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Theory and Applications

Technical progress and pollution abatement: an economic view of selected technologies and practices

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ABSTRACT. The paper first presents evidence from the engineering literature on air and water pollution control, which shows that, when the pollution abatement technologies are in place, large reductions in pollution have been achieved at costs that are small relative to the costs of production. A simulation model is then developed to study the effects of technical progress on pollution abatement, and applied to particular cases in developing countries. The results are compared with the projections of an environmental Kuznets curve: they reproduce the latter *if* policies were not to be introduced until per capita incomes reached levels comparable to those of the industrial countries when they first introduced their policies; but show dramatically lower and earlier peaks *if* policies were to be introduced earlier. The conclusion is shown to apply more generally, and it is argued that developing countries can aspire to addressing their environmental problems at a much earlier phase of development than the industrial countries before them.

1. Introduction

What is the contribution of technical progress to pollution abatement? And to what extent can it reconcile the aims of economic growth with environmental improvement? A much-neglected source of evidence that sheds light on these questions is provided in the literature on engineering and the environment. This literature is rich in its descriptions of the technologies and practices in use or under development to reduce pollution, provides evidence on their abatement efficiencies, as measured by the percentage reductions of the pollutant in question relative to the original levels, and

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provides some information on costs. There is also a growing number of field studies of the actual environmental effects of the technologies and practices in use. The aim of this paper is to provide an economic interpretation of this literature in an attempt to address the questions just posed.

It concentrates on technologies and practices for the abatement of air pollution from electricity generation; indoor air pollution, and the damage to soils and forests, from the burning of wood fuels and dung for cooking in developing countries; vehicle emissions; and the effluents in municipal and industrial waste waters. The costs and performance of emerging renewable energy technologies are also assessed, since these are now a much-discussed option for reducing CO_2 emissions in the long term. Thus it is not—and as a single paper its scope cannot claim to be—comprehensive in the technologies and practices covered; waste management and the management of a range of natural resources are conspicuous omissions. But the thought is that if we build up a picture of how the engineering and scientific community are devising ways of addressing environmental problems, in response to environmental policies, economists will be better placed to assess the contribution of technical progress to pollution abatement in the course of economic growth and development. In this respect the approach below is closer to that of the earlier residuals management studies of Kneese and Bower (1979) and Kopp and Smith (1982).

The evidence shows that the practices discussed are capable of achieving—and in important cases historically have achieved—orders-of-magnitude reductions in pollution, at costs that are sometimes large in absolute terms but which are generally small when measured in relation to the costs of production or value added in an industry. In some instances they have proved to be negative, because unanticipated sources of efficiency were discovered. The technologies and practices are also continually being developed and improved under the influence of environmental regulation and R&D programmes in the industrial countries.

In all cases they are relevant for the situations in developing countries. If we consider some of the most pressing environmental problems developing countries are encountering today—urban air pollution, the pollution of rivers and water supplies, acid deposition in Asia, and soil erosion—options have long been developed that could lead to these problems being substantially solved, at costs close to and sometimes below the damaging alternatives currently in use. With 'good' environmental policies in place there is no reason why they could not be introduced at a much earlier stage of development than was the case historically in the industrial countries. As will be seen, the likelihood would be an increase not a decrease in the rate of economic growth and development in its broadest sense.

This conclusion could not diverge more from a plethora of studies cited below of the so-called environmental Kuznets curve. There is an over-preoccupation in these studies with inadequate cross-country data on pollution and per capita incomes, which sheds little light on the contribution of technical progress to pollution abatement, even less on the importance of the timing of policy. The dynamic simulation model developed in section 3 of the paper aims to overcome these problems by combining economic evidence with insights from the engineering literature on the history of the

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technologies and practices of pollution prevention and control. Some results are also presented in section 3. Section 2 of the paper begins with a short overview of the engineering data, and section 4 concludes.

2. The abatement efficiencies and costs of selected technologies and practices

Recalling the identity, emissions = output × emissions per unit output, it is evident that, if high levels of economic output are to be reconciled with low levels of pollution, then technologies and resource management practices need to be developed and deployed having low levels of emissions per unit of output. Table 1 lists examples of such technologies now commonly in use or under development in relation to the following sources of pollution and environmental damage: *Electricity generation*—particulate matter and SO_2 emissions from the combustion of coal, and NO_x emissions from the combustion of gas and coal in power generation. *Motor vehicle emissions from petrol engines*—a range of tailpipe emissions from vehicles. *Household fuels in developing countries*—the pollution from smoke and the damage to natural resources caused by the use of dung and fuelwood for cooking. Astonishingly, this is still the primary energy source for 2 billion people, is estimated to account for approximately a billion tonnes of oil equivalent energy per year (more than the oil energy consumed by the US), and is a source of much damage to people's health and to soils and forests (World Bank, 1996). Hence two indicators of the abatement efficiencies and costs of improved technologies and practices are included in the table, one relating to the abatement of smoke, the other to the reduction of soil erosion. *Carbon dioxide*—the table lists some renewable energy technologies now under development.[1] *Industrial and Municipal Wastewaters*—the reduction of biological oxygen demands, suspended solids, faecal coliforms, phosphorous and nitrogen from municipal waste-waters.

The data on *abatement efficiency* show the percentage reduction of emissions per unit output relative to the emissions without the technology or practice noted (100 minus the index in the third column of table 1). With the partial exception of emissions from vehicles in times of congestion, such data are reasonably reliable. They are not based on laboratory experiments in ideal conditions, but on verification tests when new plant and equipment are being commissioned, the monitoring activities of environmental agencies and inspectorates, and field studies of the technologies in use. Data on the *costs of abatement* are sometimes more uncertain, and the indicators in table 1 are put forward with the customary qualifications.

[1] Further options for reducing CO_2 emissions include the reforming of natural gas or coal-bed methane to produce hydrogen and CO_2 with the hydrogen being used for combustion or fuel cells and the CO_2 sequestered on a non-net carbon emitting cycle. The paper edited by Socolow (1997) provides an overview of approaches to decarbonizing fossil fuels, carbon sequestration, and 'deep' storage. When CO_2 is injected into coal beds it is adsorbed on to the coal surfaces, releasing methane; the methane can be split into hydrogen and CO_2 using a commonly used practice known as steam reforming; the CO_2 can then be re-injected, in principle, on a closed cycle with no emissions of CO_2 to the atmosphere other than those from leakage.

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Table 1. *Pollution intensities and costs of technologies for the prevention and control of air and water pollution, relative to those of the polluting technologies they displace*

Source and type of emissions or effluents	*Index of pollution per unit output (polluting practice = 100)*		*Indicator of added costs, %*	*Comments on nature of low-polluting practice (see also the table's footnotes)*
	Polluting	*Low-polluting*		
Electricity generation				
PM only	100	< 0.1	< 0 to 2.0	Natural gas; 'clean coal'
PM and SO_2	100	0 to 10[a/]	< 0 to 8[a/]	technologies; low-sulphur
PM, SO_2 and NO_x	100	10 to 30[a/]	<0 to 10[a/]	fuels; low NOx boilers and emission control catalysts
Motor vehicle emissions				
Lead	100	0		Unleaded, reformulated fuels,
Volatiles (VOCs)	100	4		and catalytic converters
Carbon Monoxide	100	4		(petrol engines). Low-sulphur
Nitrogen Oxides	100	20	≈3.5%	fuels and particulate traps
SO_2 (diesels)	100	5		(diesel).The 3.5% figure is
PM (diesels)	100	<10		relative to total discounted vehicle and fuel costs and is roughly the same for diesel and petrol engines
Household fuels in developing countries				
Smoke from firewood and dung	100	0 <1 to 5	< 0	Gas, LPG and Kerosene Stoves with flues
Soil erosion (sediment yield)	100	<0 to 1	< 0	Agro-forestry and erosion-prevention practices
Renewable energy technologies for reducing CO_2 emissions				
Wind (electric power)	100	0	0 to 30	Costs declined 5-fold since 1985
Biomass (electric power)	100	<0	0 to 100	Costs vary with source of fuel
Biomass (ethanol)	100	0	≈50	Brazilian data. Costs declined by factor of 3 since 1980s
Photovoltaics (off-grid)	100	0	≤0	High insolation areas. Relative costs vary
Photovoltaics (grid)	100	0	0 to >400	greatly with application. Costs of PVs have declined 50 fold in the past 25 years
Solar-Thermal (electricity)	100	0	≈50–100	High insolation areas only. Costs also declining with technical progress
Geothermal (electricity)	100	0	≤0	Costs location specific
Fuel Cells (electricity and vehicles)	100	0	Not available	Emission assume renewable energy source for hydrogen
Industrial and Municipal Wastewater Treatment (primary, secondary and tertiary treatment)				
Primary and secondary:				
• BOD	100	5	1–2%	Based on costs of $1.9 per m^3
• SS	100	5	of value	and typical volumes of
• TP	100	5	added in	wastewater per unit value
• TN	100	65	cities	added in municipal areas
As above plus tertiary:				
• BOD	100	3	1.5–3%	Ditto, at costs of $2.5 per m^3
• SS	100	5	of value	
• TP	100	5	added in	
• TN	100	13	cities	

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Sources and notes for Table 1: Details are to be found in a working paper by Anderson and Chua (1999).

