ENERGY-EFFICIENCY AND THE ECONOMICS OF POLLUTION ABATEMENT

Dennis Anderson
The World Bank, Washington, DC

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INTRODUCTION

For reducing pollution from energy production and use, perhaps no single recommendation has received more attention recently than that of improving the efficiency with which energy is produced and used—or "energy-efficiency" (as it is often called). Improvements in efficiency have undoubtedly helped to abate pollution in the past, and will do so in the future. During the past two centuries, the efficiency of energy-producing and energy-using activities, as measured by the amount of energy needed to provide a given output or service, has improved by factors ranging from 50 to more than
100. Yet energy use expanded enormously: first, because the efficiency improvements reduced costs and prices correspondingly, and thus actually stimulated the growth of demand; second, because the improvements led to an expanding array of new applications of energy; and third, because of the growth of populations, incomes, and industry. During the present century, during which energy-efficiency grew by factors of more than 10 in key sectors such as electricity, world commercial energy consumption\(^1\) has increased 10-fold, an average growth rate of 2-1/2 percent per year.

Since the 1970s, the energy markets in the industrial countries have matured in the sense that the growth of incomes and of commercial and industrial activity no longer exert the large effect on demand that they did in the past (1). Their energy markets might even peak and then decline in the near future with continued improvements in efficiency. But this is not true of the developing countries, where per capita consumption of commercial energy is only 1/10 that of the industrial countries, more than two billion people are dependent on biomass (wood, dung, and crop residues) for cooking fuels, more than two billion are also without electricity, the per capita consumption of industrial products is less than 1/20 of that of the industrial countries, and populations are expected to double, growing by nearly four billion people, in the next 40 years. The growth of populations, incomes, and economic output, and the substitution of commercial for biomass fuels are all likely to exert a huge influence on future energy demands in developing regions. Even under an energy-efficient scenario, their demands are likely to grow 5–10-fold over the next 30–40 years, leading to a threefold increase in world primary energy demand (1–5).

Thus, important as continued improvements in energy-efficiency are, there are distinct limits to the contribution they can make to abating pollution. Much more emphasis will have to be given to low-polluting technologies in energy production and use if pollution is to be reduced. As discussed below, these technologies can abate pollution by factors of 10–20 in the case of most pollutants and by a factor of more than 1000 in the case of particulate matter emissions from coal-fired power stations, at costs that vary with the case but that typically range from 1 to 10% of supply costs, depending on the pollutant and the technology chosen. They allow us to meet rising energy demands while greatly reducing pollution—thus "delinking" environmental concerns from energy use.

There is indeed a danger that gains in energy-efficiency as a means of

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\(^1\)Commercial energy consumption is usually defined to include oil, gas, coal, and electricity generation from nuclear, fossil fuels, and renewable energy. It excludes fuels such as wood, peat, crop residues, and animal wastes.
pollution abatement can be pursued to excess, at costs far higher than those that would be incurred if low-polluting technologies were used. The growth of the commercial energy industry has brought with it immense benefits to the industrial countries, and is now doing the same in the developing countries. The important task for policy-makers therefore will be to find policies that will enable these countries to meet their growing demands efficiently while simultaneously abating socially undesirable pollution. This paper argues that this can be achieved if the economist’s criterion for efficiency—the economic rate of return to investment—is used in the choice of policies for reducing pollution. This criterion is broader in concept than energy-efficiency, since the aim of using it is to maximize (a) the net economic benefits of meeting energy demands including (b) the net benefits of abating pollution to socially satisfactory levels.

The paper discusses the relative contributions of energy-efficiency and abatement technologies to reducing pollution, and then turns to the various policy options. In addition to reviewing the elements of optimal policies for pollution abatement in the energy industry, three quantitative findings are discussed:

1. Large improvements in energy-efficiency have been achieved continually for more than two centuries. By reducing production and consumption for particular purposes, they have often helped to reduce pollution. However, because they also reduced costs, and frequently led to new and highly beneficial applications of energy in transport, homes, commerce, and industry, such efficiency improvements were associated with the expansion, not the contraction, of energy production and use. There is no guarantee therefore that energy-efficiency will always reduce pollution; much depends on its effects on costs and prices, on price elasticities, on the nature of the innovation, and on the level of a country’s development. (This is a worthy area for research.) What can be said, however, is that energy-efficiency is worth pursuing in accordance with economic principles even if it does not reduce pollution, since the economic—as well as commercial—benefits can be substantial.

2. In all countries, introducing environmental taxes and regulations, by raising costs and prices, reduces consumption and pollution somewhat. But the effect is small in comparison to the levels of abatement that can be achieved by substitution (induced by environmental policies) towards the low-polluting technologies.

3. In numerous developing countries and the formerly centrally planned economies, structural problems arising from deformities in markets, prices, and government policies have led to inefficient and excessively
polluting energy production and use. Political and economic reforms in these countries would lead to unequivocal gains in energy-efficiency and economic efficiency.

The paper begins with a short historical perspective on energy-efficiency. Despite the current interest in the subject, the search for efficiency is an old one, going back three centuries, if not to much earlier times.

THE "SEARCH" FOR EFFICIENCY

"Energy-efficiency" is a technical term, generally used to denote the output of an energy-using activity per unit of energy input—for example, the kWh output of power stations per unit of fuel used; the miles per gallon of vehicles; or the amount of light, heat, refrigeration, or motive power delivered per unit of energy consumed. Conservationists often use the term more liberally to include people's using less energy (and sometimes going without) by changing habits of consumption, for example by switching off appliances when they are not needed, by using public transport, or by using more natural lighting, heating, and cooling in commercial buildings and homes; these measures also increase energy-efficiency.

Historically, technical advances have led to enormous reductions in the amounts of energy required for any given purpose. But because costs also declined commensurately, and because they were often associated with far-reaching innovations, technical advances were generally a source of expansion—not contraction—of the energy industry. Innovations in other fields and the growth of incomes and economic activity led to an almost endlessly increasing array of applications of commercial energy, compounding the effects of cost reductions via efficiency improvements on the industry's expansion. Examples can be found in all fields and in every decade of the past three centuries. The following suffice to make the main points, along with some elementary calculations; two are from the supply side and two from the demand side.

