AIR POLLUTION CONTROL

Electricity generation contributes significantly to the supply of energy and therefore plays a major role in the production and control of emissions. About two-thirds of the world's electricity is obtained by fossil fuel combustion, emissions from which can produce urban ozone, bring about acid rain, and contribute to global climate change.

Urban ozone has been linked to respiratory problems and eye irritation and is known to be harmful to many types of trees and crops. Acid rain raises the acidity of streams and lakes, causing harm to fish and invertebrates, and has been blamed for damage to forests and structures. Elevated levels of sulfates and nitrogen oxides in the atmosphere have been linked to respiratory ailments and increased mortality rates in humans. The possibility of global warming from so-called greenhouse gases (GHG) could cause changes in crop productivity, migration of forest ecosystems, rising sea levels, and the extinction of some endangered species.

The continued growth in the demand for electricity raises some challenges to the electric utility industry to develop technologies for efficient and environmentally benign electricity generation and emission reduction. Currently available capacity options are renewable resources and demand-side management. Fuel switching and scrubber technologies are being used to reduce the emission of acid rain precursors. More efficient coal-generation technologies are being developed and are expecting commercialization in the next two decades. At the system level, operations planning and generation planning activities include emission reduction among their objectives.

This article covers the role of electricity generation in the production and prevention of emissions. It discusses some of the mechanisms by which major pollutants from electricity generation are produced and gives a summary of the effects of these pollutants. The article also gives a description of technologies that are available and are being developed for more efficient generation and for emission reduction.

Toward the end, the article also provides an overview of current international activity addressing environmental issues. It gives a summary of regulatory approaches and a background on the economic implications of environmental damage.

GLOBAL ELECTRICITY GENERATION AND THE ENVIRONMENT

The Role of Electricity in Supplying Clean Energy

Electricity has a large share in the energy system. It consumes a greater amount of primary fuels than any other single industry. Because of this, implementing emission control measures in this industry will result in considerable reductions in overall emissions. It is also worth noting that although there are generation losses, electrification, particularly in industrial processes, usually contributes to overall efficiency improvements. Electricity likewise allows the economical use of nonfossil energy sources. Many nonconventional sources of energy, such as hydro, geothermal, wind power, tidal power, wave power, and ocean thermal energy conversion, are site-specific and need the electrical transmission system to make them available to consumers. Even nuclear and solar power, due to safety and space considerations, respectively, are subject to site constraints.

In terms of supply, conventional thermal efficiencies have stabilized at around 35% to 40%. However, electricity permits the use of larger, more efficient plants due to economies of scale. Also, new technologies are coming with higher efficiencies. Combined-cycle plants generate electricity with more than 40% efficiency. Ceramic-blade gas turbines can deliver power at 50% efficiency. Molten carbonate and solid oxide fuel cells (MCFCs and SOFCs) have close to 60% conversion efficiency.

Electricity storage systems allow the efficient operation of base load plants. They permit the operation of thermal plants near rated capacity by acting as a load in the system when the demand is low and generating during the peak periods. Cogeneration systems also allow for higher conversion efficiencies by producing both heat and power at the same time. The existence of a strong electrical network ensures the optimum use of this capacity.

Electricity Projections

At the beginning of the 1990s, the world's electricity generation was a little more than 12 billion megawatt-hours ($MW \cdot h$). During the past decade, the world's electricity generation grew by an average of 3.6% per year. While the growth in electrical demand in the industrialized countries was in the neighborhood of 3% per year, the electricity requirements of developing countries increased by 7% annually, on average. Developing countries will require around 1,300,000 megawatts (MW) of new generating capacity in the next 15 years to serve their growing economies and populations. The world currently spends around $100 billion per year on new generation capacity (1), with the developing countries accounting for some $50 to $60 billion. To meet the growing demand, developing countries will have to raise this figure to $125 billion per year. The investments required for the developed world are also substantial. If current trends continue, the countries of the Organization for Economic Cooperation and Development (OECD) will need to add about 400,000 to 500,000 MW of new generating capacity in the next 15 years.

Fuel Use for Electricity Generation

The estimates in Table 1 show a projected increase in the global electricity production from 12393 billion kilowatt-hours

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Table 1. World Electric Energy Projections

Region/Country	1993 Generation TW·h	1985–1993 Growth (%)	1995 Estimate[a] TW·h	2000 Projection TW·h	2005 Projection TW·h
OECD countries[b]	7,483	3.1	7,967	8,475	9,382
North America	3,920	3.5	4,215	4,278	4,684
Europe	2,470	2.2	2,562	2,915	3,246
Pacific[c]	1,093	4.3	1,190	1,277	1,438
Non-OECD countries	4,910	3.9	5,847	7,545	9,752
Africa	343	3.8	396	497	624
Latin America	565	5.3	779	1,011	1,312
Asia[d]	635	9	762	1,116	1,784
China	839	9.3	870	1,200	1,510
India	356	8.7	436	670	1,030
Europe	423	0.4	447	471	496
Former USSR	1,460	0.7	1,849	2,083	2,347
Middle East	288	8	308	447	649
World	12,393	3.5	13,814	16,020	19,134

[a] Figures for OECD countries are estimates. Figures for non-OECD countries are projections.
[b] Hungary and the Czech Republic are not included with OECD countries.
[c] Australia, Japan, and New Zealand.
[d] Asia does not include China and India.

(kW·h) in 1993 to 19,134 billion kW·h in 2005. Table 2 indicates that more than 60% of the world's electricity is generated by burning fossil fuels (see Refs. 2–6). These combustion processes produce carbon dioxide (CO_2) and are major contributors to global warming. Coal combustion, which accounts for 60% of total fossil generation, also emits sulfur dioxide (SO_2) and oxides of nitrogen (NO_x), which produce acid rain and, in the case of NO_x, are also possibly involved in the depletion of the ozone layer. These will be discussed in more detail later. The considerable amount of fossil fuel used in electricity generation, the tremendous potential for efficiency improvement, and the possibility of substitution with environmentally benign technologies makes electricity an important factor in the supply of clean energy.

Table 2. Percentages of Electricity Generation by Fuel Type for Selected Countries (1993)

Country/Region	Energy (TW·h)	Fraction (%) Coal	Oil	Gas	Nuclear	Hydro/ Others
World	12,393	38.2	9.8	14.8	17.5	19.6
OECD	7,483	40.1	7.6	11.5	23.8	16.9
Australia	163	78.7	2.2	9.1	0.0	10.2
Canada	528	14.9	2.1	2.9	18.0	62.1
France	468	5.1	1.2	0.8	78.7	14.1
Germany	522	57.5	1.9	6.6	29.4	4.5
Italy	220	9.1	51.8	18.0	0.0	21.0
Japan	897	16.7	23.7	19.5	27.8	12.3
Norway	120	0.2	0.0	0.01	0.0	99.6
Spain	155	40.9	6.1	0.8	36.1	16.2
Sweden	145	2.1	2.1	0.6	42.3	53.0
UK	322	52.2	7.1	11.1	27.8	1.8
US	3,392	53.4	3.7	13.0	19.1	10.8
Non-OECD	4,910	35.3	13.3	20.0	7.7	23.8
Bangladesh	9	0.0	11.8	79.6	0.0	8.6
China	839	72.8	8.7	0.3	0.2	18.1
India	356	70.3	3.5	4.9	1.5	19.8
Indonesia	50	23.4	47.4	13.6	0.0	15.8
Nepal	1	0.0	6.5	0.0	0.0	93.5
Philippines	27	7.8	53.6	0.0	0.0	38.5
Poland	134	94.5	2.7	0.1	0.0	2.7
Saudi Arabia	82	0.0	60.7	39.4	0.0	0.0
Singapore	19	0.0	100.0	0.0	0.0	0.0
South Africa	175	95.0	0.0	0.0	4.2	0.9
Former USSR	1,460	16.6	9.0	43.2	14.1	17.2

EMISSIONS FROM FOSSIL FUELS

Emissions from the Fossil Generation of Electricity

The exhaust stream consists mainly of gases derived from the major elements of the fossil fuel. These include water vapor (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), and some of the nitric oxide (NO). The remaining nitric oxide is produced by oxidation of nitrogen molecules in the air used in the burners and not from nitrogen in the fuel. The other exhaust gases include small quantities of hydrogen chloride (HCl), nitrogen dioxide (NO_2), nitrous oxide (N_2O), carbon monoxide (CO), and sulfur trioxide (SO_3). Carbon dioxide constitutes 12% of the flue gas. Sulfur dioxide concentrations are estimated at 1000 μL/L to 1700 μL/L and the nitrogen oxides at 400 μL/L to 600 μL/L (7). These three constitute the bulk of emissions from thermal generation, and we shall focus on these emissions and their impacts on the environment from here on.

