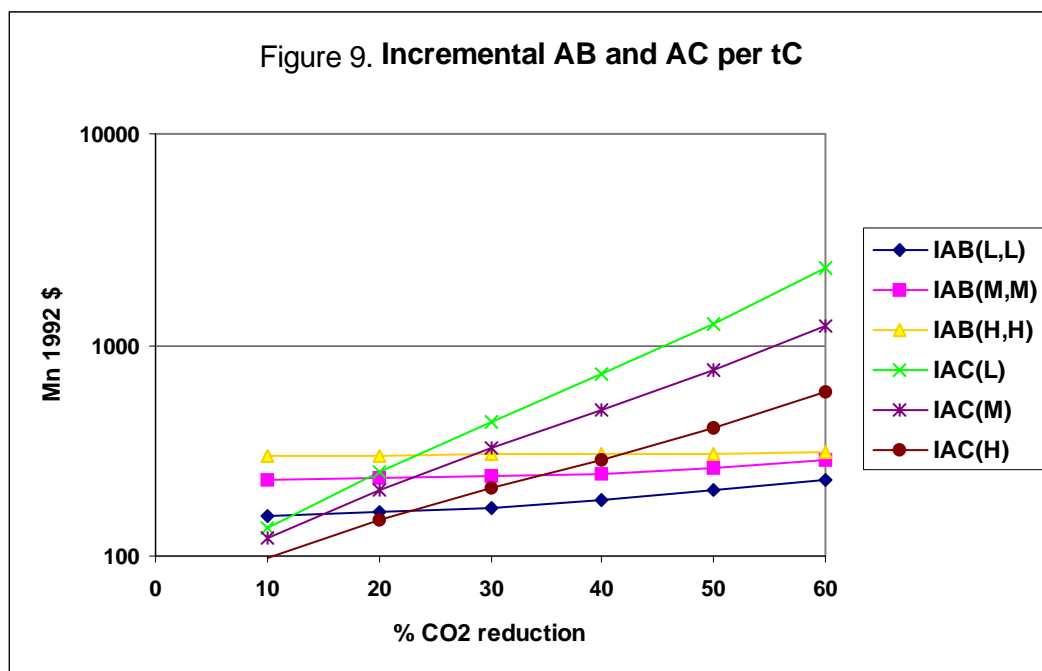


Figure 9 presents some of the same information as in Figure 8 in a slightly different format. In particular, it shows the “optimal” CO₂ abatement rate for the “worst case” (LOW,LOW), “best case” (HIGH,HIGH) and medium case scenarios. These are approximated by the points of intersection of the corresponding incremental abatement cost (IAC) and incremental ancillary benefits (IAB) curves. Thus, the mini-optimum is given by the leftmost intersection point of the IACs and IABs (around 10 per cent reduction), while the maxi-optimum is given by the rightmost intersection point (40 per cent).

In Figure 9, the positions of the three IAB curves are a function not only of the WTP estimates but also of the substitution elasticities. This is because altering the values of σ changes the baseline emissions of both CO₂ (see Table 4) and other pollutants — the higher the elasticity the higher are end-year emissions (constituting in effect a new baseline from which a given percentage emissions reduction translates into a larger volume reduction, hence larger associated health benefits).

In summary, while the range of “optimal” and “no regrets” abatement rates is rather wide, even under rather conservative assumptions about substitution possibilities and health valuations there are likely to be positive net welfare gains from CO₂ abatement up to 10-15 per cent of the 2010 baseline, considering only the health benefits in Santiago of reduced local air pollution. At a minimum, this represents a reduction of roughly 10 million tons of CO₂ (2.7 million tons carbon).