Steam Engines

The early atmospheric steam engines of Newcomen and Smeaton in the 18th century had thermal efficiencies of only 0.5%. With the invention of the steam condenser, and the use of low-pressure steam, Watt and others were able to raise efficiencies 10-fold, to 5%, by the early 19th century. Continued developments, including increases of steam pressures and tem-

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2Meyers & Schipper (1) and others sometimes refer to it as "technical energy-efficiency," though the shorter term is preferred here.
EFFICIENCY, ECONOMICS, AND POLLUTION

Table 1  Efficiencies of reciprocating steam engines, 1718–1906

<table>
<thead>
<tr>
<th>Date</th>
<th>Builder</th>
<th>Engine’s “duty”</th>
<th>Percentage thermal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1718</td>
<td>Newcomen</td>
<td>4.3</td>
<td>0.5</td>
</tr>
<tr>
<td>1767</td>
<td>Smeaton</td>
<td>7.4</td>
<td>0.8</td>
</tr>
<tr>
<td>1774</td>
<td>Smeaton</td>
<td>12.5</td>
<td>1.4</td>
</tr>
<tr>
<td>1775</td>
<td>Watt</td>
<td>24.0</td>
<td>2.7</td>
</tr>
<tr>
<td>1792</td>
<td>Watt</td>
<td>39.0</td>
<td>4.5</td>
</tr>
<tr>
<td>1816</td>
<td>Woolf compound engine</td>
<td>68</td>
<td>7.5</td>
</tr>
<tr>
<td>1828</td>
<td>Improved Cornish engine</td>
<td>104</td>
<td>12.0</td>
</tr>
<tr>
<td>1834</td>
<td>Improved Cornish engine</td>
<td>149</td>
<td>17.0</td>
</tr>
<tr>
<td>1878</td>
<td>Corliss compound engine</td>
<td>150</td>
<td>17.2</td>
</tr>
<tr>
<td>1906</td>
<td>Triple-expansion engine</td>
<td>203</td>
<td>23.0</td>
</tr>
</tbody>
</table>

a Sources: (6). See also (8).
b Forbes remarks that “earlier engineers found perplexity in expressing the power of their engines and comparing them.” The term “duty” was commonly used, the unit being million ft.-lb per bushel (84 lb) of coal.

temperatures, raised thermal efficiencies to more than 20%—more than a 40-fold increase over the early engines—by the end of the 19th century (Table 1). The initial uses of steam engines were for pumping in coal mines, but they soon became coal’s main consumer; in Britain alone coal production rose from 6 million tons in 1800 to 60 million in 1850, and to 300 million tons by 1914; in the United States, it rose from less than 4 million tons in 1860 to 455 million in 1914, and in Germany from 12 to 280 million tons in the same period (6, 7). Sadi Carnot remarked in 1824 that to rob a country “of her steam engines would be to rob her of her coal and iron [and] to deprive her of her source of wealth,” a sentiment echoed later by many historians. The contribution of coal to the industrial revolution, and doubtless the revolution itself, rested heavily on the 40-fold increase in the thermal efficiency of steam engines between the 18th and the turn of the 20th century.

Electric Power

Progress in the efficient use of steam has continued throughout the present century, in its application to electric power. In the United Kingdom, Hannah (9) notes that each ton of coal generated only 100 to 200 kWh in 1891; by 1914 each ton generated 550 kWh; by 1920, 630 kWh; and by 1939, 1566 kWh; today it would generate more than 3000 kWh in new stations. Similarly, in the United States, the overall efficiency of power stations was no more than 5% at the beginning of the century, with generation costs of $1.40 per kWh (in 1990 prices); by 1950, efficiency had increased more than fivefold to 25%, and costs had fallen more than 15-fold; efficiency
has doubled again since then to nearly 50% for modern, gas-fired, combined-cycle power plants, and costs have declined to approximately $0.05 per kWh, or to less than 1/25th of the costs of electricity generation 90 years ago (10). Assuming a price elasticity of -0.5, the cost reductions that such efficiency improvements helped to bring about themselves account for a sixfold expansion of the electricity industry in the present century; in fact, since 1910, the industry expanded more than 50-fold in the United States because of the expansion of economic activity and the growth of incomes.

**Lighting**

Possibly more than two billion people in developing countries do not have electricity, and either depend on kerosene for lighting or go without it, as they did in the industrialized countries in the 19th century, when the use of kerosene for lighting became the main source of growth for the oil industry. For low-income families in rural areas, whose demands for artificial light are minimal, and where the wick lamp is still widely used, it is often the only affordable option (at the low levels of consumption found in these areas, it is often also the economically more efficient choice). But from a technical viewpoint, it is "energy inefficient": modern electronic fluorescent lamps are 4–6 times more efficient than incandescent lamps, incandescent lamps 10–15 times more efficient than pressurized kerosene lamps, and pressurized kerosene lamps 8 times more efficient than wick kerosene lamps (Table 2) (15). Thus the modern fluorescent lamp is 300–700 times more energy-efficient than the kerosene wick lamp. For the majority of people in developing countries, even the substitution of the incandescent lamp for kerosene marks a 100-fold gain in energy-efficiency—and is much sought after when incomes rise and access to electricity is provided.

The past 100 years have also seen a continued improvement in the efficiency of electric lamps. On the incandescent lamp, MacKechnie-Jarvis

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Efficiencies (lumens per watt) of lamps*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene</td>
<td></td>
</tr>
<tr>
<td>wick lamp</td>
<td>0.1</td>
</tr>
<tr>
<td>pressurized (mantle) lamp</td>
<td>0.8</td>
</tr>
<tr>
<td>Incandescent</td>
<td>12–20</td>
</tr>
<tr>
<td>Fluorescent</td>
<td>30–75</td>
</tr>
</tbody>
</table>

*a Based on (16).

The following draws on (11–14).
wrote, “from 1885 until the close of the century there was a steady improvement in the technique of manufacturing and a gradual lowering of manufacturing costs ... [this] is reflected by the figures for lamp-efficiency, expressed in lumens per watt, which rose from about 1.4 in 1881 to 4.0 in 1900 (13); efficiency is about 20 lumens per watt today. Similarly, the ratings of the most efficient fluorescent lamps available rose from 50 lumens per watt in 1950 to 90 lumens per watt in the 1980s (11).