Calculation of Emissions

Fuel Usage Calculations

Fuel Usage Calculation Based on Average Heat Rate. Calculation of emissions begins with the calculation of the amount of fuel used based on the amount of electricity generated. One method of calculation uses the average heat rate of the plant, electricity generation in gigawatt-hours (GW · h), and the heat content of the fuel; thus,

$$\text{fuel usage (tons)} = \frac{\text{generation (GWh)} \times \text{heat rate (MBtu/GW·h)}}{\text{heat content of fuel (MBtu/ton)}} \quad (1)$$

Fuel Usage Calculation Based on Hourly Fuel Usage. Average heat rate calculations are used for estimating longer-term (say annual) fuel consumption. Hourly operations use input–output and incremental heat rate representations for more accurate calculations of fuel consumption. The input–output curve is usually a quadratic function, relating heat input to power output. Hourly fuel usage can then be calculated from the power output P, where P is in terms of MW:

$$\text{hourly fuel usage (tons)} = \frac{AP^2 + BP + C \text{ (MBtu)}}{\text{heat content of fuel (MBtu/ton)}} \quad (2)$$

Calculation of Emissions. The amount of emissions can be calculated as the product of the fuel usage, the emissions content of the fuel and the emissions production rate:

$$\text{emissions (tons)} = \text{FU} \times \text{EC} \times \text{PR} \quad (3)$$

where FU = fuel usage (tons), EC = emissions content of fuel (tons emissions/tons fuel), and PR = emissions production rate (fraction released)

CO_2 and SO_2 Emissions. Practically all of the carbon and sulfur emissions are in the form of CO_2 and SO_2. Carbon monoxide emissions are very small and come only as a result of slight inefficiencies in the combustion process. Sulfur trioxide (SO_3) emissions are much less than sulfur dioxide emissions.

Carbon dioxide and sulfur dioxide are derived from the elements present in the fossil fuel. The amount of CO_2 and SO_2 emissions can therefore be calculated directly from the fuel's carbon and sulfur contents.

The following example illustrates the calculation for carbon dioxide emissions:

$$\text{atomic weight of carbon} = 12$$
$$\text{atomic weight of oxygen} = 16$$
$$C + O_2 \rightarrow CO_2$$

The molecular weight of CO_2 is 12 + 2 × 16 = 44. Thus, complete combustion of one ton of carbon produces 44/12 = $3\frac{2}{3}$ tons of CO_2. For one ton of coal having 70% carbon content, the amount of CO_2 emissions would be 0.7 × 3.67 = 2.57 tons. A typical 400 MW coal plant uses more than 800,000 tons of coal per year. Applying this to Eq. (3) yields

$$\text{tons } CO_2 \text{ emissions} = 800,000 \times 2.57 = 2{,}056{,}000$$

The calculation for annual SO_2 emissions would be as follows:

$$\text{atomic weight of sulfur} = 32$$
$$S + O_2 \rightarrow SO_2$$

The molecular weight of SO_2 is 32 + 2 × 16 = 64. Thus, complete combustion of one ton of sulfur produces 64/32 = 2 tons of SO_2. For one ton of coal having 3% sulfur content, the amount of SO_2 emissions would be 0.03 × 2 = 0.06 tons.

If the same plant as above has a 90%-efficient sulfur scrubber, the fraction of SO_2 released would be 0.10. Using Eq. (3),

$$\text{tons } SO_2 \text{ emissions} = 800{,}000 \times 0.06 \times 0.1 = 4800$$

Nitrogen Oxide Emissions. Nitrogen oxide emissions come from two sources: (1) nitrogen found in the coal molecule (fuel-bound NO_x) and (2) nitrogen in the air (N_2) oxidized during the combustion process (thermal NO_x). NO_x is a collective term for nitric oxide (NO) and nitrogen dioxide (NO_2). Although NO emissions are usually one order of magnitude more than those of NO_2, these are usually oxidized also to NO_2.

The amount of fuel-bound N_2 converted to NO_x during combustion varies between 15% and 20% of the nitrogen in the coal. It depends on the characteristics of the coal, the firing systems, furnace conditions, flame patterns and temperatures, burning time, and furnace reducing or oxidizing conditions. The fuel-bound component of NO_x emissions can be calculated using a similar method to that for SO_2, this time using the atomic weight of 14 for nitrogen:

$$N_2 + 2O_2 \rightarrow 2NO_2$$

The molecular weight of NO_2 is 14 + 2 × 16 = 46. Thus, complete combustion of one ton of nitrogen produces 46/14 = 3.29 tons of NO_2. For one ton of coal having 1% nitrogen content, the amount of fuel-bound NO_2 emissions would be 0.01 × 3.29 = 0.0329 tons.

For a plant with no nitrogen removal, the amount of fuel-bound NO_2 emissions can be calculated using Eq. (3):

$$\text{tons } NO_2 \text{ emissions} = 800{,}000 \times 0.0329 = 26{,}320$$

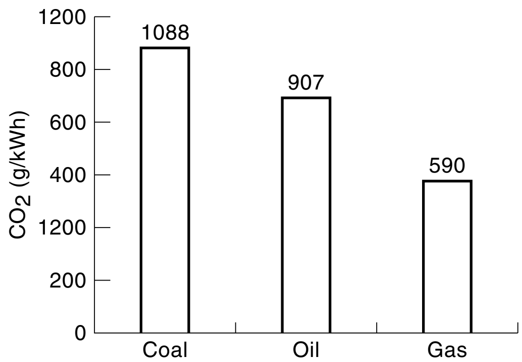

Figure 1. Average CO_2 emissions in the US in 1990 from fossil-fired power plants (8).

The amount of thermal NO_x is dependent on combustion-time–temperature factors, furnace combustion conditions (reducing or oxidizing conditions), and the type of burner and combustion air distribution.

Figures 1 and 2 show average CO_2, SO_2, and NO_x emissions from fossil-fired power plants in the US for each kWh of electricity output (8).

EFFECTS OF EMISSIONS

Table 3 gives estimated emissions for 1995 due to electricity generation in selected countries, as well as those projected for 2000. The following sections show why there is much concern about the amount of these pollutants that are produced from electricity generation.

Carbon Dioxide

It is estimated that the earth would have a temperature of −18°C were it not for what are known as the greenhouse gases (9). Carbon dioxide, water vapor, and ozone allow higher-frequency solar radiation to pass to the earth but absorb the terrestrial infrared radiation. The mechanism is different in a greenhouse, where heat is retained by preventing convective flows out of the structure; but the similarity of the effect has resulted in the use of the term "greenhouse" for the atmospheric phenomenon as well. The terrestrial biosphere and the oceans serve as sinks and sources for carbon dioxide, each exchanging with the atmosphere some 100 gigatons of carbon (GtC) per year.

The OECD estimated anthropogenic CO_2 emissions from energy use in 1988 at 6.3 GtC per year, growing at the rate of 2.5% per year (6). About 1.7 GtC was contributed by power generation (10). Half of the CO_2 emitted appears to remain in the atmosphere and causes the rising trend in air concentrations of the gas.

Carbon dioxide is only one of several greenhouse gases produced by human activity (anthropogenic emissions). Also included in this category are methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and the chlorofluorocarbons (CFCs). All of these have a greater warming effect than CO_2 on a molecule-for-molecule basis. Calculations based on concentration, radiative effectiveness, and lifetime, however, show that CO_2 accounted for 66% of greenhouse gas contributions to global warming between 1880 and 1980 (11), and 55% between 1980 and 1990 (9).

While models predict that the increase in greenhouse gas concentrations should already have caused global warming, there is some doubt as to whether the experienced trend of slightly less than half a degree Celsius (°C) [one degree Fahrenheit (°F)] can be attributed to them. The models differ in representation, particularly in the effects on cloud cover and the ocean surface, as well as in the assumptions and measurement methods used. As a result, there is much variation in the estimates of predicted temperature changes resulting from the expected doubling of CO_2 concentrations in the next century from as low as 0.2°C (0.4°F) to as high as 9.4°C (16.9°F). A commonly accepted figure is 1.5 to 4.5°C (12).

Assuming that the expected increase in CO_2 concentrations will result in global warming, the next question is what effects global warming will have. Among the possibilities are worldwide changes in crop productivity, forest ecosystem migration, a rise in the sea level, and the extinction of some endangered species.