[a] The index of pollution here refers to SO_2 only, since the figure for PM is provided in the preceding row. Similar remarks apply to NO_x in the following row. The estimates of added costs are for PM in the first row, PM and SO_2 in the second row and for all three pollutants in the third row.

Electricity generation: Based on OECD (1989), Asian Development Bank (1991), Tavoulareas and Charpentier (1995), and Hall, Pekar and Sedman (1995). Descriptions of the technologies can be found in these sources, and also in any good text on environmental engineering, for example in Keily (1997). The term 'polluting practice' here refers to a coal-fired boiler with mechanical controls. The term 'clean coal technologies' is (not unmerited) public relations short-hand for a range of technologies such as the following: electrostatic precipitators and bag-house filters for removing particulate matter emissions; flue-gas desulphurization in coal-fired power plant; fluidized bed combustion (FBC) of coal (removes sulphur and raises thermal efficiencies); integrated coal-gasification, combined cycle (IGCC) technologies, which can also be used to remove sulphur and raise efficiencies; and catalytic reduction of NO_x or so-called low-NO_x burners, which reduce NO_x by lowering combustion temperatures. Costs are expressed as a percentage of electricity supply costs, for which 8 cents per kWh is taken to be a typical value. The end-of-pipe technologies (desulphurization and PM removal) generally raise costs, which explains the upper limits to incremental costs shown; gas-fired plant have lower costs for a number of reasons, the principal ones being short lead times and higher thermal efficiencies, which explains the negative cost figure shown relative to coal fired plant. Note, however, that the IGCC and FBC are also expected to raise efficiencies and reduce costs.

Motor vehicle emissions: The estimates are based on the extensive reviews by Ross (1994) and Faiz *et al*. (1996) and the data quoted by Ross from the American Manufacturers Auytomobile Association (1993). For petrol engines, the costs of three-way catalysts are quoted by Faiz *et al*. to be $630, who also notes that there is a loss of fuel economy of 5 per cent. Electronic fuel injection raises the costs to $800, but improves the fuel economy by 5 per cent. Taking the cost of a car to be $20,000, the pre-tax cost of fuel $1 per gallon, the fuel consumption 25 m.p.g., average miles per year 10,000, the lifetime of the cars 15 years, and the discount rate 10 per cent, the marginal costs of achieving these abatement efficiencies are 3 per cent of the expenditures on the vehicle with and 3.5 per cent without electronic fuel injection. For diesel engines options for reducing emissions include a range of innovations in engine design and fuel formulations, in which improvements in fuel efficiency help to offset the higher capital costs. Faiz *et. al.*, pp. 76–79 provide details. In a study which looked at alternative fuels for the abatement of urban pollution and CO_2, Krupnick, Walls, and Colling (1993) arrive at not dissimilar cost estimates to those shown here.

There is a qualification to be made regarding the pollution from vehicles in congested areas, which is that frequent stopping and starting and rapid acceleration greatly add to emission rates. While dynamometer tests attempt to allow for this, Ross (1994, p. 76) cautions that, although 'some progress has been made in improving ambient air quality in major metropolitan areas (in the US), most of these areas still do not meet clean air standards. An important part of the cause of this shortfall ... is that actual automotive emissions per mile are much higher than those measured in the regulatory test.' Another complication is that air quality is a function not only of emissions, but of their concentration, which in turn varies with topography, local weather and climate, urban population densities, and building structures.

Household fuels: Smith (1993) provides data on both indoor and outdoor concentrations in developing and developed countries. His review of particular cases (in India, Papua and New Guinea, Nepal, China, and several others), shows that the levels of indoor pollution vary from under 2,000 to over 18,000 $\mu g/m^3$, or several thousand times the levels experienced in the industrial countries using modern fuels. The switch to modern fuels, especially piped gas or LPG not only reduces indoor pollution to very low levels, but is justified in terms of its private economic benefits. Consumers' willingness to pay for gas exceeds the costs of supply, and supply expansion has long been justified without reference to its benefits for health once it is substituted for wood or coal as a domestic fuel.

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Hence the negative cost estimate shown in the fourth column. See also World Bank (1996).
Household fuels and soil erosion: The use of fuelwood and dung for cooking is not the only (and sometimes not the major) source of soil erosion, but it has long been known to be an important one. It is a problem well remedied through agroforestry practices and related soil conservation practices, which actually have economically beneficial effects on crop yields sufficient to justify the investments, even ignoring the environmental benefits (Anderson, 1989, Brandle, Hintz, and Sturroch, 1988; Gregerson, Draper, and Elz, 1989; Doolette and Smyle, 1990; Magrath, 1990; Grimshaw and Helfer, 1995; and Current, Lutz and Scherr, 1995. Further they are capable of replenishing soils and are commonly used for land reclamation; hence the index in the third column has a lower limit of < 0.
Renewable energy for reducing CO_2 emissions: The estimates are adjusted to 10 per cent discount rates, and are based on the following reviews, which themselves collectively have reviewed over 500 papers and studies. Mock, Tesler, and Wright on geothermal; Larson (1993) on biomass; Ahmed 1994 on several technologies; Gregory (1998), World Bank (1996) *Rural Energy and Development: Meeting the Energy Needs of 2 Billion People*, Anderson, Barnes, and Jechoutek (1996) and (1997). Reference should be made to these sources for details and qualifications.
Municipal wastewater treatment: Acronyms: BOD = biological oxygen demand, SS = suspended solids, TP = total phosphorous, and TN = total nitrogen. The texts of Keiley (1997) and Metcalf and Eddy (1991) note that the pollution abatement levels achieved in many regions can be much higher than indicated in the above table. For municipal wastewater plant with full-settlement, activated sludge processes, combined biological and nitrogen removal, and chemical disinfection the residual levels of pollutants in the effluents relative to the influents of such plants are as follows: faecal coliform 0 per cent, suspended solids <1 per cent, BOD <0.3 per cent, phosphorous <10 per cent, nitrogen <2 per cent. The estimates shown here are based on West European and US experience. See *Europe's Environment: Statistical Compendium*, WQI No. 4, 1993, taken from a report by Laszlo Somlyody for the Environmental Action Programme for Central and Eastern Europe, The World Bank. The footnotes to the table say that all the technologies incorporate a primary sedimentation tank and, for biological treatment, an activated sludge process. Chemically enhanced primary treatment is also assumed plus denitrification in the tertiary stage. The estimates of costs as a percentage of value added in a metropolitan area is based on data on the above costs per cubic metre times estimates of volumes of water use in cities, to be found in Metcalf and Eddy (1991).

The striking feature of the data is that, in every case shown, technologies have been developed or are under development for reducing pollution by at least one, and usually several orders of magnitude.[2] In some cases emissions of some pollutants are zero and in some others (biomass for power generation and restoration of soils) the net emissions are negative.[3] At the same time, the same product or service is provided: heat, light and power; passenger- and freight-miles in transport; and the full range of products from industry and commerce. Thus very high levels of economic output can be sustained in the cases noted with

[2] The partial exception of NO_x from vehicle fuel emissions would be solved by the fuel cell vehicle now under development, or alternatively in urban environments by the hybrid (electric/internal combustion) engine that several manufacturers are currently producing.
[3] The negative net-CO_2 emissions in the case of biomass for power generation arises from the larger standing stocks of biomass; such projects are also being considered for the restoration of soils and watershed in regions where they are badly degraded.

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greatly reduced pollution loads. Post evaluations of particular technologies in use confirm this.[4] It is the policies that led to the development and use of the technologies listed in table 1 that explain why local and regional pollution loads in the industrial countries are several times lower in the industrial than in the developing countries, even though their per capita consumption levels are several times higher (World Bank, 1992).