Traditional and Commercial Fuels
The shift from traditional fuels—wood, crop residues, and dung—to commercial fuels for cooking and other household energy uses is another example of gains in energy-efficiency. Until the development of the coal industry in the past century, biomass was the predominant fuel for home heating and cooking in the now-industrialized countries, as it is for more than 2 billion people today in the developing countries (17–21). The transition to commercial fuels as per capita incomes rise is associated with a noticeable decline in the ratio of energy use to per capita GNP (Figure 1). This decline can partly be explained by the relative efficiencies of the stoves used for cooking: Baldwin (17) and the US OTA (16) note that traditional stove efficiencies using dung, agricultural residues, and wood are 10–20%; those of improved wood and charcoal stoves 25–35%; and those of kerosene and LPG stoves 40–60%. (The efficiency of electric stoves, allowing for losses in power generation, transmission, and distribution, is lower than for other commercial fuels, around 20%; however, kerosene and LPG are the alternatives people generally turn to first when they no longer use traditional fuels in developing countries.) The transition to commercial fuels in developing countries, as in the industrial countries historically, is accompanied by not only an increase in energy-efficiency, but also a big decline in indoor air pollution (4, 22), and in the social and environmental costs of gathering and using firewood and dung for cooking (23).

As noted earlier, significant gains in energy-efficiency can be found in all aspects of commercial energy production and use. Meyers & Schipper (1) note, for example, that between 1970 and 1989, the average efficiency of the US jet-aircraft fleet nearly doubled, while the efficiency of freezers and refrigerators also doubled, and efficiency rose by around 50% for various other appliances. For new cars in the United States, they comment that Environmental Protection Agency (EPA) test data show much improvement in fuel-economy in each size class. Furthermore, although there are physical limits to efficiency, the possibilities for further improvements are far from being exhausted, in lighting, in transport, in residential applications, and in motive power, process heating, and cooling in industry and commerce.
the research communities pointing to the possibilities of up to a further two-to-four-fold increase in the coming decades, arising from technical developments (see e.g. 12, 24, 25). This may reduce energy consumption in the industrialized countries, but consumption would still rise in the developing countries, because of the growth of incomes and populations.

In relation to the problem of reducing pollution, there are four conclusions
to be drawn from the historical evidence on energy-efficiency. The first is the quantitative importance of efficiency. If all forms of energy were produced and used today at the levels of efficiency that prevailed in, say, 1950, the world’s primary energy consumption would be equivalent to around 16 billion tons of oil (toe); this is roughly twice today’s levels, because energy-efficiency has doubled since then. Actual consumption would have been less than this, around 12 billion toe, still 50% higher than today, since costs and prices would have also been at least twice as high,4 and the higher prices would have reduced demand growth. But the point remains that energy consumption (and the emissions associated with its provision and use) would have been much higher without efficiency gains.

Second, improvements in energy-efficiency over the past two centuries have been a source of growth for the energy industry and of innumerable other activities—which helps to explain the energy industry’s own commitment to improving energy-efficiency since its beginnings. Improved efficiency has brought with it immense economic benefits—associated with the most important innovations during and since the industrial revolution—and the pursuit of efficiency in accordance with good economic and commercial principles remains an important area for research and development (R&D) and investment. But improved energy-efficiency will not always reduce the use of energy and pollution. In three cases noted above—steam power, electricity generation, and lighting—efficiency rose by factors of 25 or more in the course of a century. The unit costs of supply sometimes fell by more than this (in the case of electricity) and sometimes by less (in the case of lighting), but as a rough average, improvements in efficiency would probably have reduced unit costs and thus prices by a similar order, sufficient to explain a fivefold expansion of the energy industry, other things constant. However, a widening array of applications opened up by the innovations, and the growth of industry, commerce, populations, and per capita incomes, combined with reductions in costs, actually led to yet a higher rate of expansion. For instance, annual world primary energy consumption rose from 150 to 5000 Mtoe between 1870 and 1970; thus consumption grew at 3-1/2 percent per year over the period even as huge improvements in efficiency were being achieved.5

This is likely to be the situation in developing countries for several decades (4, 5, 27a). While in the industrialized countries, whose markets have matured, continued improvements in efficiency may conceivably reduce overall energy demands in the long term, this is not the case for the

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4The estimate assumes a long-run price elasticity of −0.5. For a survey of elasticity estimates see Bates & Moore (26). The figure of −0.5 is an average of several studies.

5Figures in Crowther (27) to the 1950s, and the BP Statistical Reviews of World Energy.
developing countries, where income elasticities are still high, as they were previously in the industrialized countries. The third conclusion then is that the effects of efficiency on energy use and pollution will differ greatly between the industrialized and the developing countries: in the former, efficiency may help to reduce energy use and pollution overall; in the latter, efficiency can only help to reduce their rates of growth. The same conclusion also follows from the most informative review of Meyers & Schipper (1).

Fourth, it follows that energy-efficiency by itself will not “solve” pollution problems. In the industrialized countries, energy consumption levels would still be very high even if a twofold increase in efficiency were to be obtained in the coming decades. In the developing countries, energy demands are likely to rise more than fourfold over the next 30 to 40 years even on strong assumptions about improvements in energy-efficiency. Emissions of all pollutants would rise correspondingly in the absence of measures to reduce pollution directly.

COST-EFFECTIVENESS IN POLLUTION ABATEMENT

Reducing pollution from energy production and use therefore requires three policies, not one. The first is to address the various problems that lead to economically inefficient uses of energy; foremost among these in many countries is the subsidization of energy—e.g. of coal in many European countries, and of most forms of energy consumption in the developing and formerly centrally planned economies (28). The optimum policies will require prices to reflect the full costs of supply, including the costs of compliance with environmental policies. The second is to determine the required level of pollution abatement based on the analysis of the benefits (broadly defined) and the costs of abatement (see e.g. the admirable survey of Markandya & Pearce, 28a). The third is to achieve the required abatement by introducing appropriate environmental taxes or regulations.

The potential gains from such policies are large—both to the environment and to the economies in question. Consider the case of electricity supply in developing countries, where excessive demands for energy are being encouraged by large subsidies. A recent survey of 63 utilities revealed that retail prices average little more than 4 cents per kWh, while marginal costs, if the power systems were operating efficiently, would average about 10 cents per kWh. Much of the difference is borne by public revenues, and the resulting economic losses, which amount to more than $100 billion per year, are a source of both budgetary distress and economic inefficiency (4). Yet in important respects, this is to understate the situation, since low cash flows also lead the utilities to compromise on required maintenance and the reinforcement of distribution networks; electrical losses may range from 20
to 40% of generation (as compared to 10% or less that is achieved in good-practice situations); the thermal efficiencies of power stations are several percentage points below nameplate ratings; and plant availabilities average about 60% (as compared with 80–90% in good-practice situations). Allowing for the managerial inefficiencies induced by price inefficiencies, marginal costs are closer to 15 than to 10 cents per kWh; and the costs of implied subsidies are thus much larger than the $100 billion figure just quoted.