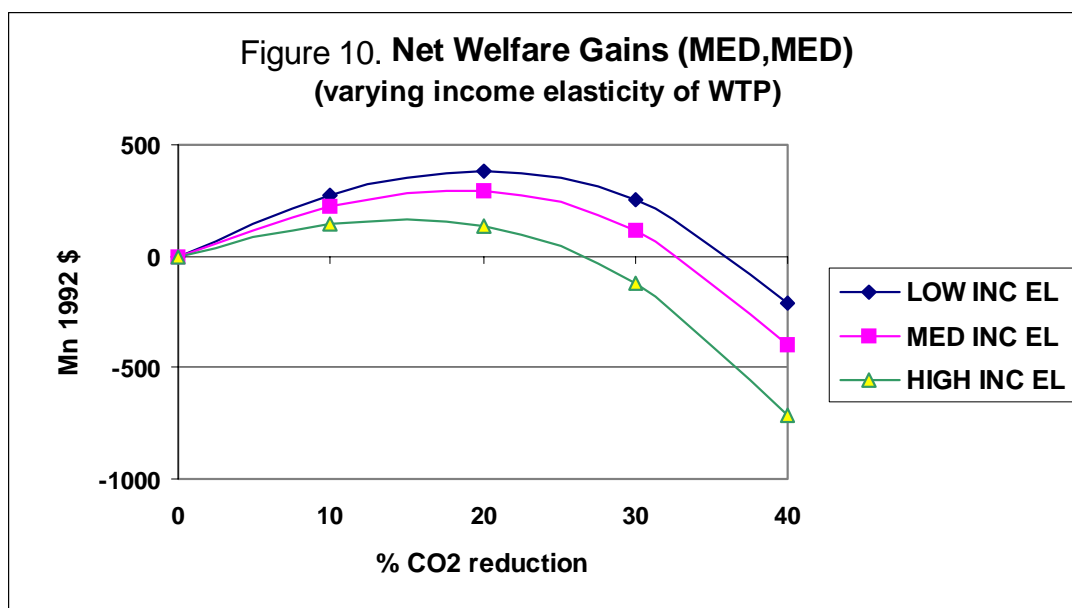
Varying Elasticity of WTP with Respect to Income

Next we consider the effect of varying the income elasticity of WTP for small changes in mortality and morbidity risk. Until now, the simulations have assumed that $\epsilon = 1$. Here we consider the effects of first halving and then doubling ϵ . The results for the MED,MED case are reported in Table 4 and shown in Figure 10.

There are two effects of altering the assumed income elasticity. First, in the base year, most WTP figures are converted from estimated values for the United States to their Chilean equivalents. The adjustment factor depends not only on the difference in PPP per

capita income between the United States and Chile but also on the elasticity of WTP with respect to income. In short, the higher the elasticity, the smaller the Chilean WTP value in the base year for a given relative PPP income. Second, as per capita income rises in Chile, so will the WTP value, but the rate at which the latter grows will depend on its income elasticity. When $\varepsilon = 1$, WTP grows at the same rate as per capita GDP; when greater than one, it grows faster than GDP and the reverse when it is smaller than one. Thus, the higher ε is, the larger the initial downward adjustment in WTP but the faster the subsequent growth. The latter partially (but not fully) offsets the former, so by 2010 the ancillary benefits remain higher with low ε than with high ε (see Table 4).

Figure 10 shows that the low-income-elasticity case yields significantly higher net welfare gains (at the “optimum”) than the high-income-elasticity case. The difference in the “no regrets” abatement level between an income elasticity of 0.5 and one of 2.0 is about 10 percentage points (roughly 27 per cent *versus* 37 per cent), while the difference in the “optimum” level is smaller (15 per cent *versus* just over 20 per cent). As noted in Section IV, there is some empirical basis for supposing that the elasticity value for morbidity risk reductions is less than unity, while the evidence is mixed on the elasticity value for mortality risk reduction. Since in estimating ancillary benefits we combine the two WTPs, we are inclined to attach a relatively low probability to the high income elasticity value ($\varepsilon = 2$).