A further feature is that, with the possible exception of CO_2, the extra costs of achieving high levels of abatement amount to small percentages of the costs of supply or value added in the industry. In some cases costs have turned out to be *negative* because unanticipated sources of cost efficiency were discovered. The substitution of gas as a domestic and industrial fuel and, more recently, for power generation is one example. This reduced PM and SO_2 to very low levels, and in the case of power generation reduced capital costs of power plant by nearly one half, increased their thermal efficiencies, and eliminated the need for the disposal of ash and water slurries. Industrial wastewater treatment is another area where reductions in wastes are often accompanied by reductions in costs.[5]

Will the costs of reducing CO_2 emissions be an exception? We know that the renewable energy option alone is capable of meeting the world's future energy demands many times over. At current conversion efficiencies an amount of land equivalent to less than *1 per cent* of the land now under crops and pasture would be required to meet all

[4] There are a large number of such studies. On municipal water pollution abatement see the reports of the UK National Rivers Authority (1995) on the Mersey, the UK Environment Agency's reports on the Thames (1997) and the Tyne (1996), and Brosnan and O'Shea (1996) on the Hudson. See also the book by Patterson (1985), which discusses the treatment of a wide range of metallic and organic pollutants, and the special edition on industrial wastewater treatment in *Water Science and Technology* 36, No. 2–3, 1997, edited by Andreadakis (1996), which includes case studies of a number of manufacturing activities. On air pollution assessments of the overall effects of the above technologies on emissions from power stations in the industrial countries can be found in reports of government departments (for example the UK Department of Trade and Industry, 1997 and OECD, 1991). Also the studies of tradable permit systems in the US by Schmalensee *et al.* (1998). For an historical perspective on the abatement of urban air and water pollution Beckerman (1973) remains durable and full of insight; the reduction of the pollution of water supplies he describes is wholly attributable to developments of water and wastewater treatment technologies, and of course the policies that led to them.

[5] See, for example, the report by Nilsen (1998) on a paper mill in Finland, in which he notes 'In 1995 the mill used 93% less water for each ton of paper produced compared with 1980 levels. Simultaneously, the quality of water effluents improved significantly—96% reduction in suspended solids for each ton produced, 99.5% reduction in BOD (biological oxygen demand), and 95% reduction in phosphorous.' The standard text on wastewater treatment is the handbook by Metcalf and Eddy (1991). Also Patterson (1985) and Andreadakis (1996). The earlier study by Hirschhorn *et al.* (1991) also contains some interesting cases of negative net costs.

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the world's energy requirements if solar technologies were used.[6] Furthermore, unused spaces such as rooftops and desert areas are often the ideal sites. The main questions ahead concern costs not technical feasibility. The cost estimates for CO_2 shown in table 1 range from $<0\%$ to $\geq 400\%$ of the fossil fuel alternatives. There is a growing number of small-scale applications for which renewable energy is cheaper than fossil fuels—off-grid markets in rural areas and remote applications, wind energy in favourable wind regimes where visual intrusion is not a factor, peak load supplementation from solar energy in sunny regions where there is a good co-incidence between the demand peaks and the solar peaks, biomass from urban and agricultural wastes for power generation, and, again in favourable locations, geothermal energy. In less-favourable locations, especially where storage is required on account of the intermittent nature of renewable energy, costs can be high.

Yet costs are not static, incapable of being reduced through technical progress. All the technologies and practices noted in table 1 took time to develop, and showed considerable improvement over time with R&D and investment.[7] The engineering literature on the subject is notable for the extent and variety of approaches being pursued in search of in cost efficiency.[8]

[6] With the exception of biomass, the ideal sites are not agricultural lands or forests, but rooftops, desert areas, and off shore (e.g., for wind, wave and tidal stream energy). Even for biomass, there are many possibilities for producing energy crops in ways that help to restore degraded agricultural lands, woodlands, and watersheds.

[7] For the early history of water and sanitation see Bruce (1958), who notes that it took half a century, from c1850 to 1900 for the technology to progress from being a 'crude craft to a science'. For flue gas desulphurization, Balzheiser and Yeager (1987) who report that it took 25 years to develop the technologies to a satisfactory level of performance; their estimates of cost are 50 per cent higher than those reported by Tavoulareas and Charpentier (1995). The use of gas for power generation also required significant development. It is now thought to be the most abundant of all fossil fuel reserves if hydrates are included (Rogner, 1997). It is remarkable to recall that, barely a decade ago, gas was widely considered to be a 'noble fuel', too scarce and too valuable for electricity generation on a large scale. The initial uses were confined to gas turbines for short duration peak power supplies only; the growth of reserves and the development of high efficiency combined cycle (gas and steam) power plant greatly reduced costs and increased the market for gas in power generation.

[8] In relation to CO_2 abatement, see especially Johansson *et al*. (1993) and Ahmed (1994) cited above. Statistical studies of learning curves for the costs of photovoltaic modules have shown costs to decline by 20 per cent for each doubling of cumulative production. See Tsuchiya (1992) and Cody and Tiedge (1992). The cost function they fitted to the data is of the form $C = AK^{-b}$, where A and b are parameters, C is cost, and K cumulative production; b has been found to be about 0.3 for photovoltaics. The use of PVs as a building material is another promising way of reducing net costs, and along with passive solar designs is attracting much interest by architects, on which several interesting papers can be found in Boer (1998). Uncertainties as to the effects of such developments on costs partly explain the uncertainties in estimates in the costs of responding to climate change, which vary from under 1 per cent of GDP to nearly 8 per cent. Actually,

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3. Implications for economic development and the environment

The technologies noted in table 1 were developed in response to environmental concerns in the industrial countries over the past 50 years for the abatement of air pollution and the past 150 years for the abatement of water pollution. They were not available 'from the shelf' when the policies were first being introduced. Now that they are well-understood and proven options, however, with costs that are low relative to the total costs of supply in the sectors in question, developing countries are evidently well placed to address environmental problems at an earlier stage of development than the industrial countries before them. This possibility is explored below by use of a dynamic simulation model of technical progress and pollution abatement. Before turning to the model itself, however, some results are first presented, since they provide an intuitive explanation of the model's properties. The first results relate to the possibilities for reducing acid deposition in Asia, after which results from other studies will be summarized for other pollutants. As will be seen, they stand in stark contrast to those of the 'inverted U-shaped or hypothesis' or environmental Kuznets curve, in which pollution is assumed to rise inexorably with per capita incomes before it declines.[9]

Acid deposition in Asia

Studies of the latter hypothesis, which have met with considerable criticism,[10] fit cross-country data on emissions or concentrations to a quadratic or cubic function of per capita incomes. For a range of pollutants, it has been found that pollution rises with per capita incomes across countries (the scale and composition effects of growth), peaks and then declines. The decline at higher per capita incomes is assumed to stem from a positive income elasticity for environmental quality when incomes are high, combined with the pressures that high-income societies are able to put on governments to introduce the required policies. Some studies have used panel data and introduced time trends and other variables such as population density in the equations, but it is generally the terms for per capita incomes that dominate.

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the range is broader than this. In a recent simulation study, Chakravorty *et al*. (1997) using the data in Ahmed (1994), found that the costs could conceivably be negative. Anderson and Papathanasiou (1999) arrive at a similar conclusion by applying Monte Carlo methods to a simulation model in which the parameters of the technical progress functions in the energy demand and supply equations are uncertain. For a plausible range of assumptions about the technical progress parameters, the possibilities of an economic surprise (negative costs) are not insignificant.

[9] See for example Grossman (1993) Holtz-Eakin and Selden (1995), Panayotou (1993), Selden and Song (1994), Shafik (1994), Grossman and Krueger (1993), Grossman and Krueger (1995), and de Bruyn (1997). These authors do recognize that policy is an independent variable, not necessarily correlated with income; but the policy variable is nevertheless omitted from the regressions reported.

[10] Reviews and critiques are provided by Ekins (1997), Barbier (1997), Stern (1998), Pearson (1994), Wallace (1996), and Chua (1999). Kuznets himself never proposed this relationship, which is flawed and misleading, and it seems to me unfortunate that his name has come to be associated with it.

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It is estimated that pollution levels do not peak until very high per capita incomes are reached. Selden and Song (1994), for example, whose estimates lie in the middle of those of several other authors, estimate that the turning points for PM and SO_2 emissions are approximately $9,000 per capita (in 1985 prices), based on the real GDP per capita measures provided in the Penn Mark IV World Tables in Summers and Heston (1991). Depending on assumptions of per capita income growth rates, this would imply that it will be several decades before the major emitters in the region (India and China) would begin to consider reducing these sources of emissions, and one-half to three-quarters of a century before these sources of pollution peaked, perhaps longer. In fact the projections of Selden and Song show global emissions of SO_2 and PM still rising rapidly in the middle of the next century, with little or no sign of peaking until the last quarter of the century is reached, if not later.[11]

In contrast, engineering-economic evidence on the abatement efficiencies and costs of the technologies discussed above suggests that, *if* policies are in place, the turning point would occur several decades (perhaps half a century) earlier, at per capita incomes barely a fifth of those projected by the above-mentioned studies.[12] To show this, it is necessary to move from single equation curve fitting exercises to a simultaneous equation model of consumer demands, of technological alternatives and substitution in supply response, of emissions and concentrations, and of costs and prices. Models of this kind have been used for studies of climate change for sometime.[13] Such a model for local and regional pollution will be discussed shortly, based on Cavendish and Anderson (1994). But let us first consider the results for the case of SO_2 emissions from coal-fired power stations in Asia, since they help to explain the relationships we are looking for. The 'Rains Asia' study by Downing, Ramankutty, and Shah (1997) commented:

> Many industrial areas of Indonesia, Malaysia, the Philippines, and Thailand experience sulphur deposition levels of 5–10 grams per square meter per year, whereas local hot spots in some industrial areas of China receive more than 18 grams . . . In comparison, the most heavily polluted parts of Central and Eastern Europe—the black triangle—were approximately 15 grams per square meter per year . . .