The above figures suggest that, taking present-day prices as a starting point, a one kWh reduction in demand brought about by an increase in price would have a marginal economic benefit of approximately $15 - 4 = 11$ cents per kWh. Pollution would be reduced correspondingly. If prices were raised further, the marginal net benefits of the demand reductions induced would be less because the difference between prices and costs would be less, but would still be positive so long as the marginal costs of supply exceeded the marginal value of consumption (the price consumers pay). The net incremental benefits of raising prices, ignoring the economic benefits of reducing pollution for the moment, would be zero at the point where prices reflected costs. Beyond this point, further increases in prices would “tax” consumers and, depending on the budgetary situation, costs could rise very steeply. The curve in Figure 2 summarizes the argument graphically. Since the curve represents the amount by which the production and consumption of energy are reduced, other things constant, as prices are raised, it provides an index of the level of abatement of all pollutants by this means.

Also shown in Figure 2 are the marginal costs and long-term abatement efficiencies of low-polluting technologies (the data are presented in more detail in Table 3, which also includes information on vehicle fuels). First consider the local and regional pollutants from electricity generation—particulate matter (PM), SO₂, and NOₓ. The abatement efficiencies and costs of the various technologies for coal- and gas-fired power plant have been well documented (see source notes to Table 3). For particulate matter emissions from coal-fired plants, abatement efficiencies of 99.9% can be achieved at a marginal cost of around 0.4 US cents/kWh using electrostatic precipitators or baghouse filters. These technologies have long been deployed in the industrialized countries, and their adoption in developing countries will do much to virtually eliminate what for them is still a major source of pollution (4). For emissions of NOₓ and SO₂ from coal plant, abatement efficiencies of 90–95% are achievable at marginal costs of approximately

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6 The calculations again assume a price-elasticity of demand of −0.5, based on the survey of Bates & Moore (26). Details of the calculations can be found in the appendix.
0.5 and 1.5 US cents/kWh, respectively, using scrubbers and catalytic devices; alternatively, for SO₂, the various fluidized-bed technologies could be deployed at similar if not lower costs (again the reader is referred to the literature cited). If natural gas is economically available for power generation, the costs of abating PM and SO₂ are practically zero, and the levels of abatement virtually 100%; as indicated in Table 3; however, there would still be some costs entailed for controlling NOₓ. But the main point is, as Figure 2 shows, the costs at high levels of abatement would be trivially low relative to those of attempting to abate pollution through demand restrictions. The main contribution of demand management comes from the “win-win” area at the lower left part of the curve, where pollution reduction occurs at negative costs though the reduction of price and related inefficiencies; but beyond that the cost-effective choices belong to the low-polluting technologies. Thanks to innovations in pollution abatement technologies, therefore, there is every reason to expect that in developing countries, as in the industrialized countries, electricity demands can be met while local and regional environmental problems are addressed fully.

Might the same conclusion eventually apply to the abatement of CO₂? Unless there is a recovery in nuclear power, much will depend on continued progress with renewable energy technologies—photovoltaics, solar-thermal, biomass for electricity production, wind, and others. Progress has indeed
### Table 3  Emissions-control (low-polluting) technologies: Abatement efficiencies and costs

<table>
<thead>
<tr>
<th>Emission</th>
<th>Without technologies (index)</th>
<th>With technologies/without technologies (%)</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sector</strong></td>
<td><strong>PM</strong></td>
<td><strong>SO₂</strong></td>
<td><strong>NOₓ</strong></td>
</tr>
<tr>
<td><strong>Electric power—coal</strong></td>
<td>100</td>
<td>&lt;0.1</td>
<td>100</td>
</tr>
<tr>
<td><strong>Electric power—gas</strong></td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td><strong>Motor vehicles</strong></td>
<td>100</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td><strong>All fossil fuels (long-run marginal costs)</strong></td>
<td>100</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td><strong>CO₂ (electricity)</strong></td>
<td>100</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

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**Sources and notes:** The abatement technologies and costs for electric power are reviewed in OECD (29), The Asian Development Bank (30), Bates & Moore (26), and Anderson (31). For coal, the reference plant is a conventional boiler using 3% sulfur coals. With combined-cycle plants for gas and coal (using coal gasification), the extra costs would likely be offset by the gains in thermal efficiencies. For motor vehicles, see OECD (32, 33) and Walsh (34, 35). For reducing CO₂, the estimates are based on the costs of renewable energy; these are reviewed in (36-42) and relate to high-insolation areas.

*Volatile organic compounds.*

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been substantial over the past two decades (4, 36–38, 42, 42a). The current costs of thermal-solar schemes in high-insolation areas are listed as about 10 to 15 cents per kWh; but because less than 400 MW have so far been installed, and because the technology is modular and well-suited to mass production, the costs projected by the US DOE and others, of around 5–8 cents per kWh, including the costs of short-term thermal storage, seem plausible; the economics of storage would also be helped by the adoption of peak-load pricing, since peak-load costs on power systems are typically twice the average cost. Wind generators and cogeneration from biomass resources are already in this 5–8 cents per kWh cost range. The costs of photovoltaics (PVs), which are currently around 35–40 cents per kWh but have fallen 100-fold over the past 20 years (42), are similarly projected to
be around 5 cents per kWh (38) (though the costs of storage are not included in these estimates). Thermal-solar would have to compete with centralized power generation, the costs of which vary between countries, but range from 4 to 7 cents per kWh (29). PVs, on the other hand, are well suited to decentralized generation, and can thus save on the costs of distribution; their costs are best compared therefore with total supply costs, the average of which range from 8 to 12 cents per kWh depending on the system to higher levels for rural electrification (again, peak-load costs are much higher). The upshot of such estimates, which are detailed in the sources cited [see especially the landmark study of Johansson et al (37)], is that the long-run costs of achieving very high levels of CO₂ abatement, should the need arise, would likely be in the range 0–5 cents per kWh in countries with high insolations, but higher in the lower-insolation countries unless they import electricity from the former using high-voltage DC transmission. The estimates are again shown in Figure 2, and the conclusion is the same as that just arrived at for local pollution, notwithstanding the uncertainties in the estimates: for high levels of abatement, the low-polluting technologies are by far the most cost-effective approach.