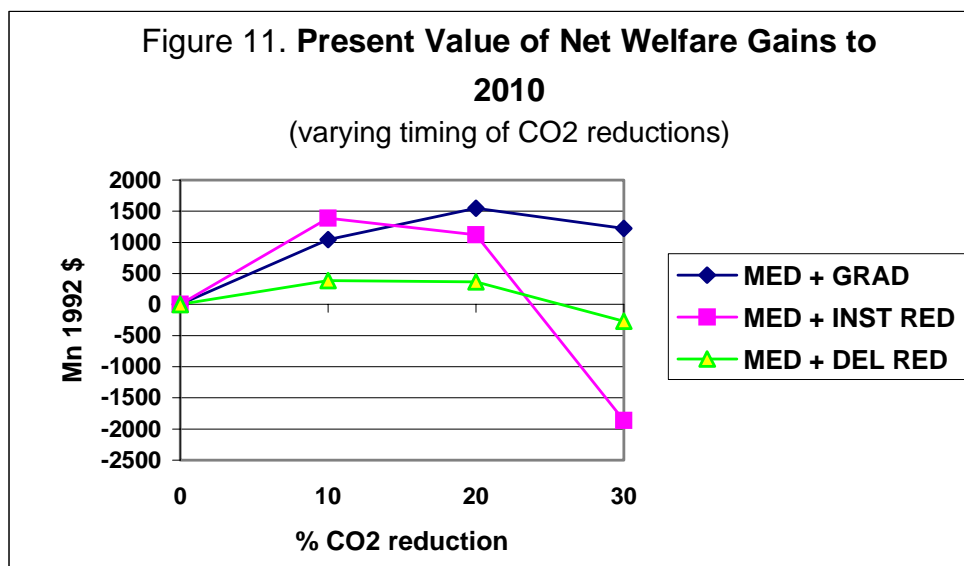


Timing of CO₂ Abatement

Finally, we consider the question of when to abate. Are the expected welfare gains likely to be greater if abatement is delayed to the end of the period, if abatement is immediate, or if it is done gradually over the entire period? Arguments for delay usually centre around the scope for lowering abatement costs by waiting for new technologies to become available (e.g. in response to Annex 1 countries’ KP-induced innovation). Arguments for early action usually cite costs averted from premature obsolescence of polluting capital equipment. We simulate three different time profiles of CO₂ reductions (up to 30 per cent) to examine how timing affects the present value of net benefits. We cannot fully capture the sorts of effect hypothesised: for instance, given the recursive model structure, the expectation of having to reduce CO₂ by a given amount by some

future date does not affect current resource allocation (e.g. it does not spur investment in carbon-saving technologies); rather, productivity and energy efficiency improvements are exogenous. As for costs of premature scrapping of capital equipment, these do get reflected in declining returns to capital in fossil-fuel-intensive sectors in response to a carbon tax. In effect, the shorter the timespan in which a given emissions reduction is to be made (whether it be done early or late), the higher the adjustment costs will be. Delay, however, ensures that a larger proportion of the capital stock is saddled with depressed returns, hence high switching costs.

Figure 11 shows that instantaneous reduction yields slightly higher net welfare gains (in present value terms, with a 5 per cent discount rate) for modest reductions, but beyond 15 per cent abatement the gradual approach yields higher gains. This result arises from the fact that benefits are realised almost immediately while, with modest abatement, costs are low. Making larger reductions, however, requires much bigger economic adjustments that are costly to realise in such a short time period. Considering that a “safe” abatement rate, taking account of various sensitivities, is between 10 and 15 per cent, it would seem that there is little penalty (and perhaps even a net welfare gain) from taking early action. In no case does it pay to delay abatement to the end of the period, since the net benefits are consistently below those for immediate and gradual reduction. Besides the cost considerations mentioned above, this also reflects the nature of the optimisation problem, wherein postponing abatement investment implies postponing realisation of health benefits. This contrasts with the standard treatment of CO₂ abatement, which neglects ancillary benefits and considers only those (primary) benefits that are expected to occur well after abatement costs are incurred (especially in the case of early abatement).



Comparison of Chile Results with Those of Other Studies

To compare our results with other studies, it is useful to calculate the ancillary benefits per ton of carbon reduction (AB/tC) for comparable levels of CO₂ abatement. Considering only emission-related benefits (i.e. excluding congestion and noise reduction), Ekins (1995) finds from his review of European studies a range of estimates of AB/tC up to \$200 with a

mean of \$100, while Burtraw and Toman (1997) report, based on a review of eight US studies, a mean AB/tC estimate of around \$24/tC (virtually identical to Ayres and Walter, 1991), with a lower-bound estimate of \$3 and an upper bound of \$79.

Burtraw and Toman acknowledge the possibility that the relatively high European estimates may reflect important differences from the United States — e.g. the higher European population densities and exposure rates, and the different transport and deposition patterns (with much air pollution in the eastern half of the United States being transported out to sea, while pollution in Europe is transported inland and deposited on productive, populated land areas).

Our Santiago, Chile estimates of AB/tC reduction range from \$150 to \$300 (at 1992 prices and exchange rates), depending on the scenario (and considering abatement rates up to 30 per cent of the 2010 baseline emissions). The mean value of AB/tC for the MED,MED case is \$235, towards the high end of the range of estimates for European countries. The relatively high Chilean AB estimates are explainable primarily in terms of the different pollution baselines in Europe *versus* Chile. Because the pre-existing concentrations of key air pollutants — PM-10, lead, etc. — are significantly higher in Santiago than in most major Western European cities, climate policy has a much greater potential in the former to contribute to air quality improvements. This should be reflected in the different degrees of responsiveness of other pollutants to a given reduction in carbon emissions, with the responsiveness higher in Chile than in Western Europe. Thus, for example, the effect of reducing Chile's 2010 carbon emissions by one ton is to reduce total particulate emissions (TSP) by 2.5 kg.; this is roughly double the C/TSP cross-emission coefficient calculated for Norway in 2000, assuming introduction of a carbon tax in 1995 (Norwegian Central Bureau of Statistics, 1991, study cited in Pearce, 1992). The relatively high Chilean cross-elasticities between CO₂ and other pollutants imply relatively low marginal abatement costs for the latter compared with Europe and the United States, a result consistent with the hypothesis that those costs should be lower in countries which have undertaken little prior abatement and are therefore still on the shallow portion of their MAC curves.