With the growth of electricity generation and coal use in the region, emissions and acid deposition are projected to double every 15–20 years with unchanged practices.

Figure 1 summarizes the results of the simulations, which are contrasted with the sort of projection that emerges from an environmental Kuznets curve (EKC). The results consider a country with an initial per capita income of $1,700

[11] Op. cit. figures 1 and 2. Some studies have estimated that the turning points will not occur until much higher incomes are attained, others lower, the actual ranges in the studies cited being $3,000 to $13,400 for SO_2 and $3,300 to $16,000 for PM. See Chua's (1999) review.

[12] Cavendish and Anderson (1994), Downing, Ramankutty, and Shah (1997), and World Bank (1992), chapter 6.

[13] See the survey by Grubb *et al*. (1993) and the recent survey by Nakicenovic, Victor, and Morita (1998).

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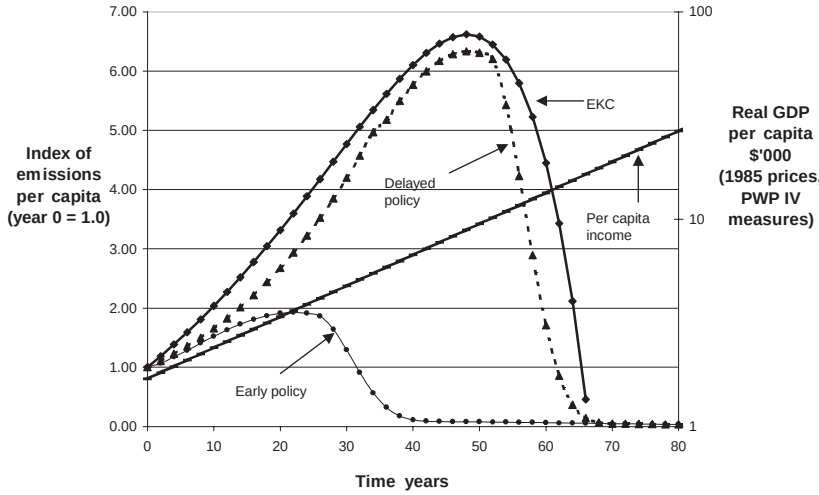


Figure 1. *Effects of environmental policy on emissions: Simulation results for SO_2 emissions contrasted with the EKC. Initial real GDP per capita $1,700. Per capita income growth rate: 3.5% p.a.*

(for comparison with the EKC studies, these are in 1985 prices, Penn Mark IV World Tables), which is lower than that of China today but higher than that of India. The long-term rate of per capita income growth is taken to be 3.5 per cent per year, which again is lower than China's on current trends but higher than India's. Per capita incomes are plotted logarithmically on the right-hand scale.

The EKC plotted here is based on an equation from Selden and Song (1994) whose estimates as noted fall roughly in the middle of the range of a number of similar studies and are widely cited. It has the quadratic form: $E_t = b_{0jt} + b_{1.yt} + b_{2.yt}{}^2$, where b_{0jt}, b_1 and b_2 are parameters, with the j denoting a country-specific effect. For the calculations shown, this relationship has been normalized and indexed such that emissions at $t = 0$ are unity.[14]

The results of two simulation studies are shown. The first assumes that the region will not address acid deposition until per capita incomes are similar to those that obtained in the industrial countries when they first began to address it in the late 1960s and early 1970s, i.e. when their per

[14] Selden and Song also introduce a population density variable (the effect is not strong, and if anything delays and increases their estimates of peak emissions) and a time-shift variable, which they find is not significant in their data. These terms have been neglected. The actual relationship used is $E_t = 1.0 + 3.85(y_t - y_0) - 0.216(y_t{}^2 - y^2a)$, where E_t denotes the emissions in year t relative to the base year. Selden and Song use values of per capita incomes based on 1985 dollar prices using Penn Mark IV tables. The peak occurs at $y_t = -b_1/2b_2 = \$8{,}900$. It should be added that this normalization procedure, which is based on setting E_t to unity at $t = 0$, does not always work well, and that ideally we need a baseline estimate of emissions for the country or region under study (Anderson and Cavendish, 1999). The income level at which the turning point occurs is however unaffected by the normalization procedure.

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capita incomes were about $8,000 (in 1985 prices). On this assumption, which underlies the studies of the EKC, it would be another half century or so before the region contemplated policies to introduce gas or the coal desulphurization technologies discussed. As can be seen, the simulations track the EKC closely over the valid (non-negative) range of the latter. The effects of alternative assumptions about income growth are straightforward. A higher initial level and/or higher growth rate of per capita incomes brings the EKC forward in time, as it does, under the same assumptions, the timing of the policies for the simulation studies; conversely, the timing of the peak is delayed in both cases if we reduce the initial level and/or the growth rate of per capita incomes.

But it is the results of the second simulation that are of more interest. Acid deposition in the region is already the subject of much investigation, and multi-lateral discussions have been in progress for more than 5 years as to how it might be addressed (Downing, Ramankutty, and Shah, 1997; Shah *et al*., 2000, provide reviews). Desulphurization technologies for coal combustion have now been well developed and proven over the past 30 years, at costs that are not far removed from those of existing coal-fired plant; gas for power generation supplied either through pipelines or the trade in liquefied natural gas (LNG) is also emerging as a medium- and long-term option.[15] There is every justification therefore for exploring the following assumptions through simulation: bringing the policies forward to the present time and phasing in the low-sulphur options gradually over a 25–35 year period, this to allow for the normal lags of implementation and for the time it will take to retire, retrofit, or phase out existing plant.[16] The results are shown in the 'early policy' curves in figure 1. The contrast with the estimates from the EKC curve could hardly be more stark: the peak occurs nearly half a century earlier, at per capita income levels one-fifth of those projected by the EKC, and the peak intensity of the pollution is reduced by a factor of three. It is hard to overstate the importance therefore of the possibilities being opened up by technical progress in pollution abatement, and of treating environmental policies as an independent variable.

The dependence on the timing of the emissions peak on policies

[15] Whether gas is developed sufficiently in the regions turns more on politics than incomes. For example there are massive reserves available for trade between Russia and China in the Siberian fields and the Russian–China border. Gas consumption in south and east Asia is growing at 7 per cent per year and is now one-third of the consumption in the US, and two-thirds of that of Europe; one-quarter of the consumption is in Japan; China, India, South Korea, Thailand and Malaysia are the most rapidly growing markets (*BP Statistical Review of World Energy*, 1998). For a discussion of the prospects for large-scale gas trade across regions, see Hamso, Mashayekhi, and Razaui. I thank John Mitchell of the Royal Institute of International Affairs for a discussion on this topic.

[16] For this simulation there is a five-year period of investment amounting to 10 per cent of new investment, followed by a simple linear 'ramp function' over the next 20 years until the new technologies occupy the whole of new investment, followed by a ten-year phase-out or retrofitting of the remaining plant. This gives a good approximation to the logistic or learning curve function commonly used to study the diffusion of new technologies (see Knapp, 1999).

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rather than per capita incomes can be further demonstrated by running the simulations separately for different countries (Anderson and Cavendish, 1999). For example, if we estimate the timing of the peak SO_2 emissions separately for China and India, the estimated peak still occurs in both countries roughly two decades after the 'early policies' are introduced, as in figure 1, as compared with about four decades (depending on growth assumptions) in China if we use available estimates of the EKC, and six to eight decades in India. Quantitative evidence on the benefits of abatement is currently lacking in the region, so it is not possible to assess whether the early policies are optimal. However, what we can say from the simulation studies is that, in both countries (a) the marginal costs of abatement would be around 5 per cent of the total marginal costs of supply, since they rest on similar technologies, (b) the extra costs would likely be offset by gains in the thermal efficiency of power plant, and (c) earlier simulations have shown that any extra costs would also be small in relation to efficiency reforms in the electricity industry, particularly in India's case, where there is a long history of subsidy and controls on electricity prices, from electricity price reforms.[17] In other words, costs are not a self-evident 'barrier' to policy, and on this count alone developing countries need not be confined to repeating the environmental experiences of the industrial countries before them, on a much larger scale, and with larger populations at risk.