Similar conclusions also apply to both local and global pollution in the vehicle fuel markets, as can be inferred from the data in Table 3. One quantitative difference, however, is that the costs of reducing CO₂ emissions will likely be much greater, since it will be difficult indeed for nonfossil fuel technologies to compete in these markets. One possibility is the fuel cell–electric vehicle fueled either by hydrogen or by methanol from renewable energy sources, and another is the battery-powered electric vehicle. Estimates of incremental costs, relative to the internal combustion engine, are still very uncertain, and vary over a wide range from less than $0.5 to more than $1.5 per gallon of oil-equivalent energy (39–41); these estimates allow for the superior efficiencies of the electric vehicles relative to the internal combustion engine (60% in the former, 20% in the latter). While such differences in costs are of course large, it is worth noting that (a) they are only half of the difference in fuel costs “at the pump” between the United States and Europe on account of differences in fuel taxes, and (b) much depends on the price assumptions for oil, since the estimates just quoted are based on $25 per barrel. From (a), and also from the emissions data in Table 3, it can readily be inferred, once again, that the decisive effects on pollution abatement would come from substitution towards the low-polluting technologies, not demand reductions.

As with the reduction of pollution through improving energy-efficiency, the time required for low-polluting technologies to be introduced and have
their full effect is often appreciable, since much depends on the rates at which the new technologies could be developed, tested, and deployed, and on the lifetimes of the existing capital stock. The dynamics of the response to policies will be discussed shortly. But first, and concentrating on the long-term effects for the moment, it might be useful to sum up the four main conclusions by reference to the case of electricity supply in developing countries.

First, energy-efficiency gains through improvements in price and managerial efficiency would likely reduce pollution by about one-third in developing countries relative to trend levels. In addition, there would be substantial economic gains, averaging about 5 cents per kWh (see Figure 2), totaling around $125 billion per year (the current level of electricity production, which is 2500 TWh, times $0.05). The benefits would rise over time with demand growth, induced by the growth of per capita incomes. The additional effects of nonprice-induced gains in efficiency, such as those arising from energy-efficiency or demand management services, may conceivably push the "energy-efficiency frontier" out further, perhaps to the point where pollution could be abated by about 35–40% by a combination of price and institutional reforms.\(^7\)

Second, beyond a certain point, the cost curve rises rapidly---even huge tariffs, of the order of 40 or 50 cents per kWh, or 4 or 5 times the real costs of supplies, would not abate pollution by more than about 70%. The most cost-effective measure, once the "win-win" options of energy-efficiency are achieved, is investment in low-polluting technologies.

Third, developing-country demands for electricity are doubling on average every 7 to 10 years, owing to the growth of per capita incomes, populations, urbanization, and the substitution of commercial fuels for fuelwood. Without efficiency reforms, demands and emissions would be four times their present level by around 2010, but still more than twice their present level even if ambitious efficiency reforms were in place. Given the low levels of per capita kWh consumption in developing countries, demands will likely continue to grow well beyond this period. As noted earlier, energy-efficiency alone cannot be counted on to reduce pollution in developing countries, only its rate of growth; low-polluting technologies, in contrast, would permit significant increases in energy consumption in the long term while reducing pollution.

\(^7\)The relative contributions of price and nonprice measures to improvements in energy-efficiency are not known in developing countries. The survey by Nadel (43) of experience of US utilities suggests that efficiency improvement percentages of up to 5–10% of demand may be reduced by these nonprice interventions on the demand-side.
Fourth, so long as consumers are willing to pay for the (sometimes) higher costs of energy supplied by low-polluting technologies, there is therefore nothing wrong, from an environmental or an economic perspective, with high levels of energy production and consumption in the developing or in the industrialized countries—quite the opposite. Much public discussion of environmental issues explicitly regards energy-efficiency and conservation as a desirable end in itself. But this is not a well-grounded objective, and if pushed too far would lead to policies as costly as they would be unnecessary. The examples of the expansion of energy noted above serve to indicate the historical dependence of economic growth and development on the efficient production and use of commercial energy, and the recent simulation studies of Blitzer, Eckaus, Lahiri, and Meeraus (44) on the economies of Egypt and India have shown that severe restrictions on the use of commercial energy would greatly diminish the economic prospects of developing countries. On the other hand, if energy-efficiency is pursued according to the principles of economic efficiency (the “win-win” region on the lower left of figures such as Figure 2), economic growth will be increased, not reduced. When such principles are combined with appropriate incentives for the use of low-polluting technologies, pollution will be much reduced also, not increased, as demand rises.

Parallel conclusions have been arrived at for vehicle fuels (4, chapter 6). The big “win-win” gains would come from congestion pricing, related urban planning measures to reduce traffic in towns, and a removal of deformities in energy taxation. But the main source of pollution abatement would stem from the technological developments noted.

LEAD-TIMES AND LAGS IN THE POLICY RESPONSE

In practice, the move to an energy-efficient scenario that incorporates low-polluting technologies is time-consuming. The pace of the response depends on several factors: (a) how rapidly the low-polluting technologies can be developed, tested, and incorporated in new investment; c.f. the analysis of Balzhiser & Yeager (45) on flue gas desulfurization in the United States, who commented that “only ... after a quarter-century of experience, have scrubbers approached an acceptable level of reliability”; (b) the lifetime of investments, since pollution and inefficiencies will still be associated with the inherited capital stock even if the new investments are low-polluting or energy-efficient; (c) whether retrofitting is practical and is being encouraged by policy (it is generally more expensive than incorporating improved technologies and practices in new investment); and (d) the strength of the incentives provided by the environmental policy itself. Hence the actual
transition to a low-polluting scenario is more likely to follow the sorts of patterns shown in Figure 3, which is based on some simulation studies of electricity generation in developing countries, undertaken for the World Bank's 1992 World Development Report (4, 46). The calculations relate to three regional and local pollutants—PM, SO$_2$, and NO$_x$—and use the coefficients shown in Table 3; similar studies for the abatement of CO$_2$ have been reported elsewhere (36).