VII. POLICY IMPLICATIONS

To achieve the desired CO₂ reductions, whatever the chosen level of abatement effort, climate policy makers must select an appropriate instrument. Without a detailed source-by-source CO₂ emissions inventory, it is not possible to state a clear preference between source-specific controls (which might be appropriate if a few sources account for the overwhelming share of total emissions) and more flexible instruments (generally preferred when there are multiple sources with varying abatement costs). Nevertheless, given the fairly wide sectoral distribution of emissions shown in Figure 4 above, and assuming abatement costs vary significantly across sectors, use of a flexible policy instrument would seem justified.

There are essentially two sorts of flexible instrument for climate policy, carbon taxes and quantitative restrictions with tradable permits. In choosing between the two, the degree of uncertainty facing policy makers regarding the abatement cost and benefits functions needs to be considered. Suppose for the moment that the positions of both the ancillary benefits curve and the abatement cost curve are uncertain. As Weitzman (1974) has shown, mis-estimation of the benefits curve will result in equivalent welfare losses whether a tax or a permit scheme is used. In the case of a mis-estimated abatement cost curve, however, which instrument is preferred depends on the relative slopes of the marginal benefits and marginal cost curves. If the cost curve is steeper than the benefits curve, a tax yields smaller welfare losses than a permit scheme. Indeed, this is the case here, with marginal ancillary benefits being almost constant in abatement (a function of the linearity of the underlying relationships), while abatement costs rise steeply beyond some modest level of abatement. Thus, we choose to implement the climate policy as a tax on carbon content of fuels sufficient to achieve a given CO₂ reduction relative to the 2010 baseline.

Table 5 shows the tax per ton carbon for different abatement rates and a range of substitution elasticity assumptions. The lower the substitution elasticities, the higher the tax needed to achieve a given percentage CO₂ reduction — this despite the fact that the absolute reduction is smaller with low σ than with high. Thus, to achieve a 10 per cent reduction would, in the worst case, require a carbon tax of \$90/tC (at 1992 prices) by 2010.

Table 5. **Carbon Tax Schedule for Different Substitution Elasticities**

TAX (\$/tC)	% reduction	0	10	20	30	40	50	60
<i>SubElast</i>								
LOW		0	90	221	424	788	1517	3134
MED		0	60	140	254	440	772	1437
HIGH		0	31	69	121	199	325	535

Table 5 provides too little information to determine the “optimal” carbon tax. Remember that there is a different “optimal” abatement rate, hence a different optimal tax for each set of assumptions regarding WTP and substitution elasticities (i.e. each scenario). To make use of all the information available, we can estimate, using OLS, a quadratic function relating changes in disposable income relative to the baseline (DI)¹² to the carbon tax, both in log form:

$$\ln DI = \beta_1 \ln tax + \beta_2 (\ln tax)^2 + \sum_i \alpha_i S_i + u$$

where the S_i are fixed-effect dummies for the nine scenarios discussed above¹³ and u a random disturbance term. Setting the first derivative equal to zero, we can solve for the “optimal” (welfare maximising) tax, which turns out to be \$116/tC. The average “optimal” tax based on separate estimation for each of the nine scenarios is \$139/tC, while the MED,MED “optimal” tax is estimated at \$129/tC. So, we have an “optimal” tax range of roughly \$115-140/tC in 2010. Introducing and gradually increasing a carbon tax to around \$120/tC by 2010 should, at the very least, reduce CO₂ emissions by somewhere between 10 and 20 per cent from baseline levels with “no regrets”. At best (i.e. if substitution elasticities turn out to be high), it could reduce emissions by as much as 30 per cent. With medium substitution elasticities, imposing this tax level would yield an increase of 32, 27 and 19 per cent, respectively, in the consumption price of coal, oil and gas in 2010.

A carbon tax of \$116/tC by 2010 would have significant fiscal implications: applied to the 18 million tons of carbon that would still be emitted in 2020 in the MED,MED scenario with just under a 20 per cent CO₂ reduction, the tax would generate revenue of roughly \$2.0 billion. This amounts to one-tenth of the baseline 2010 government revenue of \$19.7 billion. Trade taxes alone account for some \$3.3 billion of baseline 2010 revenue. In our simulations, the carbon tax revenues are redistributed to households in lump-sum fashion. In future work, we hope to examine the potential for reaping a “double dividend” from substitution of a carbon tax for trade (or other) taxes.