Further pollutants

Similar conclusions regarding the central role of policy and its influence on the development and use of 'clean' technologies and practices apply to a wide range of other pollutants. The results of further simulations for two kinds of vehicle emissions, PM and NO_x, are shown in figures 2a and 2b (two other emissions, VOCs and CO form an intermediate case and are not shown). As can be seen, even allowing for the considerable uncertainties that underlay such estimates, the contrasts between the early and the delayed policies are immense. Table 2 provides estimates from simulations studies on the turning points of emissions for other pollutants, and sets the results alongside those reached above. For the reasons just discussed, instead of defining the turning point in terms of per capita incomes, it considers the *timing* of the turning point under two policies—early and delayed. The 'delayed policies' case roughly corresponds to a developing country with a per capita income similar to that of India today *not* introducing a policy until its per capita incomes approached those obtaining in the industrial countries when they began to reduce the pollutants listed, the tacit assumption of the inverted U-shaped hypothesis. The last column also provides estimates of the effects of early policies on the peak intensities of the emissions. The estimates are unavoidably approximate since much depends on assumptions of growth rates in the latter case; for example, the difference in 0.5 percentage points in assumptions about income growth in the case of the inverted U-shaped hypothesis makes

[17] Cavendish and Anderson (1994).

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Table 2. *Timing of the turning point of peak emissions according to simulation studies of early policies and the U-shaped hypothesis*

Pollutant and source	*Simulation results for 'early policies'*	*Simulation results for 'delayed policies' (corresponding to U-shaped hypothesis)*	*Peak intensity of pollution: delayed/ early policy*
Electricity generation • PM • SO_2 • NO_x	Quarter of a century	Three-quarters of a century	500%
Vehicles • Lead in fuels • VOCs • NO_x • SO_2	Two decades	Half a century	>400%
Water and sanitation • Population with access to safe water • Population with access to good sanitation services	• Less than a decade for air pollution, • Two decades (see notes to table)	Not estimated, but as with estimates very long term	Not estimated, but very large (see source)
CO_2 emissions	Half a century or less	Century or longer	400% or greater

Sources and notes on the calculations: The simulation model and the data for emissions from electricity and vehicles are available on the web site of the Imperial College Centre for Energy Policy and Technology (www.icept.ic.ac.uk).

For *electricity generation*, Anderson and Cavendish (1999). The simulation results correspond to a country with an initial per capita income of $1,700 (1985 prices, Penn Mark IV data), a per capita income growth rate of 3 per cent per year, and policies being introduced in 50 years time. The simulation model was the same as the one described below, and applied to particulates and SO_2. The earlier study by Anderson and Cavendish (1994) also included NO_x, which showed that, in principle, the timing of the peak emissions would be the same under parallel policies for this pollutant.

For *vehicles*, the same simulation model was also used with appropriate emission parameters (see table 1) and allowing for the shorter lifetimes of the vehicle fleets (about 15 years in developing countries). See also our earlier simulations (Anderson and Cavendish, 1992).

For *water and sanitation*: see World Bank (1992: 112). The index of environmental damage used by the World Bank is the absolute number of people without access to safe water and sanitation respectively.

For CO_2 *emissions* estimates of future trajectories can be found in more than 150 peer-reviewed simulation studies complied for the IPCC's Special Report on Emissions Scenarios, which are summarized by Nakicenovic, Victor and Morita (1998). The estimated timings and ratios of peak intensities vary enormously; the estimate in the last column corresponds roughly to the mid ranges of the lower estimates (early policies) and the mid ranges of the higher estimates (delayed policies) from these sources.

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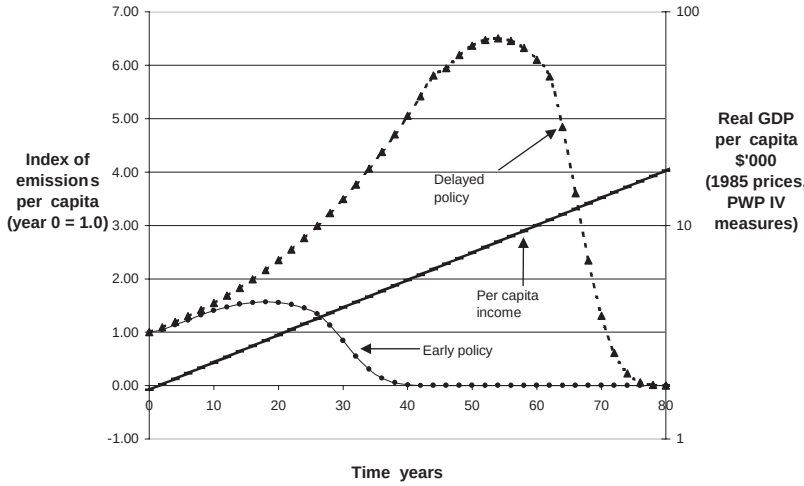


Figure 2a. *Effects of environmental policy on emissions: Simulation results for vehicle emissions. Case a: Lead. Initial real GDP per capita $1,700. Per capita income growth rate: 3.0% p.a.*

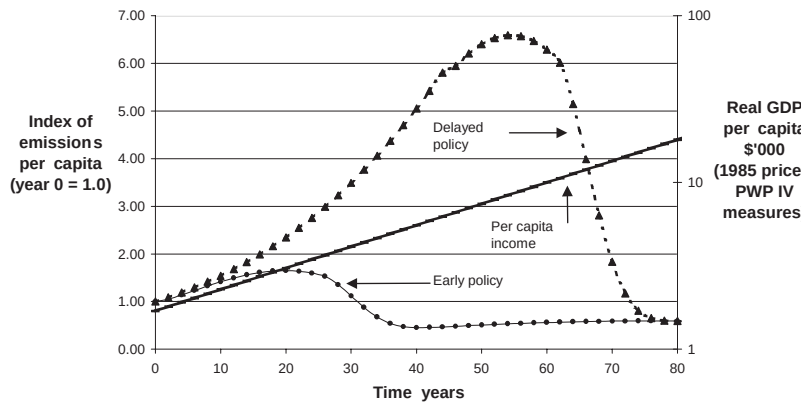


Figure 2b. *Effects of environmental policy on emissions: Simulation results for vehicle emissions. Case b: NO_x. Initial real GDP per capita $1,700. Per capita income growth rate: 3.0% p.a.*

roughly a decade's difference to the projected turning point. The sources and details of the calculations are footnoted in the table.

A few supplementary remarks on the estimates: For *PM emissions* from electricity generation, the turning points would be similar to those for SO_2 if gas were to be the main approach since this simultaneously solves the SO_2 and PM problem; if coal were the main route, PM would probably peak earlier since the technologies[18] are relatively inexpensive and are now standard features of new

[18] Electrostatic precipitators and bag-house filters.

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plant. For *vehicle emissions* the relatively near turning point from early policies is feasible because of the shorter lifetimes of the vehicle fleets and the role of cleaner fuels, such as unleaded petrol in abating emissions; the main lags, in practice, would likely arise from the difficulties of making the institutional arrangements to ensure proper monitoring and compliance with policies. For *water and sanitation*, it likewise is, once again, policy commitment rather than incomes which is the key policy variable. As the World Bank (1992) concluded: 'Far more important [for the extension of services to unserved populations] is the combination of policy reforms and accelerated investment . . . which could bring dramatic increases in access to sanitation and clean water within the next generation.' The same simulation exercises for the 'no reform' case showed unserved populations continuing to rise exponentially, with no turning point in sight even 30 years from now. For *the abatement of* CO_2, the Special Report on Emissions Scenarios by Nakicenovic, Victor, and Morita (1998), which surveys the estimates of more than 150 peer-reviewed studies, the estimated timing of the peak emissions again turns on policies not per capita incomes. Specifically, it depends on the influence of economic and environmental policies on the rate of development and diffusion of the sorts of non-carbon technologies identified in table 1. It is hard to disagree with the assessment of Moomaw and Unruh (1997) that the U-shaped hypothesis fails to provide us with an understanding of the possibilities ahead for pollution abatement, and that we are in need of models that provide us with a means of understanding the role of policy and structural transformation in pollution abatement.