The upper curve shows the growth of the main pollutants (SO$_2$, NO$_x$, and PM) from electricity generation when no environmental policies are in place; this is the "unchanged practices" scenario, in which pollution rises exponentially at around 6% per year with the growth of output. In the second scenario, policies to encourage the economically efficient use of energy are gradually phased in. The growth of demand for electricity is fully 2 percentage points lower, as is the growth of emissions. But it is the introduction of the low-polluting technologies that has the decisive effect on pollution abatement, as shown in the lower curves. The curves are distinctly bell-shaped, with pollution often getting worse before it gets better, on account of the growth of demand (even as energy-efficiency is improving) and the various lags noted above. The combination of energy-efficiency and low-polluting technologies, when pursued in a cost-effective way, is clearly powerful from both an economic and an environmental perspective.
PRICE AND NONPRICE INTERVENTIONS

This section revisits the ground rules for environmental policy-making in the energy sector, and is especially concerned with the electricity supply situation in developing countries. It first comments on the difficulties of implementing environmental policies in these regions, and then points to the over-riding importance of achieving a reasonable degree of economic efficiency in prices and in institutional arrangements if the policies are to succeed.

The Supply Side

When an environmental tax or regulation on a pollutant is introduced, its first effect is to bid up prices and reduce demand. But the effects on demand are quite small. For instance, the costs of regulations on the main local or regional pollutants from electricity production might aggregate to 1½ to 2 cents per kWh in cases where only high-sulfur coals are available, less if low-polluting fuels such as gas are economically available, or if advanced coal-combustion technologies are used. The effects on demand, however, would be relatively small. A 20% increase in prices would probably reduce long-term demand by 10% overall—a rather small effect for so large a price increase, and one that would soon be offset by the new demands arising from the growth of per capita incomes and populations in developing countries; in fact, it would generally amount to about a year's growth. A far more important effect would be the substitutions towards low-polluting technologies that the taxes or regulations would give rise to, sufficient to eliminate pollution in some instances and reduce it to very low levels in others (Table 3).

However, environmental policies are unlikely to succeed unless the institutional arrangements are in place, whether the regulatory or the tax approach to environmental policy is followed, or whether energy-efficient or low-polluting technologies are being introduced. Deficiencies in institutional arrangements as they relate to a utility's relationship with its government are particularly acute in (but of course not confined to) developing countries. The Onosode Commission's Report (47) on state-owned and operated industries in Nigeria commented that "he who pays the piper calls the tune" is as true of a government's relationship with state enterprises and utilities as it is in other affairs, and documented the extraordinary intensity and detail of government interventions in the policies, investment decisions, and the day-to-day administration of the state enterprises, including the electric utility. Nigeria is, alas, not an exception (2, 28). The upshot is that valuable managerial and staff resources are caught up with the problems of coping with government interventions and regulations rather
than with providing electricity and services to consumers; much equipment is consequently ill-maintained, capacity utilization is low, outages are frequent, and consumers in large numbers resort to installing their own diesel generators—all of which lower energy-efficiency and are exempted from environmental controls.\footnote{In 1983 in Nigeria, private autogeneration capacity amounted to a very large fraction of supply (48). A recent World Bank report found that private diesel autogeneration capacity in the country was 2200 MW; peak load on the grid was 2300 MW, and system capacity, much of it in disrepair, 6000 MW (49). See also Lee \& Anas (50).} Such situations impede good environmental policy-making as much as they do the efficient provision of electricity, and are the main reason why institutional reforms are now considered to be central to any policy initiative (28).

Institutional reforms are also required if good financial rates of return are to be achieved and if there is to be more recourse to private finance and investment. Although the opportunity costs of capital are much greater in developing countries than in industrialized countries, the average financial rates of return are appreciably lower, because of government controls on prices. Between 1979 and 1989, for instance, the average real financial returns on revalued net assets declined from 5.4\% to 2.8\% (Figure 4), or to roughly one-quarter of the opportunity cost of capital.

It is in this context—of poor regulation and low financial rates of return—that the potential for private power generation in developing countries will need to be assessed. Private (or independent) power generation emerged as a significant new source of generating capacity in the United States, following the 1978 Public Utilities Regulatory Act (PURPA). The experience is of much relevance to other countries from three perspectives: efficiency, finance, and the environment. Reviewing this experience, Hirst \& Goldman (51) report that since the mid-1980s, "thus far (in 27 states in the U.S.) capacity offered by private producers has often been 5–15 times greater than the utilities’ requirements ... Gas and coal-fired projects dominate, accounting for about 70\% of the winning projects, while various renewable resources provided about 20\% of the capacity of the projects selected by utilities."

If independent producers are to succeed, however, the prices charged by the public utilities need to reflect the level and structure of costs, according to time of day, season (where seasonal factors are important), and voltage level. Independent producers cannot be expected to compete "at cost" if the utilities are not expected to do so. This applies to not only the average level of tariffs, but also their structure. Supplying peak loads is significantly more costly than supplying off-peak loads; a tariff structure that makes the required distinction, raising prices at peak-load times, will (a) favor, say,
renewable energy that can compete at peak-load times, and (b) also favor the development and use of energy storage systems for renewables (fuel cells and thermal storage for solar schemes, for example) when the peak load is not coincident with their own peak supply times. One of the main consequences of introducing time-of-day tariffs in the United Kingdom in the 1960s and 1970s, for example (as part of the demand-side management policy of the electricity supply industry), was the widespread use by household consumers of heat-storage units; these improved economic efficiency by economizing on-peak capacity and using lower-cost, base-load energy, and also improved energy-efficiency because base-load energy was used for providing the energy stored.19

The Demand Side

In all energy markets, price and nonprice interventions ideally serve complementary functions. Economically efficient prices have a better effect, for example, if they are supplemented by planning policies and services that