How important are the expected welfare gains of an “optimal” carbon tax in the basic policy scenario? The net gains from a 20 per cent (MED,MED) CO₂ reduction (\$292 million) come to a mere 0.3 per cent of baseline Chilean disposable income of \$89 billion in 2010. Total ancillary benefits (for Santiago only) under the same scenario and abatement rate are close to \$1 billion, or 1.1 per cent of 2010 disposable income, while the costs of achieving that level of CO₂ abatement come to less than 0.8 per cent of disposable income.

One important unknown in this analysis is what impact efforts in Annex 1 countries to meet their Kyoto commitments might have on the costs of CO₂ abatement, e.g. through accelerated technological innovation. If that effect is significant, then by 2010 Chile is likely to face an abatement cost curve closer to that given by high substitution elasticities than by low.

VIII. CONCLUSIONS

The main finding of this study is that, for CO₂ reductions over the next decade of 10-15 per cent of baseline emissions, the benefits to Chile are quite likely to exceed the costs. This result is based on rather conservative assumptions about both benefits (taking a low WTP value and considering only ancillary benefits related to health improvements) and costs (low substitution elasticities, hence high abatement costs). The potential for “no regrets” CO₂ abatement arises from the fact that the instrument to achieve it, a carbon tax, causes changes in patterns and levels of fuel consumption that, on balance, reduce other air pollutants and their associated health damages, from premature death to chronic bronchitis to headaches and sore eyes. Hence, climate policy without tears.

Our estimates of “optimal” and “no regrets” abatement rates for Chile are consistent with findings of other studies, if slightly higher, for example, than those obtained by Boyd *et al.* (1995) for the United States — where LOW,LOW estimates of “optimal” and “no regrets” CO₂ abatement rates are 5 per cent and 8 per cent, respectively. For reasons discussed in the preceding section, we would expect to find higher ancillary benefits of CO₂ reduction in Chile than either Europe or the United States (especially the latter). Also, specific features of the Boyd *et al.* analysis help explain their lower estimates, e.g. the static nature of their exercise and the assumption that carbon tax revenue is retained by the government. Even so, their range of estimated “no regrets” abatement rates (depending on WTP and elasticity assumptions) is as wide as ours — exceeding 60 per cent in a HIGH,HIGH scenario¹⁴.

The analysis has identified two pollutants — PM-10 and lead — as the likely sources of most ancillary benefits for Santiago. Given high initial concentrations and the rapid rate of economic growth, even rather strong assumptions about government policy to control these emissions do not succeed in stabilising them between now and 2010. The growing demand for private motor vehicles occasioned by rising prosperity contributes to the expansion in lead (and also NO_x, CO and VOC) emissions. This effect could even be exacerbated with the expected depressing effect of Annex 1 country policy control measures on world oil prices, which are not considered in the analysis. Meanwhile, even if natural gas does come to supply a growing share of electricity in Chile, the rapid growth in electricity demand combined with limited hydro capacity expansion possibilities virtually guarantee strong increases in carbon-rich fossil fuel use (with modest substitution away from coal towards oil). This in turn complicates efforts to stabilise PM-10 and SO₂ emissions. In the circumstances, climate policy may well be able to play a valuable supporting role.

The analysis for Chile could, given the data and a suitable model, be replicated for other developing countries. Indeed, work is ongoing for China (Jorgenson *et al.*) and the OECD Development Centre intends to perform similar analyses for a few other developing countries. Even if each case is unique, the similarities in urban air pollution problems in the major cities of the developing world, and the fact that ancillary benefits studies for Annex 1 countries consistently find some positive level of “no regrets” CO₂ abatement, would lead one to expect at least modest welfare gains from measured CO₂ reductions in many developing countries. It is also quite possible that, in terms of health endpoints (mortality and morbidity changes), the benefits of climate policy in other developing countries studied would also be relatively large by comparison with more developed countries with

stricter environmental standards already in force. (It bears emphasis that our analysis here for Chile has been in terms of abatement relative to a baseline — put differently, a slower growth of carbon emissions than in the baseline — not absolute reductions from a base-year level as in most Annex 1 country Kyoto commitments.) The key contribution to be made in future work is therefore not in establishing the existence of such “no regrets” possibilities but in improving the measure of their magnitude (and, by implication, of all the underlying parameters and relationships to which that magnitude is sensitive). Given better measures, developing country policy makers should be clearer about what level of CO₂ abatement effort is justified by the near-term welfare gains alone and perhaps also more willing to “take the plunge” of committing themselves to emissions targets.