Outline of the simulation model[19]

The starting point is a demand-for-product relationship

$$D_t = f(y_t, P_t, N_t) \tag{1}$$

where D_t denotes demand, y_t per capita incomes, P_t energy prices, and N_t population. This has been re-expressed in terms of demand per capita, d_t, relative to the base year, such that $d_t/d_0 = (y_t/y_0)^{\alpha}\,(P_t/P_0)^{\beta}$ where α is the income elasticity and β the price elasticity. For energy, econometric studies have found income elasticities to decline with per capita incomes, from around 1.5 at low

[19] In an otherwise impressive econometric analysis of data on 20,000 firms in the US, Hartman, Wheeler, and Singh (1997) comment (too harshly I think) that since engineering-economic models 'are not derived from behavioural data, such models do not capture the broad adjustment possibilities which are available to some firms. The result has been sometimes an egregious *overestimate* of abatement costs' (their emphasis). However, engineering studies likewise point to a rich range of 'adjustment possibilities' for addressing pollution problems and reducing costs. For example, many economists (including Hartman, Wheeler, and Singh) assume 'end-of-pipe' treatment. But the majority of practices listed in table 1 are not end-of-pipe, but involve fundamental shifts in production possibilities with appreciable effects on costs and abatement efficiencies. In some cases, and in contrast with prior expectations, the marginal costs of pollution abatement have turned out to be *negative* (again see table 1 and notes) because unanticipated sources of cost-efficiency were discovered, a possibility that economic models might find hard put to explain and easily overlook. Berndt and Wood (1979) also comment on the usefulness of engineering-economic evidence when evidence is otherwise scarce, a view shared here.

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incomes to one-fifth of this at high incomes as markets mature (Bates and Moore, 1992; Dargay and Gately, 1995; and Judson, Schmalensee, and Stoker, 1999). For the purposes of the present study, the following relationship summarizes the change of elasticity with incomes quite well: $\alpha = \alpha_0(1 + r)^{-(y_t/y_0-1)}$, where $\alpha_0 = 1.5$ is the initial elasticity and $r \approx 0.1$ is the rate of decline of the elasticity with the growth of per capita income. (Note that since the elasticity is greater than unity in the early decades, there are strong scale and composition effects on energy demands and, other things constant, on emissions arising from the growth of incomes in the early and middle phases of development.)

Second, we require supply equations to reflect the point when, depending on the incentives offered to abate pollution, there is a choice of technology or practice that enables the same product or service to be provided in polluting or low-polluting ways. There are a several possibilities for modelling these options, including models in which each technology or practice is represented individually, and alternative 'mixes' are explored over time through simulation or optimization methods. For the purposes of the present analysis, however, there are four characteristics of the evidence presented in table 1 and notes that we are seeking to reflect in the model. The first is the large and discrete difference in the emissions co-efficients of what were termed polluting and low-polluting practices, which suggests that we need a minimum of two supply equations to represent the alternatives. The second is the possibility of achieving further improvements in the abatement efficiencies of the low-polluting technologies over time, as measured by reductions in the emissions co-efficients. The third is the possibility for further reductions in costs. The fourth is the problem of diffusion, since none of the new technologies and practices can be substituted for old ones immediately after a policy has been announced, even if they have already been developed; the longevity of existing investments alone will set limits to this.

Let Q_t denote the total supply in period t, S_t the share of the incremental investment in low-polluting practices, δ the retirement rate of investments, and the subscripts p and o the polluting and low-polluting options respectively.[20] Taking the case where we have equilibrium between demand and supply, the incremental output required from new investments will be equal to the incremental demand, ΔD_t, plus the amount of investment retired, δQ_t, with $Q_t = Q_{pt} + Q_{ot}$. Both demand growth and the retirement of old practices provide an opportunity to 'change course' since (if the practices are already developed) a rising share of $\Delta D_t + \delta Q_t$ can be met through the low-polluting options. In addition, polluting assets can be retrofitted, or retired early. This possibility is denoted by a choice variable R_{pt}, which is the retrofitting (or early retirement) rate of that portion of the capital stock that has not reached the end of its normal economic lifetime. Once a plant is retrofitted or retired early it either becomes a low-polluting plant or must be replaced by a new one. The output from the low-polluting technologies in period t thus equals

[20] For simplicity, the following relationships assume an exponential-decay type retirement function. It is not difficult to consider alternative forms, such as a normal distribution round an expected plant lifetime. See Cavendish and Anderson (1994).

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the output from those newly installed in the period, plus the outputs from those left over from the preceding period, plus the retrofits

$$Q_{ot} = S_t\{\Delta D_t + \delta \cdot Q_{t-1}\} + (1-\delta)Q_{o,t-1} + (1-\delta)R_{pt} \cdot Q_{pt-1} \quad (2)$$

similarly

$$Q_{pt} = (1-S_t)\{\Delta D_t + \delta \cdot Q_{t-1}\} + (1-\delta)\, Q_{p,t-1}(1-\delta)\, R_{pt} \cdot Q_{pt-1} \quad (3)$$

It is readily seen that if we add (2) and (3) the relationships satisfy the equilibrium condition $\Delta Q_t = \Delta D_t$. For the simulations reported in figure 1, $\delta = 0.03$, corresponding to a 30 year lifetime for electric power plants, and in figures 2a and b $\delta = 0.07$, corresponding to a 12–15 year lifetime for vehicle fleets. In the simulations, these equations are re-expressed to solve for Q_{ot}/Q_t and Q_{pt}/Q_t.

There are two ways of treating the variable S_t (the share of new investment in low-polluting options) in these relationships. The first is to make it an endogenous function of pollution taxes or regulatory policies. The second, which we have preferred, is to make it an exogenous decision variable and to explore the implications of different paths for S_t. This enables the user to consider alternative scenarios and estimate the costs of pollution abatement for different time paths of abatement, from which the imputed pollution taxes of alternative policies can estimated directly. In the estimates in figure 1, S_t rises from zero to unity over 25 years with a gradual phase-out of the remaining polluting plant over the following ten years—a 35 year phased policy overall. This is hardly a 'rushed' policy; but it is about the time it is taking the industrial countries to reduce SO_2 emissions, whose policies were introduced in the late 1960s and early 1970s. The simulations first consider this policy being introduced in 50 years time, and then today. Similar assumptions were made for the simulations for vehicle emissions in figures 2a and 2b, the main differences relating to the differences in the turnover rates of the capital stock and the emissions co-efficients.

Third, there are equations for emissions. Let θ_{pjt} and θ_{ojt} denote the emissions of pollutant j per unit output of the polluting and low-polluting practices at time t respectively, then the total emissions of the pollutant, denoted by E_{jt}, are given by[21]

$$E_{jt} = \theta_{pjt} \cdot Q_{pt} + \theta_{ojt} \cdot Q_{ot} \quad (4)$$

Relationships to allow for accumulations and irreversibilities follow

[21] As written, this equation assumes that the low-polluting technology simultaneously addresses a range of pollutants, not just one; this is often the case, for example, wastewater treatment, tailpipe controls and reformulated fuels for vehicles, future forms of energy such as hydrogen and renewable energy, or when gas is introduced as a domestic and industrial fuel, which eliminates PM, SO_2, ash and wastewaters slurries from power generation. Some technologies (e.g. flue gas desulphurization) apply to one pollutant only however, though it would be rare for a power station or industrial activity to have a desulphurization technology without PM controls as well, even if the technologies are distinct. Nevertheless, it will often be necessary to add new equations to the model to represent a broader range of pollutants.

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straightforwardly, but will not be pursued here.[22] For the results in figure 1, the emissions are indexed to unity at $t = 0$, and the ratio of E_{jt}/E_{j0} is plotted. The emissions ratio $\theta_{jot}/\theta_{jpt}$ is taken to start at 0.1 initially, improving at a rate of 5 per cent per year, corresponding to the ratio declining to 0.023 after 30 years. This is not an optimistic assumption: the starting point is at the lower end of the performance of current technologies if coal is used, while a transition to gas or coal-gasification-combined (i.e. gas-steam) cycle technologies would result in a long-term ratio of <0.01. For the results in figure 2a, the co-efficient for unleaded fuels is zero, while for NO_x, which is proving more difficult to control, it starts at 0.2; even for NO_x and other vehicle emissions, however, there is the possibility of zero emissions in the long term if fuel cell vehicles emerge or, in urban areas, with the recent development of hybrid vehicles.

Lastly, it is necessary to introduce equations to represent prices as a function of marginal costs and costs as a function of Q_{pt} and Q_{ot}. In the above simulations the price elasticity is -0.5, based on the review of Bates and Moore (1992), and P_t has been put equal to the marginal costs of the low-polluting technology. The difference between the marginal costs of the low-polluting and polluting technologies gives the minimum value of the environmental tax (or imputed tax if the regulatory route is preferred) to bring about substitution toward the former. As noted earlier, the effects on marginal costs are relatively small for reducing SO_2 emissions (and also for PM), amounting to about 5 per cent of the total marginal costs of electricity supply costs; hence the price effect on demand is also quite small in the present case, about -2.5 per cent. Similar remarks apply to vehicles.