A direct effect of global warming on the utility industry is the change in the demand for electricity. Once the uncertainties of temperature changes are resolved, however, these would be much easier to quantify. A more difficult problem is the assessment of the effects of emission control laws on the cost of operating electric utilities.

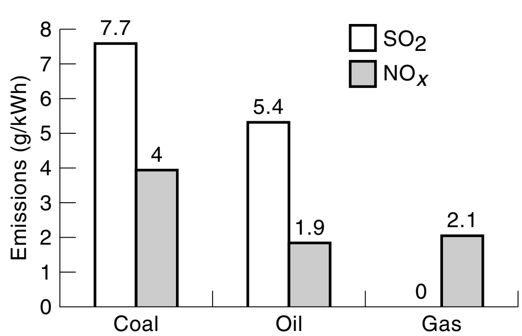

Figure 2. Average SO_2 and NO_x emissions in the US in 1990 from fossil-fired power plants. Note: SO_2 emissions from gas-fired plants are negligible (8).

Sulfur Dioxide

Sulfur dioxide is a colorless gas produced mainly from the combustion of fossil fuels. It can react catalytically with such oxidants as ozone, hydrogen peroxide, and organic free radicals to produce sulfur trioxide (which hydrates quickly to sulfuric acid), sulfuric acid, and sulfates:

$$OH + SO_2 \rightarrow HSO_3$$
$$HSO_3 + O_2 \rightarrow HO_2 + SO_3$$
$$SO_3 + H_2O \rightarrow H_2SO_4$$

Fog, suspended particulate matter, and sulfur dioxide form smog, which is known to have health effects particularly on

Table 3. Carbon Dioxide, Sulfur Dioxide, and Oxides of Nitrogen Emissions from Fossil Fuel Generation of Electricity (Estimates for 1995 and Projections for 2000)

	Emissions					
	1995			2000		
Country/Region	Carbon (10^6 metric tons)	SO_2 (10^3 metric tons)	NO_x (10^3 metric tons)	Carbon (10^6 metric tons)	SO_2 (10^3 metric tons)	NO_x (10^3 metric tons)
World	2,041	48,742	24,368	2,420	52,804	27,472
OECD	1,084	24,357	12,724	1,200	21,248	12,696
Australia	47	1,378	564	52	1,542	632
Canada	32	902	391	37	1,067	454
France	13	388	156	20	528	242
Germany	97	2,749	1,198	104	2,886	1,292
Italy	48	1,088	571	57	1,294	695
Japan	117	226	271	124	235	282
Norway	0	2	1	0	2	1
Spain	25	724	301	30	769	376
Sweden	2	36	19	3	52	30
UK	62	1,687	740	63	1,597	782
US	566	13,250	7,580	620	8,950	6,750
Non-OECD	957	24,385	11,643	1,220	31,555	14,776
Africa	85	2,474	1,018	107	3,106	1,278
Latin America	46	900	537	60	1,169	698
Asia	111	2,775	1,278	170	4,247	1,956
China	205	6,269	2,410	283	8,646	3,324
India	97	2,965	1,148	149	4,555	1,763
Europe	89	2,593	1,083	94	2,733	1,142
Former USSR	271	5,463	3,540	305	6,153	3,987

the elderly, the young, and those with respiratory ailments. There are also effects on the vegetation, on structural materials, and on the atmosphere. These effects are described in the following paragraphs. The reader can refer to Elsom (13) for a more thorough discussion of the effects of SO_2 and NO_x emissions.

The best known example of the health effects of SO_2 happened in London in 1952, when 4700 deaths occurred above the expected number on account of respiratory failure. The largest single contributor was bronchitis, although death from diseases involving the impairment of respiratory functions also rose. The number of deaths due to heart disease increased, possibly due to the strain on the heart caused by those respiratory problems. Sulfates suspended in the emissions are suspect for increased asthma attacks, aggravation of heart and lung disease, and a lowering of resistance to respiratory diseases.

Low added levels of SO_2, have been seen to enhance plant growth by the addition of soil nutrients. At higher levels, however, SO_2 causes bleaching of plant chlorophyll and lowers soil pH values, resulting in reduced growth and yield. Effects are more pronounced on plants such as lichen that contain relatively little chlorophyll. Such information has been used to map sulfur dioxide levels by experimental transplantation of lichens and observing their fate.

Sulfur dioxide also leads to corrosion of building stone. It converts the calcium carbonate in limestone, sandstone, roofing slate, and mortar into soluble calcium sulfate (gypsum). The material increases in volume, resulting in scaling, blistering, and disintegration. The loose material is then washed away by rain. Sulfur dioxide also affects fabrics (especially such textiles as nylon), leather, paper, electrical contacts, paints, and medieval stained glass. It accelerates the corrosion rates of metals such as iron, steel, zinc, copper, and nickel.

Another effect of SO_2 emissions is the reduction in visibility due to light absorption and scattering by sulfates. This suspended particulate matter also enhances condensation and freezing, leading to the formation of cloud and fog, increased precipitation, and reduced sunshine levels.

Nitrogen Oxides

Oxides of nitrogen account for 30% of acid rain precipitation in the US (next to sulfur compounds, which account for 65%). *Acid rain* (precipitation having a pH lower than 5.6) is known to result in the depletion of fish stocks, a reduction in forest productivity, human health problems, increased material corrosion and erosion, and reduced visibility.

The most important oxides of nitrogen are nitric oxide and nitrogen dioxide; the other oxides are not known to be biologically significant. Anthropogenic nitrogen oxides are produced during combustion when the temperature is higher than about 1000°C. Its principal sources are the combustion of fossil fuels in stationary sources and in motor vehicles. Like sulfur dioxide, nitrogen oxide emissions have effects on health, on vegetation, and on the atmosphere. In addition, they are believed to act as catalysts in the depletion of the ozone layer.

Aside from promoting photochemical pollution, nitrogen oxides have health effects of their own. High concentrations of NO_x (600 $\mu g/m^3$) to 900 $\mu g/m^3$) have been found to result in increased susceptibility to respiratory infections, increased airway resistance, and decreased sensitivity to bronchoconstrictors.

POLLUTION CONTROL TECHNOLOGIES

Technologies for pollution control in the utility industry are available at different stages of electricity production and consumption. On the supply side, technologies for efficient combustion are being developed, and techniques are available for capturing pollutants before, during, and after combustion. Indirectly, demand-side processes reduce emissions by lowering generation requirements. System level planning and scheduling activities determine the most effective use of these technologies for overall economic operations in the context of regulation and policy signals from the government.

Supply-Side Technologies

Efficient Coal Combustion Technologies. The efficiencies of traditional coal combustion technologies average around 33%. With advanced coal-fired power systems, average efficiencies are expected to increase to 50% and in specific technologies can approach 85%. These technologies have the potential to reduce carbon dioxide emissions by more than 40% and sulfur dioxide emissions to a fraction of the levels allowed by federal air standards. Among these are integrated (coal) gasification combined cycle (IGCC) technology, pressurized fluidized bed combustion (PFBC), and the steam-injected gas turbine (14,15).

Integrated Gasification Combined Cycle. In the IGCC, coal is transformed into synthesis gas composed mostly of hydrogen (H_2) and CO, as well as methane, CO_2, and H_2S. The coal gasifier partially combusts coal and limestone in an oxygen-rich environment to produce a coal-gas fuel of low or medium Btu content. Sulfur and particulates are removed from the gas before its complete combustion in a gas turbine. A coal gasifier retrofit to a combined-cycle unit typically reduces the megawatt output by 5% and increases the heat rate by 1500 Btu/kW · h.

Pressurized Fluidized Bed Combustion. Fluidized bed combustors burn coal with limestone or dolomite while the mixture is suspended in jets of air. This allows the limestone to take up about 90% of the sulfur that would otherwise be emitted as SO_2. Since the constant churning facilitates the transfer of heat to the tubes, the temperature of combustion can be lower than in a conventional boiler. This reduces the formation of NO_x.

In the PFBC, the pressure is 6 to 16 times higher than in the atmospheric fluidized bed combustor (AFBC). The pressurized hot gases in the combustion chamber of the steam boiler can then be used in a combined cycle to run a gas turbine.

Steam-Injected Gas Turbine. In the steam-injected gas turbine, natural or synthesis (coal) gas is used to produce electricity. The exhaust gases from the turbine are then used to produce steam. Injection of this steam to the combustion chamber increases the energy output and efficiency and reduces NO_x emissions.