NOTES

1. What the US literature calls “ancillary benefits” the European literature refers to as “secondary benefits”.
2. Like the other studies, ours focuses on the major GHG, CO₂, which accounts for two-thirds to three-quarters of total GHG emissions in most countries.
3. In that case, of course, any climate-related benefits from reducing GHGs would be ancillary to the primary benefits of PM-10 reduction.
4. We follow the convention of using “ton” to refer to a metric ton.
5. The exception is Ostro *et al.* (1998), which also examines data on ozone levels and, in certain model specifications, finds a significant link to frequency of clinic visits for children’s respiratory problems.
6. See Appendix H of U.S. EPA, *The Benefits and Costs of the Clean Air Act, 1970 to 1990*, for a discussion of evidence on health and other effects of air toxics.
7. As noted by Krupnick *et al.* (1999), one problem with transferring hedonic-wage-based VSL estimates to a pollution context is that the risk in the former case is of accidental death, while that posed by the latter often involves delayed effects (e.g. cancers) or risk changes that occur only later in life. Also, with some pollution effects, the period of illness prior to death can be protracted and painful. Finally, occupational risk is in a sense voluntary (in that the individual normally has the option either to refuse a job offer or to quit), while to a large degree pollution exposure risk is not.
8. The VSL estimates for each of the policy simulations discussed in Section V will be slightly different, since they are a function of end-year per capita income, which will vary with the welfare effects of the scenario.
9. Bowland and Beghin (1998) use an income elasticity of 2.27 in their calculations, which further reduces the base-year VSL but with a faster increase in VSL with income growth than in the case of unitary elasticity.
10. As noted above, the level is only *quasi*-optimal, since the analysis abstracts from the primary benefits of CO₂ abatement.
11. Note that these are gross emissions (mostly related to fossil-fuel use), so that the sink functions of the agriculture/forestry sector mentioned above are not captured.
12. DI is defined as the sum of disposable income in the baseline scenario plus the welfare change corresponding to a given abatement rate.

13. Note that in this exercise we are implicitly assigning an equal probability to each scenario (i.e. each combination of WTP and σ).
14. Whereas global and regional CGE-based climate models are generally more pessimistic about CO₂ abatement costs than most bottom-up engineering models, CGE-based ancillary benefits studies are generally more optimistic about the size of ancillary benefits per tC abated than bottom-up energy-sector models. In both cases, this reflects the more comprehensive assessment that is possible within a CGE framework.

APPENDIX. THE MODEL

The model used in this paper originates directly from a prototype model (Beghin, Dessus, Roland-Holst and van der Mensbrugge, 1996) built for the OECD Development Centre research programme on environment and trade. It is calibrated on the data contained in the Chilean Social Accounting Matrix (SAM) estimated for the year 1992. The version of the SAM used in this paper includes 1 household, 72 sectors, 1 labour type, 2 trade partners (Annex 1 and non-Annex 1 countries) and 14 different polluting emissions (of which 7 are air pollutants). The model is dynamic and solved recursively for the years 1992, 1995, 2000, 2005, 2010. The behaviours of economic agents are modelled according to neo-classical economic theory, and the rest of the equations consist in accounting identities. The following subsections briefly describe the main characteristics of the model.

Production

The Constant Elasticity of Substitution production function is a nested structure taking into account optimising behaviour in the choice of production factors. It assumes constant returns to scale. Output results from two composite goods: non-energy intermediates and energy plus value added. The intermediate aggregate is obtained by combining all products in fixed proportions (Leontief structure). The value added (VA) and energy component is decomposed in two parts: aggregate labour and capital & energy (KE). The capital-energy bundle is further disaggregated into its basic components. By using a putty/semi-putty specification, the model distinguishes between the allocation of capital existing at the beginning of the period, or already installed (*old* capital), and that resulting from current investment (*new* capital), assigning different substitution elasticities to each. Finally, the energy aggregate includes four types of energy that are substitutes: coal, oil, gas and electricity. Figure A.1 depicts the nested decision process in the choice of production factors. Substitution elasticities reflect adjustment possibilities in the demand for production factors originating from variations in their relative price. In particular, the central (MED) elasticity values in the model are: 0.00 between intermediates and value added with *old* capital plus energy; 0.50 between intermediates and the VA/KE aggregate incorporating *new* capital; 0.12 between aggregate labour and the *old* capital-energy bundle; 1.00 between aggregate labour and the *new* capital-energy bundle; 0.00 between *old* capital and energy; 0.80 between *new* capital and energy; 0.25 among different sources of energy associated with *old* capital; 2.00 among those associated with *new* capital.