Where the technologies are still under development, as they are for example with responses to climate change, the cost functions assume greater significance. Consider for example the 'learning-by-doing' cost function $C_t = k\left(\Sigma_{v\leq t}\Delta Q_v\right)^{-b}$, where C_t denotes costs, k is a constant, b is the learning curve parameter, and the summation of outputs over all past vintages v of investment up to time t represents cumulative experience. In the earliest phases of application, a new technology may represent one thousandth or much less of total output, and costs, as indicated in table 1, may be several times those of the technologies they are intended to displace. In these situations, experience accumulates rapidly and costs decline correspondingly. In simulations of responses to climate change, this makes a considerable difference to estimates of long-term costs; further, if we use Monte Carlo procedures to explore a range of assumptions with respect to the technical progress parameter b and other parameters, it turns out that the possibilities of an economic surprise (of negative costs) are not insignificant.[23] For local and regional pollution, we are dealing with more established technologies, and the effect is less important; but the result

[22] For example let A_{jt} denote the level of accumulations of the pollutant in the ecosystem, and d_j the natural rate of recovery of the ecosystem from pollutant j, then: $A_{jt} = (1-d_j)A_{t-1} + E_{jt} - r_{jt}.A_{t-1}$ where r_{jt} is a policy variable to denote the rate of recovery being brought about remediation, repair and 'clean up' activities.

[23] Papathanosiou, Anderson and Cavendish (1999), a result also arrived at byChakravorty, Rohmasset, and Tse (1997).

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once again confirms the necessity of allowing for technical progress in assessments of future paths of pollution and the costs of abating it.

Pollution in the long-term and policies in the transition

The long-term equilibrium of emissions relative to their initial levels once substitution is complete is given by

$$E_{jt}/E_{j0} = \theta_{ojt} \cdot D_t/\theta_{pjt} \cdot D_0 \qquad (5)$$

By far the most important factor in (5) is the ratio of θ_{ojt} to θ_{pjt}, whose decline with technical progress can swamp the scale and composition effects of economic growth working through increases in the ratio on the demand side, D_t / D_0. For SO_2 using 'clean coal' technologies θ_{ojt} to θ_{pjt} is as noted in the range 0.01–0.05; if combined with coal washing and low sulphur coals, it is about one-third of this; and if gas is available through trade via pipelines or liquefied natural gas, or from domestic resources, it is virtually zero.[24] This is why once substitution is complete the emissions become very low, and close to the time axis, as can be seen in the simulations shown in the figure 1, notwithstanding very large increases in energy demands.

Similar results follow for other pollutants such as the control of PM emissions, CO, a variety of tailpipe emissions from vehicles (figures 2a and 2b), with the partial but important exception of NO_x (and the photo-chemical smogs this gives rise to), the indoor pollution in developing countries from the use of wood and dung for cooking, and the reduction of pollution in water supplies and industrial and municipal waste-waters. For CO_2, assuming no shocks from 'runaway feedback' effects in the carbon cycle, there is the long-term possibility that the net fluxes could be reduced to zero or less if substitution to the non-carbon energy forms were ever completed, such that a degree of decumulation of CO_2 concentrations in the atmosphere might become feasible in the long term. Several of the scenarios reviewed by the IPCC imply this possibility (Nakicenovic, Victor, and Morita, 1998), which arises because net fluxes in the absence of carbon emissions from energy production and use would be minus 3 gigatons per year.

The main issue thus is not whether environmental damage can be 'delinked' from economic growth through technical progress but what the timing of policies should be. Given the considerable time lags before the substitutions begin to have their full effect, there is also much policy work to be done in the transition once a policy is announced. Here again the inverted U-shaped hypothesis deflects attention from important issues of policy, particularly those that arise in connection with the *development and diffusion* of new technologies and practices.

1 *The choice of instruments*. The rate of retirement of existing plant and equipment and the possibilities for and costs of retrofitting set limits to the rate of diffusion. Exceptions are when existing plant and equipment can be used with cleaner fuels if these are available, the recent movement towards low sulphur coals under the influence of emissions trading in the US being an excellent example of this (Joskow, Schmalensee, and Bailey, 1999;

[24] See Hamso, Mashayekhi, and Razavi (1994) on international gas trade.

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Schmalensee *et al*., 1998; and Stavins, 1998). Schmalensee and colleagues report 'dramatic over-compliance' with the SO_2 caps in the US in the 1990s, which they ascribe, on the one hand, to the incentives provided by the permit systems, and on the other to the availability both of 'clean coal' technologies and of low sulphur coals, the latter supported by a good railway system. They attribute about 45 per cent of the reductions in emissions to the use of scrubbers, and 55 per cent to switches to lower sulphur coals. Thus the policy also benefited from an inheritance of technological options made possible by R&D programmes—in this case for reducing pollution from coal (on which see Balzheiser and Yeager, 1987), though the same point could be made about the emergence of gas as a clean fuel for power generation, which likewise benefited from both military and non-military R&D expenditures on the development of high efficiency turbines (Norbert-Bohm, forthcoming). The point is then that, given the importance of technology development in reducing pollution, an early emphasis on the development of options and reducing costs through R&D and demonstration programmes is a good complement to the standard instruments of environmental policy, such as environmental taxes and marketable permits, and improves the effectiveness of the latter. In short, we need two instruments of policy, not one. Nowhere is this likely to be more important than for the creation of options for—and for reducing the costs of—responding to climate change.[25]

2 *Institutional issues*. These vary greatly between sectors. For example, in the control of vehicle emissions the main problem facing developing countries is not technological, but of securing compliance with policies; it will require not only the setting up facilities for monitoring and vehicle inspection, but a system of law and oversight that precludes the dangers of widespread avoidance of compliance through bribery in a vast network of garages and inspection stations that would also need to be certified and monitored. In a different vein, methods for eliminating the damage to soils and forests arising from the burning of firewood and dung are well known and can draw on more than a century of field research on soils, forests and agricultural practices; further, it has been shown that such practices yield significant benefits to agriculture because they increase farm yields.[26] The main barriers to their wider adoption include the resolution of property (tenure) rights in many regions, such that the incentives to adopt the practices exist, and the need to develop the capacities of the extension services to provide the appropriate advice.[27]

3 *Poor regulation and state monopoly.* These historically have often increased lags—and sometimes stalled—the development and use of new technologies completely, on account of biases in public regulatory systems for the *status quo*. Examples are numerous: the subsidy of coal and nuclear power for half a century throughout the OECD; until c1990, the historical resistance to gas as a fuel for power generation ('too noble a fuel' and

[25] See US President's Committee of Advisers on Science and Technology (1999).
[26] Doolette and Smyle (1990), Grimshaw and Helfer (1995), Brandle, Hintz, and Sturrock (1988), Gregerson, Draper, and Elz (1989), Current, Lutz, and Scherr (1995), and Anderson (1989).
[27] Gregerson, Draper, and Elz (1989) and Anderson (1989).

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restricted to use, until the late 1980s, for peak load gas turbines only); historical restrictions on the prices and marketing of LPG as a cooking fuel in developing countries;[28] the massive use of state funds for nuclear R&D relative to all other technologies for 50 years;[29] and so forth.

4 *Trade and foreign investment in new technologies.* Much of the economics literature on trade and the environment has been concerned with the hypothesis that, with the tightening of environmental regulations in the industrial countries, 'dirty' industries will migrate to developing countries, where such regulations are weak. The extensive review by Chua (1999)[30] reveals that the evidence on this hypothesis is ambiguous, and in addition that most studies have (surprisingly) overlooked the role of trade and foreign investment as conduits for the spread of low-polluting technologies to developing regions. If local policies are in place, the possibilities for improving the rate of diffusion of environmental technologies through open trade and foreign investment are appreciable, and should be expected to increase the rate of substitution of low for high-polluting practices. The trade of gas is an example, but there are others; all the technologies and practices identified in table 1, with the exception of those required to protect soils and forests, are tradable goods and services.

5 *Poverty and the affordability of services.* There is one major aspect of the pollution problem the resolution of which is crucially and directly dependent on income growth. It is, as Beckerman (1992) has tirelessly drawn to our attention, the pollution associated with poverty.[31] Prime examples are the poor access to safe water and sanitation services and the two billion people who are dependent on the use of dung and wood as cooking fuels. One should add to this pressures on soils and forest resources arising from the latter. Such deprivations are highly concentrated among the most impoverished people, but decline rapidly if and when their incomes grow. It thus turns out that, even from an environmental perspective, the 'inverted-U' relationship that is most relevant is *not* the one estimated by the above-mentioned curve-fitting exercises, which was not put forward by Kuznets himself, but the relationship he *actually* identified, concerning income distribution and growth, and all the issues this poses for development policy. Too much attention has been given to the influence of the *average* per capita income variable on pollution, studies of the U-shaped hypothesis being especially culpable in this respect.