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19 The development of peak-load pricing and related demand management services owes much to Turvey (52, 53). See also (54).
remove "barriers" to efficiency, such as those that may arise from high transaction costs in some markets. Conversely, nonprice measures to improve efficiency are more likely to succeed if good pricing policies are in place—indeed they are unlikely to succeed without them. Consider, for example, the interventions promoted in the United States for raising the efficiency with which electric power is used. They are often described under the headings of demand-side management (DSM) and integrated resource planning (IRP), are actively pursued by conservationists, and can be very complicated. Some proposals involve the utility or service company in paying consumers or some intermediary to install an energy-efficient (energy-conserving) device and recovering costs by charging consumers for electricity not consumed. Recent articles have shown that the approach can be reconciled in theory, if subsidies are avoided, with the goal of using resources efficiently; but it has not been without its difficulties or controversies (55, 56). To begin, it is difficult to measure reliably, audit, and arrange payments for the amount of energy saved. Not only is this quantity not directly measurable, allowances ought to be made, in principle, for the effects of lower prices on demand and innovation; while savings are sometimes made, energy use may at other times increase, not decrease. It is also a nontrivial problem in developing countries that consumers often do not pay for the electricity they actually consume, because of theft and bribery; the problem is to establish satisfactory metering and billing systems for the electricity they consume, let alone the electricity they do not consume. The approach has also involved subsidies and cross-subsidies. Hirst & Goldman (51) note that several states in the United States "adjust for DSM-induced revenue losses. These adjustments ensure that utilities collect from customers the net revenue that they would have gained had the DSM program not reduced electricity sales. A related option is to decouple utility profits from sales ... [hence in some cases] regulatory mechanisms guarantee that utility earnings are independent of the amount of sales ..." The idea "breaks the link between sales and profits, thus eliminating a major disincentive to utility DSM programs." In some schemes, customers not participating in the DSM programs face higher bills to support the energy-efficient investments of those who do, on which Joskow remarked (56, p.20): "While

10 Hirst & Goldman (51) give a good review of the various schemes in practice.
11 Interestingly, there is an historical precedent for this, provided by James Watt in the 1770s and 1780s, who apparently sought and obtained a royalty from the users of his steam engines equal to one-third of the savings in the cost of fuel, as compared with that of the "common engine." However, as a supplier of energy-efficient engines at the time, Watt did not rely on fuel companies to charge their consumers for fuels not consumed, and to split the benefits between themselves, Watt, and the consumers. He made careful tests of existing engines to determine the amount of fuel his engines saved, and collected the royalty himself (see Dickinson, 8).
conservationists and an increasing number of regulators seem to revel in their ability to exploit this taxation power, they have not yet heard the last (or even the first) word from the nonparticipating customers who will inevitably learn that they are being asked to pay for something that they are not receiving."

The efficient use of energy does not require subsidies or cross-subsidies. Since energy production and use are already heavily subsidized in many countries, the danger is that one subsidy will be "fighting" another, one encouraging electricity production and use, the other discouraging it. Such subsidies for the public utilities necessarily undermine the financial positions of the private or independent producers, on which much weight is now being placed by policy-makers to raise efficiency and reduce pollution, unless they too were to be supported by yet a third—and necessarily a large—subsidy. Some underwriting of the costs of R&D and of reducing "barriers to entry" may be justified in some cases, notably for new technologies; lines of credit (at cost) are another promotional device where users are still uncertain about the product. If, on the other hand, a utility itself is somehow barring consumers from using energy efficiently or the manufacturers who make energy-efficient appliances from entering the market (though there is no reported case of this), then this is surely a question for law and antitrust rather than for creating a policy, unique in the industrial history of open societies, and of questionable economic validity, of using regulatory mechanisms to "guarantee that utility earnings are independent of the amount of sales achieved" (19).

Alternatively, if the thought is that profits can only be made out of "pollution," but not out of its abatement, then the better alternative, where pollution needs to be reduced, is to tax or regulate pollution appropriately so as to make the low-polluting options profitable and the polluting ones unprofitable, and thus bring about a convergence of social and private interests in the policy, rather than to redefine commercial objectives so radically. This in turn would help to make demand management services financially self-sufficient, and less dependent on manipulations of prices and regulations pertaining to the provision of electricity services.

In sum, efficiency gains and environmental improvements arising from demand management could be achieved more directly through more familiar and transparent policies—cost-reflecting tariffs, open institutional arrangements, public accountability, taxing or regulating pollution, permitting the entry of private producers, and the provision of customer services, on a commercial basis, in energy-efficiency as in other areas.

Ground Rules

It may be worth restating therefore some ground rules for the policies required to achieve a cost-effective response to environmental problems.
The following are confined to electricity production and consumption; similar ground rules can be stated for other energy sectors, bearing in mind obvious differences in the nature of the markets and institutional arrangements:

1. Prices reflect the level and structure of the marginal costs of supply, differentiated as necessary by time-of-day, season, and voltage level.
2. Marginal costs include the costs of compliance with environmental policy—i.e. they include environmental taxes if taxes are used and the costs of meeting environmental laws and regulations if laws and regulations are used.
3. Environmental standards are set, as far as practicable, through analysis of the costs and benefits of achieving different standards. They are also phased-in with proper regard to the benefits, costs, and difficulties of achieving given standards by given dates.
4. Institutional arrangements encourage the entrance of private (non-utility) producers, who are also required to comply with environmental policy.
5. The development and use of new and commercially promising technologies and practices for improving efficiency, and for reducing pollution, are supported by research, development, and demonstration programs. When transactions costs are high, they are also supported by such devices as lines of credit at cost and, where merited, by open and explicit tax incentives. R&D portfolios are also diverse, and do not focus on one or two options at the expense of others.

All five conditions are interdependent. The more prices reflect costs (including external costs), the more private producers are able to compete, the better are the returns to energy-efficient devices, and the more diversified and innovative are R&D portfolios likely to become. In turn, the achievement of efficiency in prices and in energy production and use depends on institutional arrangements. When "arm's-length" regulation is in place, cost-reflecting prices become necessary for the running of utilities because the subventions associated with day-to-day interventions and control are reduced; equally important, the managerial resources of the enterprises can be used for improving the efficiency and quality of services, instead of being consumed in coping with the huge administrative overburden that intervention, at its worst, gives rise to.