A variation called an intercooled steam-injected gas turbine system attains higher efficiencies by cooling the combustion air between compression stages and diverting some of it to the turbine blades. Cool air requires less power for compression, and lower blade temperatures enable the blades to withstand higher gas temperatures. In addition, precombustion catalytic reaction of natural gas with steam produces H_2 and CO, and results in chemical energy greater than that of the natural gas itself. This can result in efficiencies greater than 52%.

Integrated gasification combined cycle turbines, pressurized fluidized bed combustion turbines, and steam-injected gas turbines are expected to play major roles in future power systems in view of their greatly reduced SO_2 emissions and their higher efficiencies, which essentially reduce CO_2 emissions per kilowatt-hour of electricity generated. However, these technologies still produce a considerable amount of carbon dioxide emission because of the very nature of fossil fuel combustion.

The other available supply-side options also encounter obstacles. The fusion reactor is still decades away from commercialization, and even the supposedly benign hydro is meeting considerable opposition from environmentalists. Solar and other renewable technologies hold considerable promise but are yet to take off with large-scale applications, primarily due to cost constraints.

Pre- and Postcombustion Control of Sulfur Dioxide Emissions. Compared with the above technologies for removing sulfur during combustion, those for sulfur removal before and after combustion are more mature. Some of these are described below. The interested reader may refer to Refs. 16–17 for more information.

Fuel Switching. One way of removing sulfur before combustion is by switching to low-sulfur fuels such as gas and low-sulfur coal. The sulfur content of coal can vary between 0.5% and 10% by weight, allowing the flexibility for immediate low-cost implementation without producing extra waste.

Coal Washing. This process involves the cleaning off of inorganic sulfur, resulting in a reduction of around 30% of the total sulfur content.

Wet Limestone System Process. In the wet limestone system, the limestone received goes through a pulverizing mill to get the required size consistency. The ground limestone is then combined with water. The resulting slurry is fed to the SO_2 scrubber–absorber vessel, where it is sprayed on the flue gas stream. This direct contact between the slurry and the SO_2-laden gas removes the SO_2 from the flue gas through the following chemical reaction:

$$CaCO_3 \cdot 2H_2O + SO_2 \rightarrow CaSO_3 \cdot 2H_2O + CO_2$$

A demister section in the scrubber vessel removes water entrained in the flue gas. A flue gas reheater then evaporates any remaining water and superheats the flue gas prior to stack inlet. This step minimizes corrosion of equipment and material downstream of the scrubber and provides plume buoyancy at the stack exit to ensure dispersion and mixing in the atmosphere.

The scrubbing liquid stream (limestone slurry) containing absorbed SO_2 goes to a reaction tank beneath the scrubber vessels. The reaction produces calcium salt ($CaSO_3$–$CaSO_4$) precipitates and sulfurous acid (H_2SO_3). The limestone slurry recycles, returning to the SO_2 scrubber vessel, while makeup slurry is fed to the reaction tank. The flue gas desulfurizer

(FGD) sludge goes to waste storage tanks for further processing or for subsequent disposal.

Wet Lime System Process. The wet lime system process uses lime (CaO) as reagent instead of limestone. Mixed with water, this produces calcium hydroxide [$Ca(OH)_2$] or slaked lime. The calcium hydroxide reacts with SO_2 in the scrubber, absorbing it from the flue gas with the following chemical reaction:

$$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O$$

The rest of the process is similar to that of the limestone system.

Dual Alkali FGD System. This system uses sodium hydroxide (NaOH) as the scrubber reagent. To provide this reagent, soda ash (Na_2CO_3) and lime (CaO) are fed to the system, providing the NaOH and calcium hydroxide [$Ca(OH)_2$] for absorbent regeneration, respectively. The chemical reaction in the scrubber follows:

$$2NaOH + SO_2 \rightarrow Na_2SO_3 + H_2O$$

The absorbent is regenerated with the following basic reaction:

$$Na_2SO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaSO_3$$

As in the wet limestone FGD process and for similar reasons, flue gas leaving the scrubber is reheated.

Wellman–Lord Process. This consists of two stages. The first stage consists of a wet absorption process wherein SO_2 from the flue gas reacts with sodium sulfite ($NaSO_3$) to form sodium bisulfite ($NaHSO_3$) and some sodium sulfate (Na_2SO_4). The primary absorber reactions are

$$Na_2SO_3 + H_2O + SO_2 \rightarrow 2NaHSO_3$$
$$Na_2SO_3 + \tfrac{1}{2}O_2 \rightarrow Na_2SO_4$$

The absorber effluent liquor then goes through a filter to remove solids and divides into two streams, one for regeneration and the other for purge treatment to reject the unreactive sodium sulfate. Double-effect evaporator–crystallizers convert the dissolved $NaHSO_3$ to crystalline Na_2SO_3 and liberated SO_2. The regenerated Na_2SO_3 crystals return to the absorbers after dissolution, while the regenerated SO_2 stream is converted to elemental sulfur by reduction with natural gas.

Magnesia Slurry Process. This wet scrubber process uses a magnesium sulfite slurry to absorb SO_2. This produces hydrate crystals of magnesium sulfite and sulfate precipitates, which are then centrifuged and dried. Calcination of these crystals with a small amount of coke under controlled conditions produce solid MgO and an offgas of 7% to 9% SO_2. The regenerated MgO goes back to the absorbent slurry preparation area, while the SO_2 is converted to sulfuric acid in a conventional contact acid plant.

The following chemical reactions occur in the magnesia slurry process:

Absorption:

$$MgO + SO_2 \rightarrow MgSO_3$$
$$MgSO_2 + H_2O + SO_2 \rightarrow Mg(HSO_3)_2$$
(primary absorption reaction)
$$MgSO_3 + \tfrac{1}{2}O_2 \rightarrow MgSO_4$$
$$MgSO_3 + 6H_2O \rightarrow MgSO_3 \cdot 6H_2O\ (s)$$
$$MgSO_4 + 7H_2O \rightarrow MgSO_4 \cdot 7H_2O\ (s)$$
$$Mg(HSO_3)_2 + M(OH)_2 + 4H_2O \rightarrow 2(MgSO_3 \cdot 3H_2O)\ (s)$$

MgO Regeneration:

$$MgSO_3 \rightarrow MgO + SO_2$$
$$MgSO_4 + \tfrac{1}{2}C \rightarrow MgO + SO_2 + \tfrac{1}{2}CO_2$$

Dry SO_2 Scrubber System. The dry SO_2 scrubber system uses an alkali reagent such as soda ash (Na_2CO_3) mixed with water. The alkali solution is pumped to the SO_2 absorber vessel, where spray atomizers mix fine droplets of the soda ash with the SO_2, forming sulfites and sulfates (Na_2SO_3 and Na_2SO_4). The thermal energy in the flue gas evaporates the water. This results in a dry powder mixture of sulfites and sulfates similar in size and characteristics to the fly ash in the flue gas. The fly ash, the dry powder mixture, and any unreacted soda ash are removed by the baghouse filter facility from the dry SO_2 scrubber system.

The reaction between the soda ash and the SO_2 is given by the following chemical balance equation:

$$Na_2CO_3 + 2H_2O + SO_2 \rightarrow Na_2SO_3 + CO_2 + 2H_2O$$

Although the technology is already available for reducing SO_2 emissions, it puts an additional financial burden on the utility and, ultimately, the electricity consumer. Scrubbers cost around $175 to $200 per kilowatt to install, and they penalize the plant efficiency. Lower-sulfur coals (those with less than 1% sulfur content) can be bought only at a premium. One electric utility estimated that its electricity prices would increase by about 5% on the average (and up to 20% for some customers) due to acid rain compliance. Low-NO_x burners likewise entail an additional cost.

Control of Nitrogen Oxide Emissions (17–19). Thermal NO_x is a major source of the total NO_x produced when low-NO_x fuels are burned. However, it forms only a small fraction when high-nitrogen fuels are used. Thermal NO_x is produced under conditions of high temperatures, low heat extraction rates, high excess air levels, and high volumetric heat release rates.

Fuel-bound NO_x is less dependent on temperature and is produced with fuel-rich mixtures in pyrolysis, a large evolution of volatile nitrogen species, and low heat extraction rates.

Control of the Combustion Process. Control of NO_x emissions takes advantage of the above characteristics of NO_x production. The popular technique is to design combustion chambers and burners for staged combustion—one under a fuel-rich mixture and the other under a fuel-lean mixture. The initial stage involves partially burning coal in reduced atmosphere, allowing it to retain part of the fuel-bound nitrogen in the residual unburned fuel. The burned fuel from the initial burning stage then undergoes combustion in the fuel-lean mixture using furnace secondary air supply. Of the 20% to 35% of fuel nitrogen retained in the char, only 20% is converted to NO_x, regardless of stoichiometry. This allows good char burnout under high-excess-air conditions without a significant increase in NO_x levels.