Income Distribution and Absorption

Labour income is allocated to the representative household. Likewise capital revenues are distributed among households, corporations and rest of the world. Corporations save the after-tax residual of that revenue. Private consumption demand is obtained through maximisation of a household utility function following the Extended Linear Expenditure System (Lluch, 1973). Household utility is a function of consumption of different goods and saving. Income elasticities are different for each product, varying in the range from 0.50 for basic products to 1.30 for services. The calibration determines a per capita subsistence minimum for each product, which is constant over the different simulations,

except for health care expenditures, which adjust to reflect changes in health status from reduced pollution. Government and investment demands are disaggregated into sectoral demands once their total value is determined according to fixed coefficient functions.

International Trade

The model assumes imperfect substitution among goods originating from different geographical areas (Armington, 1969). Import demand results from a CES aggregation function of domestic and imported goods. Export supply is symmetrically modelled as a Constant Elasticity of Transformation (CET) function. Producers decide to allocate their output to domestic or foreign markets responding to relative prices. Elasticities between domestic and foreign products are of comparable magnitude for import demand and export supply. Their values are 3.00 for agricultural goods, 2.00 for manufactured goods and 1.50 for services. The small country assumption holds, Chile being unable to change world prices; thus, its imports and exports prices are exogenous. Capital transfers are exogenous as well. The balance of payments equilibrium therefore determines the final value for the current account.

Model Closure and Dynamics

The equilibrium condition on the balance of payments is combined with other closure conditions so that the model can be solved for each period. First consider the government budget. Its surplus/deficit is exogenous and the household income tax schedule shifts in order to achieve the predetermined net government position. Second, investment must equal savings, with these originating from households, government and rest of the world. The dynamic structure of the model results from the last condition of equilibrium between savings and investment. A change in the savings volume influences capital accumulation in the following period. Exogenously determined growth rates are assumed for various other factors that affect the growth path of the economy, such as: population and labour supply, labour and capital productivity, and energy efficiency improvements. Agents are assumed to be myopic and to base their decisions on static expectations about prices and quantities. The model dynamics are thus recursive, displaying a sequence of static equilibria.

Emissions

Emissions are determined by intermediate or final consumption of polluting products. In addition, certain industries display an autonomous emission component linked directly to their output levels. This is done so as to include some polluting production processes which would not be accounted for by considering only the vectors of their intermediates consumption. It is assumed that labour and capital do not pollute. Emissions coefficients associated with each type of consumption and production are derived from a previous study on the determinants of pollution intensity for the United States (Hettige et al., 1995; Dessus et al., 1994) and adapted to the Chilean case. A change in sectoral output or in consumption vectors, either in levels or composition, therefore affects emission volumes. Formally, the total amount of a given polluting emission takes the following form:

$$E = \sum_i \sum_j \alpha_j C_{i,j} + \sum_i \beta_i XP_i + \sum_j \alpha_j XA_j$$

where i is the sector index, j the consumed product index, C intermediate consumption, XP output, XA final consumption, α_j the emission volume associated to one unit consumption of product j and β_i the emission volume associated with one unit production of sector i . Thus, the first two elements of the right hand side expression represent production generated emissions, the third one final consumption generated emissions.

There are 7 air pollutants. Carbon dioxide (CO_2), Sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), volatile organic compounds (VOC), suspended particulates (PART), and bio-accumulative emissions to air (BIOAIR), which include lead. BIOAIR emissions result from the production of various mineral products, the use of lead in certain industrial processes and the use of leaded gasoline in the transport sector. Emissions levels of CO_2 , SO_2 , NO_2 , PART, CO and VOC depend primarily on fossil-fuel consumption. VOC emissions result also from the consumption of chemicals.

Welfare

The chosen yardstick for welfare is a measure of compensating variation (CV) proposed by Sadoulet and de Janvry (1995), to which we add a term to reflect the exogenous component of welfare change from reduced health damages. If E is the monetary equivalent of the utility function, and y disposable income, then measurement is as follows for period t :