CONCLUSION: THE CASE FOR ECONOMIC EFFICIENCY

The theme of this paper has been to emphasize economic efficiency rather than energy-efficiency for policy-making in the field of energy and the environment. Although the argument may seem self-evident to many, it has
undoubtedly been lost sight of in much of the public policy arena in recent years. Not only the developing countries, but the industrialized countries too, have much to gain, both economically and environmentally, from following economic principles more closely. Economic efficiency requires investments to be chosen on the basis of their rates of return and prices to reflect costs, including the costs of addressing environmental concerns. The application of the criterion for economic efficiency to energy and environmental policies has several advantages. 1. By recognizing the social and economic costs of environmental damage, it gives proper weight to the importance of environmental policies. 2. By requiring the costs of compliance with environmental policies to be reflected in supply costs, it provides a commercial incentive for the development and use of low-polluting technologies. 3. In both industrialized and developing countries today, its application to pricing, tax, and investment policies would improve energy-efficiency. 4. It leads to a cost-effective mix of energy-efficient and low-polluting technologies in addressing pollution problems and supports innovations in both. 5. It is fully consistent with the various institutional reforms discussed above—in particular, the emergence of private (non-utility) generation in electric power—since these developments too have emerged out of public demand for greater economic efficiency in the sectors. Not least, 6. It favors the continued growth of the energy sector so long as (a) there is a willingness-to-pay for its products, and (b) the demands are met in environmentally satisfactory ways.

The criterion also leads to a consistency of policies—and a better allocation of resources—across sectors, such as water supply and sanitation, education, agriculture and forestry, industry, and infrastructure services. Achieving efficiency in each of these sectors is as important for economic growth as is efficiency in energy production and use, and is especially relevant for developing countries where economic waste is even less affordable than it is in the industrialized countries. The 1992 World Development Report (4) noted that 2 billion people are without access to sanitation facilities, 1 billion without access to safe water (57), half the adult populations are illiterate and innumerate, and the large majority are without access to health and family planning services, and outlined the immense problems of doubling world agricultural production in the next three to four decades to meet the food demands of 4 billion more people. The claims on financial and human resources in all these areas are immense, and, in each case, investments are (a) capable of earning good economic rates of return and (b) being improved through economic efficiency.

Indeed, raising economic efficiency in energy production and use, in the circumstances of developing countries, would liberate considerable public and private resources that could then be allocated to these sectors. The
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approximately $125 billion per year of cost-savings estimated above for electricity production in developing countries, for instance, amounts to several times the financial requirements of accelerated programs in each of several other sectors such as education, water and sanitation, health, soil erosion control, agricultural research and extension, and family planning (4, chapter 9). Price and institutional inefficiencies in energy supply are not only damaging to the (environmentally responsible) growth of the energy industry itself in developing countries, but are a huge burden on the rest of the economy. It is for these reasons that recent reports have placed the highest priority on institutional reforms and the achievement of price efficiency in energy supply—i.e. of prices that would reflect costs, including external costs (54). Economic efficiency in the energy sector thus not only would help the development of the sector itself in developing countries, but is crucial for the development of other sectors. However important the achievement of energy-efficiency may be, therefore, it is the achievement of economic efficiency that should be the main priority.

ACKNOWLEDGMENTS

I would like to thank Joel Darmstadter, David Pearce, and one other reviewer (anonymous) for most helpful comments.

APPENDIX

Table 4 Pollution abatement through price efficiency reforms in electricity demand and supply, with special reference to developing countries

<table>
<thead>
<tr>
<th>Abatement, A%</th>
<th>Price required, $P_0 = P_0 (1-A)^{-1/e}$ (US cents/kWh)</th>
<th>Marginal cost, $P_t - P_0$ (US cents/kWh)</th>
<th>Marginal cost including gains managerial efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.0</td>
<td>-6.0</td>
<td>-11.4</td>
</tr>
<tr>
<td>10</td>
<td>4.9</td>
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<tr>
<td>20</td>
<td>6.3</td>
<td>-3.7</td>
<td>-6.4</td>
</tr>
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<td>30</td>
<td>8.2</td>
<td>-1.8</td>
<td>-3.0</td>
</tr>
<tr>
<td>40</td>
<td>11.1</td>
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<td>16.0</td>
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</tr>
<tr>
<td>70</td>
<td>44.4</td>
<td>34.4</td>
<td>34.4</td>
</tr>
</tbody>
</table>

*Basis: When prices are increased by a certain amount, the decrease in demand can be estimated from the standard price elasticity formula. With unchanged technologies, the decrease in pollution is proportional to the decrease in demand. Alternatively, we can postulate a percentage level of abatement, relative to the case of unchanged prices, and estimate the price that would be needed to achieve it. This is the approach followed here, the results being shown in the first two columns. The demand function assumed is $(Q_t/Q_0) = (P_t/P_0)^{-e}$, where $Q_t$ is the demand at price $P_t$, $Q_0$ is the initial demand at prevailing prices, $P_0$, and $e$ is the (numerical value of the) price elasticity, which we take to be 0.5, based on the survey by Bates & Moore (26). Per unit abatement, $A$, is by definition $(1 - Q_t/Q_0)$, so $A = 1 - (P_t/P_0)^{-e}$, from which we get the price required to achieve $A$, shown in the second column.
Table 4 Continued

The benefits from reforming prices are calculated in two steps. The first, shown in the third column, corresponds to what are called the price efficiency benefits. The actual price consumers pay, $P_r$, is the marginal benefit to them of an extra kwh of consumption; if $P_1$ represents the actual (unsubsidized) marginal cost (MC) of supply (sometimes called the efficiency price since $P_1 = MC$ for efficiency), then the cost of reducing demand by one kwh is simply $P_r - P_1$, and this is negative when, as occurs in the above case, $P_r < P_1$. (This calculation neglects the external benefits of reducing pollution, since we are comparing the cost-effectiveness of pollution abatement via energy-efficiency vs using low-polluting technologies.) $P_0$ is taken to be 4 cents/kwh (slightly below the present average in developing countries), and $P_1$ 10 cents/kwh.

The second step is to allow for what are sometimes called "X" or "managerial inefficients," after Liebenstein (1966). These tend to be correlated with shortages of finance, and can add 50% or more to costs. For $P_r < P_1$, we have assumed they are proportional to the per unit distortion in prices, or $(P_1 - P_r)/(P_r - P_0)$, such that the closer $P_r$ is to $P_1$, the lower the level of managerial inefficiency losses induced by price inefficiencies. Based on the evidence discussed earlier in the chapter, we have used a managerial of inefficiency factor of $M_r = 1 - M_0(P_1 - P_r)/(P_r - P_0)$, where $M_0 = 0.35$, i.e. when $P_r = P_0$, managerial efficiency is only 65% of that when $P_r = P_1$. Managerial inefficiency losses relative to best practice cases are assumed to be zero for $P_r = P_1$. For other cases they equal $P_0/M_r - P_1$. [See Anderson & Cavendish (46) for a further discussion.]

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