Two-stage combustion is achieved with tangentially fired furnaces, using corner firing and tilting burners with overfire air nozzles. This makes it possible to fire the initial fuel-rich mixture with reduced air flow. Reduced flame temperature and extended burning time control NO_x formation in the furnace. A two-stage burner proportions secondary combustion air between the fuel-rich mixture in the initial zone and the secondary combustion zone. This results in a reduction in the range of 40% in conversion of fuel-bound nitrogen to NO_x.

Fuel Reburning. Another method being studied uses *fuel reburning* for chemically reducing the NO formed in the combustion stage. It involves burning the fuel in the lower furnace under slightly air-rich conditions. Additional fuel is then added downstream of the first zone to reduce most of the NO generated in the first stage and convert it to N_2 under slightly substoichiometric conditions. Tertiary air is then added to the fuel-rich products to complete the combustion under slightly air-rich conditions.

Other Options. The following options for limiting NO_x emissions are also available:

1. Use additives such as controlled NH_3 injection in the presence of a catalyst in the flue gas. This converts NO_x compounds to elemental nitrogen and water vapor.
2. Inject water into the furnace to reduce the flame temperature and increase combustion time. This reduces NO_x formation.
3. Use additives such as copper oxide sorbent and catalysts for scrubbing the flue gas to remove NO_x.
4. Use a catalyst in a fuel denitrogenation process.

Control of Carbon Dioxide Emissions. Carbon dioxide comes from the oxidation of carbon in the fuel. Coal has the highest carbon content among the fuels and produces about 32% more CO_2 than oil and more than two times as much as gas per unit energy. As yet, there are no known methods of reducing carbon dioxide emissions that are economically feasible. Among the schemes for CO_2 control are afforestation, which is the planting of forests to absorb CO_2 from the atmosphere, and sequestering of the gas before it exits to the air and then piping it into the ocean or to such natural geologic formations as natural gas reservoirs.

The proposed methods for CO_2 gas recovery include the following:

1. Use a sorbent called selexol to recover CO_2 from the gasified coal in IGCC.
2. Use molecular sieves that are permeable to some gases but not to others.
3. Use a monoethanolamine [MEA, $HO(CH_2)_2NH_2$] scrubber to capture CO_2 from the flue gas.
4. Replace air with oxygen in the boiler to ease CO_2 recovery.
5. Use molecular sieves that are permeable to some gases but not to others.

There are also several ways of indirectly reducing CO_2 emissions from electricity generation. These include the reduction of demand for electricity, use of more nonfossil energy sources, switching to fossil fuels with a lower carbon content per unit of energy, and lowering the rate of emissions from fossil fuels through improvements in combustion efficiency and electricity transmission and distribution (20). The next section describes demand-side technologies that can help reduce coal burn for the same amount of energy service delivered.

Demand-Side Technologies

Improved generation efficiencies reduce emissions by reducing coal burn per unit of energy produced. In addition, the utility can avail itself of demand-side alternatives that delay the requirement for additional investments.

Three demand-side management (DSM) load profile objectives utilities may consider are peak clipping, valley filling, and load shifting (21). Peak clipping reduces peak demand without affecting off-peak demand. This strategy is effective in reducing operating costs and postponing the need for additional capacity. Valley filling increases off-peak demand, which improves the efficiency of utilizing existing generating capacity, thereby reducing costs of delivering power. Finally, as the name implies, load shifting moves energy consumption from on-peak to off-peak periods, resulting in the combined benefits of peak clipping and valley filling.

If DSM strategies designed to achieve the three objectives are applied successfully, theoretically the result will be a lower peak and a smoother load profile (a higher load factor, the ratio from off-peak to peak load). With a smoother load profile, utilities can operate their generating units more efficiently. Combined with peak reduction, this can allow power companies to postpone capacity additions, resulting in cost savings and environmental benefits. Postponed capacity additions not only delay the emissions of pollutants from power plants, but also can potentially avoid them. A plant addition postponed for a few years can be fitted with the latest technologies for emissions control, which will pollute less than the previous generation of power plants.

Electric Power Research Institute (EPRI) studies show the benefits of load shifting, peak shaving, and valley filling not only in the reduction of the load and in improving operating efficiencies but also in emission reduction (22). Studies show that considerable improvements can also be achieved in the efficiencies of residential appliances such as lighting, refrigerators, air conditioners, and heaters (use of heat pump). Better energy management control systems and variable-speed motors can also be used to reduce the total electric energy consumption (23).

Among the appliances that have enjoyed efficiency upgrades are refrigerators. The efficiency improvement potential for refrigerators of 100 to 300 L (the size normally used in developing countries) is in the neighborhood of 400 kW · h/year, representing 30% to 40% of their total energy consumption. In extreme cases, this can even go as high as 50% to 75%. In Japan, for example, the refrigerators are now about 66% more efficient than in 1973.

Another possible area for electric energy savings is electric fans. Newer electric fans can save about 10% off the consumption of standard fans.

High-efficiency air conditioners have efficiencies 30% to 40% higher than those of the average new air conditioners. In regions requiring space heating, heat pumps are available that use less than 50% of the electricity needed for electric resistance-based systems. High-efficiency heat pumps, which are 25% more efficient than standard heat pumps, can also be used. These have been claimed to be more economical than gas heaters. With their introduction into the industrial sector, they are becoming more effective in reducing the overall consumption of energy for heating.

Improved incandescent lamps save 5% to 20% of the electricity use of standard incandescent lamps. Compact fluorescent lamps, on the other hand, can save 60% to 75%. Improved fluorescent lamps are now available with 5% to 15% higher efficacy, and electronic ballasts can reduce energy consumption by 20% to 25% relative to using ordinary ballasts. Combinations of rare earth fluorescent, low-temperature compact fluorescent lamps and high-frequency electronic ballasts have attained efficiencies that are 50% greater than those of conventional fluorescent lamps.

In the US, motors are estimated to account for 57% of total electricity use, 60% of which is in the industrial sector. In developing countries where the percentage of electricity use by industry is higher, this figure will also be higher. Depending on motor size, high-efficiency motors can reduce energy consumption by 2% to 15% in the US, at a cost of 10% to 30% more than standard-efficiency motors. They normally pay for this additional investment within one year. Even higher-efficiency motors are available in Japan. High-efficiency motors are available at standard frame sizes, facilitating their use for new plant constructions and when existing motors need to be replaced at the end of their useful life.

Prudent motor sizing and the use of variable-speed drives allow savings of between 15% and 40% in energy use. Friction, windage, and core losses are reduced by avoiding the tendency to oversized motors. Variable-speed drives modify the power going into the motor instead of allowing it to run at full power and controlling fluid flow by throttling.

There have also been reductions in the specific energy consumption of electric arc furnaces. Use of microwave and far-infrared rays is also promising. Household use of the microwave oven has reduced electricity consumption for cooking, and there is already talk of microwave clothes dryers.

Environmental Policy Options

The policy instruments available to the government for implementing environmental policy can be classified into two major groups—command-and-control approaches and economic incentive systems (24,25). Earlier legislation leaned toward the former, but more recent ones have taken advantage of the market orientation of the latter.

Command and Control. A command-and-control approach to pollution abatement involves the setting of standards and direct regulation of polluters. This conventional regulatory mechanism either specifies the technology that must be used (technology-based) or sets a cap on the emission rate that all sources must meet (a uniform performance standard). The command-and-control approach has included the setting of ambient air and water quality standards, objectives, and targets, and the imposition of emission and discharge limits and/or products or process standards through a licensing and monitoring system. Compliance is made mandatory for polluters, and noncompliance results in sanctions on the polluters.

Uniform Performance Standard. Uniform standards that have been used include

1. Limitation on the maximum rate of discharge from a pollution source
2. Specification of the degree of pollution control required, such as percentage of removal of particles from the emission
3. Limitation of the density of pollution discharged or emitted
4. Bans on discharges based on pollution concentration or damage costs
5. Discharge limits based on the use of specified inputs to or outputs from the production process

Technology-Based Pollution Control Approaches. The 1970 Clean Air Act was based on achieving air quality pollution standards through strict formulation of technology standards. *National ambient air quality standards* (NAAQSs) were to be implemented by states under *state implementation plans* (SIPs). Ambient standards for ozone and other pollutants were set together with new source performance standards (NSPSs).

Between 1970 and 1976, SIPs fell behind schedule, and the EPA started to formulate its offset policy. This allowed new and modified sources in "nonattainment areas" when *lowest available emission rate technologies* (LAERTs) were applied and when any additional emissions were offset.