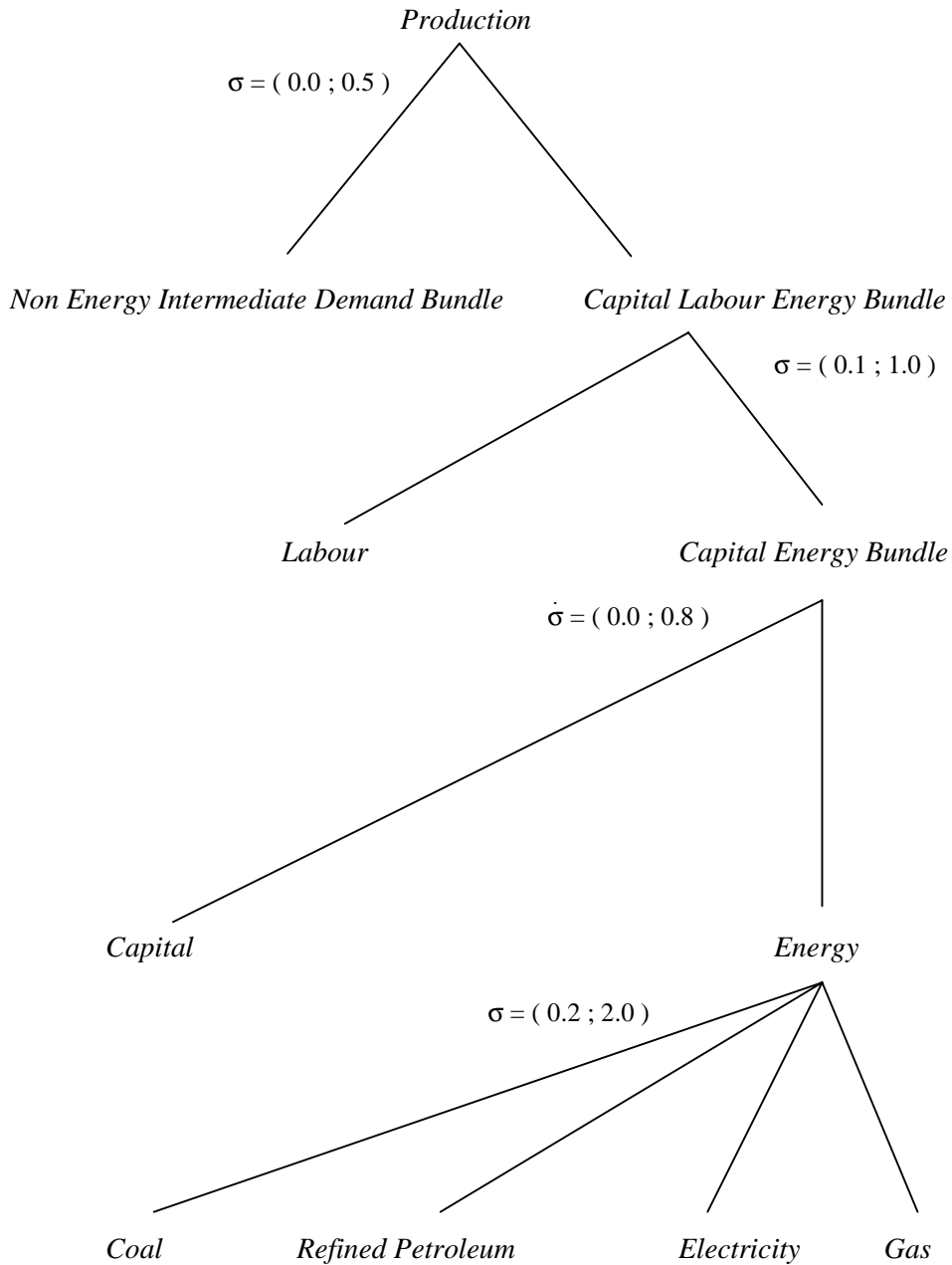
$$(y^* - y) - (E(p^*, u) - E(p, u)) - (D^* - D)$$

where u is utility, p the price system, and the star exponent the policy outcome. The first term, $y^* - y$, measures the gain (or the loss) of disposable income caused by the policy shock. The second term measures the change in expenditure needed after the policy shock to obtain the same level of utility as before. The third term represents the exogenous welfare component, with $(D - D^*)$ equalling the change in health damages based on measures other than "cost of illness".

Policy Instruments

The model includes a variety of instruments of economic policy: direct and indirect taxes on production, consumption and income, tariffs and other taxes and subsidies on international transactions. Each of these tax/subsidy items is differentiated by sector, production factor, consumption type or income source. The shock introduced in the policy simulations is a tax levied on the carbon content of fuel. The tax level is endogenously calculated by targeting rates of CO_2 emission abatement relative to a growth baseline. Carbon tax revenues are redistributed lump-sum to households.

Figure A.1. Production Nesting



Notes:

1. The elasticities are derived from the relevant literature (cf. Burniaux, Nicoletti and Oliveira-Martins, 1992).
2. Each nest represents a different CES bundle. Substitution elasticities separated by a semi-colon indicate, respectively, the central CES substitution elasticity for *old* capital and for *new* capital. The elasticity may take the value zero. Because of the putty/semi-putty specification, the nesting is replicated for each type of capital, i.e. *old* and *new*. The values of the substitution elasticity will generally differ depending on the capital vintage, with typically lower elasticities for *old* capital.
3. Intermediate demand, both energy and non-energy, is further decomposed by region of origin according to the Armington specification. However, the Armington function is specified at the border and is not industry specific.

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