Effects on growth

Various studies of national policies, for example those by Davies and Mazurek (1998) of the US experience and by the World Bank (1992) in

[28] See the case of LPG markets in Hyderabad, reported in World Bank (1996).

[29] Even when the UK non-fossil fuel obligation (NFFO) programme was introduced in the 1990s to support the development of non-fossil technologies, over £8 billion of funding went to nuclear power, over ten times more than went to the development of renewable energy over the decade. See the review by Mitchell (forthcoming).

[30] See also her Ph.D. thesis (draft), Chua (1999).

[31] See also his history of water and air pollution. Beckerman (1974).

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relation to the requirements of developing countries have estimated that the costs of environmental protection amount to around 2–3 per cent of GNP.[32] Such estimates are consistent with the assessments summarized in table 1 above of the costs of pollution control using advanced technologies and practices, the World Bank's estimate being based on an earlier assessment of the costs of environmental protection for a wide range of economic activities (ibid.; table 9.1, p. 174). If such estimates hold then, *even neglecting the benefits of pollution control*, the costs of introducing the low-polluting technologies on growth are likely to be very small. A diversion of 3 per cent of GNP through environmental policy to environmental ends, for example, would reduce investment by $0.25 \times 3 = 0.75$ percentage points if the investment rate was 25 per cent; if the incremental capital–output ratio were unchanged, a developing country with, say, a 4 per cent long-term rate of growth, would find its growth rate reduced to 3.9 per cent. This is, moreover, too pessimistic, since, as Chua (1999) argues, we need to allow for the positive feedback of environmental protection on people's health and productivity. In cost–benefit analysis, expenditures on pollution abatement are routinely treated as an investment having a social return. When the economic benefits of the policies outweigh the costs we are looking at an increase in the incremental output–capital ratio and an overall increase in the long-run rate of economic growth.

Such conclusions echo the review of Davies and Mazurek of US experience, who conclude (1998: 148): 'The macroeconomic effects of pollution control and regulation are generally modest. Regulation has had some adverse effects on GDP growth, but most economists think that the effect has been relatively small, and the negative effect fails to take into account most of the benefits of regulation … When looked at as a whole, US environmental progress has made economic sense. It can be shown that benefits exceed costs in a great number of cases.' In the case of developing countries the net effects on growth should be even greater, since for their main environmental priorities—safe water, the reduction of PM from smoke, and soil conservation and management—the economic benefits can be expected to be substantially in excess of costs.[33]

Nevertheless, there is still much to be done to rectify deficiencies in existing models of environment and growth, and to compile evidence. In an extensive review Chua (1999) found no macro-economic model that had attempted to incorporate the positive feedback of environmental improvement on productivity and growth;[34] in addition, there were deficiencies in the ways technical progress in pollution abatement had been modelled (where it was modelled at all), something I hope the preceding analysis will help to address. We are also in need of further case studies on the lines of those reported in Kemp (1997) and for Clayton, Spinardi, and

[32] The estimates for the US ranged from $100 billion to $200 billion per year in 1997. GNP was around $8 trillion. Cf. the 1992 World Development Report of the World Bank, chapter 2, which came up with a similar percentage figure.

[33] Some evidence on this was discussed earlier. Also see World Bank (1992, chapter 9).

[34] See also her thesis: Chua (2000).

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Williams,[35] and for *ex post* evaluations of past policies, since experience with environmental policy and its effects on technology development is accumulating rapidly. What can be said is that, so far, there is no evidence to suggest that the economic prospects of any country, rich or poor, will be diminished by environmental policies pursued in ways consistent with the now well-understood principles of environmental policymaking, and mounting evidence that they will be improved.

Conclusions

The paper first sought to assess the contribution of technical progress to the reduction of environmental damage by reference to specific practices for reducing air and water pollution. In every case high levels of abatement have been shown to be achievable at costs that amount to small percentages of the costs of production and of value added. Kneese and Bower (1979: 112–113) arrived at the same conclusion 20 years ago following a series of case studies:

> even for major residuals-generating industries … (and for) relatively high levels of reduction in residuals discharges per unit of product or per unit of raw product processed, the total production costs represented by residuals management costs amounts to only a few percentage points. However, as 'zero discharge' of liquid and gaseous residuals is approached, the marginal costs of reduction in discharge increases substantially.'

There is also evidence of costs declining and abatement efficiencies improving with innovation in important cases. In some instances—soil management, water supplies, and the effects of gas on the abatement of acid deposition and PM emissions—the net marginal costs of pollution abatement are negative in the sense that the investments can be and routinely are justified by their private economic returns, without reference to

[35] Kemp reviews case studies on wastewater treatment in the food and beverage industry, CFCs (on which also see the review by Ahmed, 1995, low solvent paints (to replace organic solvents), membrane technologies in the metal plating industry (to reduce metallic wastes in the water effluents). The findings on costs and abatement efficiencies are similar to those reported in section 2 of this paper. Kemp cites a study by a Dutch consulting firm, which concludes that the costs per unit emission reduction of flue gas desulphurization has decreased by 4 per cent per annum over a period of 20 years. The cost of phosphate removal in municipal waste-water treatment plants, declined by a rate of 3.7 per cent per year since 1975. Similarly, the cost of catalytic converters, he noted, dropped by 9 per cent over ten years. For industrial low-NO_x techniques, the per annum cost reduction they found was even higher—between 17 and 31 per cent a year over a period of six years. Clayton, Spinandi, and Williams (1999) provide case studies on petroleum refining, fine chemicals, pharmaceuticals, electroplating, and the dairy, brewing, sugar and paper mills sectors. See also the studies cited earlier on the clean up of river pollution in the UK and the US. A referee commented that we are also in need of studies into the environmental side effects of new technologies intended to address pollution, to assess whether they are giving rise to new and more complex forms of pollution. I agree.

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the environmental benefits, important as the latter are. From a technological and an economic perspective therefore there are good reasons to be sanguine about the possibilities of reducing pollution to socially satisfactory levels in the course of economic growth, in ways that would likely be beneficial for growth.

Developing countries especially should be able aspire to reducing pollution at much earlier phases of development than was the case historically in the industrial countries. The recent spate of studies on the 'inverted U-shaped hypothesis' have suggested that they may *not* aspire to reducing emissions of PM, lead compounds from car exhausts, acid deposition, water pollution, and a variety of other pollutants until their per capita incomes have reached the levels reached by the industrial countries in recent decades—a process that could take half a century or longer in the higher-income, high-growth developing countries, and a century or longer in the others. They could be massively in error. They also assume, implicitly, that alternatives to fossil fuels will not be available for many decades (if ever), since no 'inverted U' has been found for CO_2. Such assumptions are misleading, are contrary to reason and evidence, and are easily refuted by simulation studies of the kind undertaken above and in the literature reviewed. Technical progress has created options that developing countries may draw upon to address local, regional and global pollution problems at income levels that the industrial countries reached more than half a century ago, and in some cases a century ago.

The problems to be addressed in bringing the required substitutions about also reveal that we need to explore a wider range of options than is usual in the analysis of environmental policies. R&D and demonstration programmes are generally needed to develop and prove the new technologies and practices, and may also require investment incentives in support of the positive externalities of innovation, as Baumol (1995) has argued. Pricing and institutional development policies in the sectors in question offer not only much-discussed 'win–win' opportunities, but have a large bearing on the rate of uptake of the low-polluting practices. Distribution and poverty reduction policies are also central, not only because the lowest income groups are most affected, but because they have a large and direct bearing on the rate of reduction of the most severe forms of environmental damage in developing countries today—unsafe water, the lack of sanitation, indoor air pollution, and the damage to soils and forests from the use of wood and dung for cooking fuels. In this respect, the original hypothesis of Kuznets on distribution and growth, and the immense literature that followed, is far more relevant for the environment debate than curve fitting exercises associating emissions with average per capita incomes.

The technologies and practices discussed, with the exception of soil erosion control, are all tradable goods. For both industrial and developing countries, therefore, there is the conclusion that trade and foreign investment are likely to be good conduits for the spread of environmentally improved practices—in water supply and waste-water treatment equipment, for example, in gas trade and investment, in unleaded fuels and the control of tailpipe emissions, in technologies to reduce acid deposition,

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urban smogs, and climate change, to name a few. In this respect, openness to trade and investment, supported by local environmental policies, may well help to address some of the world's most serious environmental and health problems.

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