The amendments of 1977 allowed the extension of deadlines for achieving NAAQSs and the formulation of new technology standards. Existing sources in nonattainment areas were allowed to use *reasonably available control technology* (RACT) which considered technological and economic feasibility.

Specifying a uniform performance standard instead of a particular technology allows more flexibility for the firms to decide how they will meet the goal, e.g., a limit on the amount of pollutant that can be emitted per product output. Both of these approaches, however, tend to impose high social costs. For example, the cost to control certain pollutants may vary by a factor of 100 or more because of the differences in location and technology used for the different plants. If the government desired to allocate the pollution control burden effectively, it would have to require all sources to control at the same marginal cost—something that would require detailed information on the operating cost of each individual source.

Economic Incentive Systems. In order to allocate the control burden more effectively, the US government is now taking advantage of economic-incentive approaches. These policy options use market forces to find the most cost-effective manner of pollution control. Economic-incentive approaches can be grouped into four major categories: (1) pollution charges, (2) subsidies, (3) deposit-refund systems, and (4) market creation.

Pollution Charges. Pollution charges take several forms. Effluent charges can be collected on discharges into the environment based on the quantity and/or quality of the effluent.

These may (distributive effluent charges) or may not (incentive effluent charges) be returned to the polluter in the form of subsidies for new pollution control equipment. User charges for the cost of collective or public treatment of effluents can also be imposed. Product charges can be added to the price of products that are polluting or are difficult to dispose of. Administrative charges in the form of control and authorization fees can also be used.

Subsidies. Subsidy instruments include grants, soft loans, tax allowances, and the elimination of subsidies, each of which is linked to the adoption of pollution abatement measures. Grants are forms of financial assistance that need not be repaid. Soft loans carry below-market rates of interest. Tax allowances include accelerated depreciation, tax exemptions, or rebates. Subsidies that promote economically inefficient and environmentally unsound development can be eliminated.

Deposit-Refund Systems. These systems impose surcharges on the price of the potential to pollute, and give a refund of the surcharge on the return of the product or its residuals.

Market Creation. The government can also create artificial markets where participants can buy and sell rights for actual or potential pollution. One example of this is emissions trading (bubbles, offsets, netting, and banking) within a plant, within a firm, or among different firms [e.g., Clean Air Act Amendment (CAAA), 1990]. Another instrument is price intervention to stabilize markets, typically secondary materials (recycled) markets. Polluter liability has also led to development of a market for liability insurance. Still another instrument is the removal of barriers to allow more competition among firms and permit least-cost bidding to promote economic efficiency [e.g., Public Utilities Regulatory Policies Act (PURPA) and EPA].

By imposing absolute standards, command-and-control policy instruments attempt to ensure that certain levels of emissions will be met. The drawback to this type of policy is that unless the policy is strictly enforced, it is difficult or even impossible to achieve the desired results. Incentive methods, on the other hand, are easier to enforce, since their flexibility makes compliance less formidable. For example, SO_2 tradable permits give power plants the opportunity to weigh the cost-effectiveness of complying with emissions standards or to purchase allowances to postpone this cost to a later time. The limited number of total allowances available attempts to ensure that emissions levels will remain below a particular threshold.

INTERNATIONAL AGREEMENTS AND COUNTRY INITIATIVES

Acid Rain and the Clean Air Act Amendments of 1990

Among the provisions of the Clean Air Act amendments of 1990 (26), Title IV (Acid Deposition) has the greatest effects on the utilities. This provision requires that sulfur dioxide emissions be cut 10 million tons below the 1980 levels to 8.9 million tons. This is to be accomplished in two phases.

The first phase began January 1, 1995, and affected the 111 dirtiest power plants. At that time, those plants would have had to reduce their SO_2 emissions to 2.5 pounds per million British thermal units (lb/MBtu), or 4.5 kilograms per gigacalorie (kg/Gcal). The EPA will issue allowances, each permitting one ton of SO_2 emissions. Facilities that cut their emissions further than the 4.5 kg/Gcal rate can then sell or apply their unused allowances to other facilities that cannot meet their limit. Title IV also provides extra allowances for utilities using conservation and renewable energy resources and for most of the affected sources in the Midwest (Illinois, Indiana, and Ohio) for each year from 1995 to 1999. A two-year deadline extension is given to plants that commit to installing flue gas desulfurization (FGD) systems capable of eliminating 90% or more of their SO_2 emissions. The EPA will allocate for these units allowances approximately equivalent to their uncontrolled annual emissions during the extension period. In addition, qualified units using FGD also received one bonus allowance in 1997, 1998, and 1999 for each ton of reduction below 1.2 lb/MBtu (2.16 kg/Gcal).

Phase II, in effect January 1, 2000, sets an emissions limit for utilities of 1.2 lb/MBtu. Bonus allowances are to be given to states where utilities emit less than 0.8 lb/MBtu. Another 50,000 allowances will be given in phase II to plants in 10 states (Illinois, Indiana, Ohio, Georgia, Alabama, Missouri, Pennsylvania, West Virginia, Kentucky, and Tennessee, with certain plant exceptions) that meet phase I limits. Plants reducing SO_2 emissions by 90% will receive allowances on a two-for-one basis.

Greenhouse Gases

The Framework Convention on Climate Change. The Framework Convention on Climate Change (27,28) is an international agreement to stabilize levels of greenhouse gas concentrations in the atmosphere to prevent dangerous anthropogenic interference with the climate system. It directs that "such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner." It also suggests, as believed by most climatologists, that some change is inevitable and calls for adaptive as well as preventive measures.

The parties to the Convention agreed to take climate change into account in such matters as agriculture, energy, natural resources, and activities involving sea coasts and to develop national programs to slow climate change. The Convention encourages the countries to share their technologies and supports cooperative activities for reducing greenhouse gas emissions, especially from energy, transport, industry, agriculture, forestry, and waste management sectors. It promotes scientific research on climate change and creates a "subsidiary body" for "scientific and technological advice" to assist governments in decision making. It also calls for a greenhouse gas inventory listing its national sources and sinks to allow the monitoring of changes in emissions and evaluating the effects of measures for emissions control.

Noting that the largest share of historical and current emissions originates in developed countries, and recognizing the right of poorer nations to economic development, the Convention places the major share of the responsibility for battling climate change on the industrialized countries. Specific commitments relating to financial and technological transfers apply only to the 24 developed countries of the Organization for Economic Cooperation and Development (OECD). Commitments on efforts to limit greenhouse gas emissions and enhance natural sinks apply to OECD and the so-called economies in transition, which consist of 12 countries in Central and Eastern Europe and the former Soviet Union.

The Framework Convention asked OECD and transition countries to seek to return their greenhouse gas emissions to 1990 levels by the year 2000. With the adoption of the Berlin Mandate in 1995, the policy focus shifted to establishing post-2000 emissions targets. Participants in this first conference of parties (COP) to the convention acknowledged the inadequacy of the provisions of the present convention in preventing global warming. They agreed to start negotiations as soon as possible to prepare a protocol and complete a study of approaches for the years beyond 2000 before the 1997 conference of contracting parties.

Climate Change Programs in the US

The Energy Policy Act of 1992. The Energy Policy Act of 1992 (29) was legislated to promote more competition in the electric utility industry, provide tax relief to oil and gas drillers, encourage energy conservation and efficiency, advance renewable energy and the use of alternative fuels on cars, facilitate the construction of nuclear power plants, and promote energy-related research and development through the infusion of funds.

While not attacking the issue of greenhouse gases directly, it creates an office on climate protection and requires an administrative study on the methods and costs of curbing greenhouse gas emissions. It also requires the Energy Secretary to develop a least-cost energy strategy that promotes energy efficiency and seeks to limit the emission of carbon dioxide and other greenhouse gases.

The provisions of the Act that have a greater effect on the utilities include the creation of a category of exempt wholesale power producers. This change allows utilities to operate independent wholesale plants outside their own service territories and encourages the operation of generating plants by independent producers. The provision also allows wholesale electricity generators to request that the Federal Energy Regulatory Commission order a utility to transmit their power.

A range of standards and incentives on energy efficiency, on renewable and alternative energy sources, and on energy and coal research are also expected to have results in the intermediate and the far future.

The US Initiative on Joint Implementation. Joint implementation (JI) (30) was introduced during the negotiations leading up to the 1992 Earth Summit in Rio de Janeiro. Since then, the term "JI" has been used for a wide range of possible arrangements between interests in two or more countries for implementing cooperative development projects to reduce or sequester greenhouse gas emissions. Such projects are significant in that while costs of reducing or sequestering greenhouse gases vary among countries, all such gases affect the global climate in the same way, regardless of where they are emitted. Joint implementation allows the reduction of emissions at lower global cost than would be possible if each country acted alone.

The US Initiative on Joint Implementation (USIJI) was launched in October 1993 as part of President Clinton's Climate Change Action Plan. It is a flexible, nonregulatory program that encourages private-sector participants in the US to engage in overseas projects that will reduce net GHGs.

The program provides public recognition and limited technical assistance to participants in approved projects. The emissions reduced or sequestered by each project are tracked and recorded. USIJI is administered by an interagency Secretariat chaired by the Environmental Protection Agency and the Department of Energy with significant participation by the Agency for International Development. Other participating agencies include the Departments of State, Agriculture, Commerce, Interior, and Treasury.

The USIJI has the following objectives:

1. To encourage the development and implementation of cooperative, cost-effective, voluntary projects between US and foreign partners, especially projects that promote technological cooperation and sustainable development
2. To promote projects to test and evaluate methodologies for measuring, tracking, and verifying costs and benefits
3. To contribute to the formulation of international criteria for JI
4. To foster private-sector investment and innovation in the development and dissemination of technologies for reducing or sequestering GHG emissions
5. To encourage participating countries to adopt more complete climate action programs, including national inventories, baselines, policies and measures, and appropriate specific commitments

Benefits offered to US participants include the following:

1. Public recognition for their efforts to reduce the threat of climate change and contribute to sustainable development
2. Limited technical assistance in the form of workshops, guidance documents, papers examining specific issues, and hotline assistance
3. Affiliation with a US government program in gaining entry into new markets overseas
4. Official tracking and recording of the project's emission reductions, while the information gained can contribute to the development of international criteria for joint implementation

Benefits offered to foreign participants include the following:

1. Technology transfer through US private sector investment in additional resources in the dissemination of innovative technologies
2. Reduction of transaction costs to facilitate investments in technologies and projects that reduce greenhouse gas emissions and contribute to overall host country development objectives
3. Generation of other local environmental and human health benefits by preventing or reducing air, water, or soil pollution and/or contributing to more sustainable use of natural resources
4. Creation of local economic benefits through training, construction of new or improved facilities, public participation in projects, and provision of new energy services

The first USIJI solicitation in the Autumn of 1994 generated 25 proposals and resulted in seven projects representing more than $40 million in investments. Encompassing technologies and practices ranging from sustainable forest management to renewable energy technologies; these projects take place in Belize, Costa Rica, the Czech Republic, Honduras, and Russia.

The second solicitation closed in July 1995 and resulted in 21 proposals. Countries participating in the second round are Costa Rica, Nicaragua, Russia, and Honduras, with projects involving forestry management, renewable resources, and fugitive methane gas capture.

The US Climate Challenge Program. The US Climate Challenge Program (31) is a voluntary partnership between the US Department of Energy (DOE) and the electric utility industry. Under this program, nearly 500 electric utilities have signed more than 100 participation accords with DOE to voluntarily reduce, avoid, or sequester greenhouse gases by the year 2000. It has been one of the most successful programs under the US Climate Change Action Plan instituted by President William Clinton in October 1993 in accordance with his domestic commitment to return US greenhouse gas emissions to 1990 levels by the year 2000. DOE estimates that these accords will reduce GHG emissions by 47 million metric tons of carbon equivalent from expected year 2000 levels.

Underlying the climate challenge program are two key framework instruments. The first of these instruments is the Climate Challenge Program Memorandum of Understanding (MOU) which was signed on April 20, 1994. This established the fact that the parties involved had agreed on a voluntary partnership to reduce greenhouse gas emissions, and set forth the guiding principles and key provisions for individual DOE–utility agreements to follow.

The second instrument was the Model Climate Challenge Participation Accord. Completed in July 1994, this document provided the model from which the numerous individual participation accords have subsequently been drafted, negotiated, and concluded. In order to suit those utilities with less than 50,000 customers, DOE also provided a letter agreement approach.

The MOU set forth three core elements of every participation accord:

1. A specific commitment or commitments to reduce, avoid, or sequester greenhouse gases
2. A commitment to report annually on activities and achievements under the Climate Challenge Program; and
3. A commitment to confer at reasonable intervals to evaluate jointly the progress of the utility participant in achieving its Climate Challenge goals and to discuss possible adjustments to its voluntary commitments

One or more of the following specific commitments are expected of utility participants:

1. Make a specified contribution to particular industry initiatives
2. Reduce greenhouse gas emissions by a specified amount below the utility's 1990 baseline level by the year 2000
3. Reduce greenhouse gas emissions to the utility's 1990 baseline level by the year 2000
4. Reduce greenhouse gas emissions by or to some other specified level
5. Reduce or limit the rate of greenhouse gas emissions to a particular level
6. Undertake specific projects or actions, or make specific expenditures on projects or actions, to reduce greenhouse gas emissions

Utilities have two principal means of implementing their commitments under the Climate Challenge Program. The first is through a number of individual activities that utilities are engaging in. These activities are catalogued in the *Options Workbook,* which was published by DOE and the electric utility industry in October 1994. This workbook has nearly 200 pages of options, ranging from supply-side and demand-side management programs, to public and private partnerships, and to cross-sectional activities that involve utility customers, other sectors of the economy, and international projects.

The second approach is through a set of industry initiatives that utilities are engaging in collectively. These initiatives currently include five Edison Electric Institute (EEI) industry initiatives and five being conducted by other utility trade associations and utilities.

The following are EEI's five major initiatives (31):

1. The National Earth Comfort Program, which is a consortium of more than 150 electric utilities and allied organizations established to expand the geothermal heat pump market
2. EnviroTech^{SM}, which is an investment fund created to develop promising electrotechnologies and renewables to help reduce greenhouse gas emissions
3. EV America, a multiphase market demonstration of 29 electric utilities established to promote and increase widespread use of electric vehicles
4. The Utility Forest Carbon Management Program, a group of more than 50 electric utilities which is forming the Utilitree Carbon Company to develop projects for forest management and carbon sequestration
5. The International Utility Efficiency Partnerships (IUEP) program, a group of 10 electric utilities established to identify international energy project development opportunities and to sponsor workshops with host country government officials to facilitate project investment and development

The five initiatives that are being conducted by other utility trade associations and utilities are as follows (31):

1. Electric End-Use Efficiency Technology Initiative
2. Tree Power
3. Partnerships in Joint Implementation Projects
4. International Donated Equipment Initiative
5. Combined Purchasing Initiative

The International Utility Efficiency Partnerships. Among the more successful activities in the Climate Challenge is the IUEP program (32). It is a separately funded activity within the EEI. Formed in February 1995, it is designed to identify international energy project development opportunities to work with host country government personnel to facilitate project investment and to demonstrate US utility commitment to voluntary approaches to global climate issues.

The IUEP identifies and supports international activities to reduce, limit, or avoid emissions of greenhouse gases (for example, energy efficiency, fuel switching, and renewable energy projects). In addition, it monitors developments in the world's fastest-growing emerging markets and provides access to new business opportunities. US electric utilities then evaluate and select proposed IUEP projects for financial and technical assistance.

Working closely with officials from the USIJI, the IUEP pursues official recognition for selected IUEP projects as JI. It also intends to coordinate the diverse technical and managerial skills of its membership in management training programs held in the developing world.

Climate Change Programs in Other Countries

Japan. The Japanese government instituted the Action Program to Arrest Global Warming in 1990 in its effort to find a systematic and comprehensive solution for global warming. It calls for the stabilization of per capita CO_2 emissions in the year 2000 at 1990 levels. The Japan Action Report on Climate Change submitted to the convention secretariat in September 1995 predicts per capita CO_2 emissions at about 2.6 tons for fiscal year 2000, which is almost the same as the 2.59 tons calculated in terms of carbon for fiscal year 1990.

However, total CO_2 emissions are expected to increase by 10 million tons between 1990 and 2000 to 330 million. In compliance with the Berlin Mandate, the Japanese government is considering new approaches to check the advance of global warming for the years beyond 2000.

One of Japan's largest electric utilities is Tokyo Electric Power Company (TEPCO), which therefore plays a major role in Japan's efforts to control CO_2 emissions. Among TEPCO's thrusts are the following (33):

Promotion of a Best-Generating-Mix Effort that Centers on Nuclear Power. This involves increasing the proportion of nuclear power, new energy, and nonfossil energy sources in relation to others. It also includes promoting the introduction of liquefied natural gas (LNG) and other fossil fuels with a low carbon content. To this end, TEPCO targets an increase of two percentage points each in the share of nuclear, hydro, and LNG generation for the year 2000 over that of the year 1994.

Improvement of the Thermal Efficiency of Thermal Power Generation. TEPCO successfully improved the thermal efficiency of thermal power generation from 38.3% in 1970 to 39.2% in 1994.

Effective Use of Hydroelectric Power. Between 1979 and 1994, TEPCO increased its hydroelectric power capacity by nearly 35,000 kW by remodeling or renewing its water turbine generators.

Promotion of the Effective Use of Resources. This effort includes development of geothermal power and purchasing surplus power from waste-to-energy, photovoltaic, and other new energy-based power generation facilities.

Denmark. Denmark (34) was a major oil importer before the 1973 oil crisis. Having been greatly affected by the crisis, the country aggressively promoted other power generation options. It reduced dependence upon imported oil through energy conservation programs, through development of indigenous oil, natural gas, and renewables, and through switching from oil to coal as the primary fuel for electric power generation.

The Danish government became dedicated to environmental reform in the 1990s. The country's measures for reducing dependence on oil imports resulted in an increase in the proportion of CO_2 produced by the power plants to electricity generation due to the switch from oil to coal as primary fuel for electricity generation.

Denmark's new energy policy, Energi 2000, was enacted in 1990. Energi 2000 includes provisions for further development of wind power and more research into solar and biomass energies in an effort to reduce global emissions. In 1991, about 3% of Denmark's total electricity generating capacity, or 273 MW, was produced by windmills. That number is expected to go up to 10% by the year 2000. The country is even attempting to produce wind power offshore to decrease the local environmental effects of wind generation, which include visual effects as well as the effects of audible and electromagnetic noise. In the near future, the country expects to add 450 MW of biomass-fueled capacity. When combined with replanting, the combustion of biomass has no detrimental effect on the global environment.

The Danish program has had high success with its renewable energy program due to its implementation of high energy taxes on fossil fuels. High taxes on electricity have slowed growth in power demand, further reducing local and global power plant emissions. In addition to the strides Denmark has already made, when signing the Framework Convention on Climate Change (FCCC) agreement in 1992, it estimated that through the year 2005, it can reduce gross energy consumption by almost 15%, CO_2 emissions by almost 30%, SO_2 emissions by about 60%, and NO_x emissions by 50%. These percentages are relative to the respective 1988 levels.

Denmark expects to meet the goals outlined in the FCCC through legislation tailored to (1) improve end-use energy efficiency and conservation, (2) enhance efficiency in energy supply, (3) increase use of environmentally benign energy sources, and (4) promote research and development. The Danish Parliament also included a CO_2 tax in its plan as partial incentive to decrease such emissions.

McGowan (35) suggests that the barrier of politics is the most important one to surmount in the case of renewables. The Danish energy policy program is an example of how politics, legislation in particular, can spur progress toward environmental reform by making provisions for the use of renewables.

France. Like Denmark, France (34) was able to significantly reduce its power plant emissions beginning in the early 1980s. France accomplished this by implementing an energy policy that heavily promoted nuclear power and energy efficiency. As a result, by 1991, the country's CO_2 emissions due to energy transformation (including power plants, heat plants, and refineries) were about half of what they were in 1980, despite growth in population and higher electricity generation every year.

Although France has already significantly reduced its CO_2 emissions below 1980 levels, the country has dedicated itself to decreasing such emissions to below two tons per capita per year by the year 2000. (France's energy-related CO_2 emission per capita was 6.8 tons in 1991.) The country intends to achieve these goals by imposing thermal efficiency regulations on buildings, promoting wood-burning furnaces for space heating in buildings, expanding its public transportation, establishing GHG reduction programs for GHG intensive industries, labeling energy consumption of products in new housing, and possibly imposing a tax on the carbon content of fossil fuels.

France's commitment to the goals outlined above is contingent upon the establishment of similar goals in other industrialized countries. Since GHGs affect the global environment, France would like to ensure that all countries that are economically able to control their global power plant emissions contribute their fair share. The country recognizes that a global emission control commitment is necessary in order to achieve significant results.

Germany. Germany (28) attended the 1992 Earth Summit in Rio de Janeiro and signed the Convention. It deposited the instrument of ratification at the United Nations in December 1993, and hosted the first conference of parties (COP) in 1995. German efforts at international cooperation started much earlier, however, with the establishment of the Enquête-Commission in 1987 to recommend "preventive measures to protect the earth's atmosphere." Upon the commission's recommendation, the federal government decided to work towards international agreements for the protection of the climate.

Among the measures recommended by the Enquête-Commission were a total stop to the production and use of CFCs and halons, restoration of tropical forests to 1990 levels between 2010 and 2030, region-specific reductions in per capita emissions of CO_2 of between 10% and 30% by 2005, and adoption of an overall strategy on the protection of the earth's atmosphere by the year 2000 (36).

The official government position supports joint implementation contingent on the stipulation of clearly defined reduction commitments by the parties to the convention towards attainment of the stabilization goal. It provides detailed inventories of the country's greenhouse gas emissions and reports on the state of implementation of the CO_2 reduction program.

Germany's own plans, unveiled in August 1993, included cuts in carbon dioxide emissions of between 25% and 30% and a reduction in all greenhouse gas emissions (excluding CFCs, which are already banned, and including methane, nitrous oxide, nitrogen oxides, volatile hydrocarbons, and carbon monoxide) of 50% from 1987 emission levels by 2005 (36). Its CO_2 reduction program combines regulatory measures, market-based elements, and other supporting instruments such as consulting, information, and training. It favors the increased use of economic instruments to incorporate environmental costs into energy prices and supports a revenue-neutral energy tax that does not distort competition. In addition, the government supports specific energy-saving measures and the use of alternative sources of energy.

The CO_2 reduction program proposes actions in the sectors of energy, buildings, industry, households, agriculture, forestry, and R&D. Of the 29 measures identified by the Enquête Commission as the most promising measures available, 17 had taken effect by 1994, which included the following:

1. A wind energy promotion program
2. A photovoltaic promotion program
3. Tax benefits for heat–power cogeneration
4. An energy diagnosis program for buildings
5. A credit–loan program for efficient energy use and for the use of renewable energy by small and medium-sized enterprises
6. A thermal insulation ordinance
7. An ordinance on heating installations

Other measures include an ordinance on small firing installations, an ordinance on heat use, an energy management act, an emissions-based motor vehicle tax, and a criterion to limit CO_2 emissions from motor vehicles.

Expected Results of Climate Change Programs. At the Rio Summit of 1992, the world's leaders agreed to draft the Framework Convention on Climate Change (FCCC) to address the challenge of global warming. Because of the significant role played by electric utilities in the energy balance and the subsequent production and potential control of greenhouse gases, the FCCC has possible major repercussions in the electric utility industry and the whole energy sector in general. Compliance with the FCCC can take several approaches: demand reduction, use of nonfossil resources, fuel switching, and efficiency improvements. Other techniques are afforestation and CO_2 sequestration, which is not economically viable at present. The use of these technology options can be promoted with economic-incentive or command-and-control policy options. In either case, compliance with FCCC entails high costs. There is also the problem of uncertainties on the relationships between human activities and GHG emissions, the resulting climate effects, and the effects of climate change on environmental and economic systems. To better inform the process, EPRI has taken an active role in supporting research on these relationships. It has likewise initiated integrated assessment efforts for evaluating global climate change management proposals.

Several US government programs also address CO_2 reduction through its Initiative on Joint Implementation and other programs such as the Clinton Administration's Climate Change Action Plan and the DOE's Climate Challenge Program.

As a result of the FCCC, industrialized countries have committed to reductions in CO_2 emissions mostly to 1990 levels by the year 2000. This indicates, however, that CO_2 will continue to accumulate in the atmosphere. For industrialized countries to cut emissions to 20% below 1990 levels by the year 2005 as proposed during the first COP would cost about $2.7 trillion, according to one estimate. Relaxing short-term targets but meeting longer-term objectives, however, can drastically reduce costs to around $500 billion.

The first round US Initiative on Joint Implementation has generated $40 million in private investments in GHG reduction. Second-round proposals were also approved in December 1995. Together, these proposals have the potential to reduce CO_2 emissions by tens of millions of metric tons per year. At the same time, the voluntary government–utility partnerships to mitigate GHG emissions called the US Climate Challenge program is expected to reduce GHG emissions by 47 million metric tons of carbon equivalent (MMTCE) from the baseline year 2000 level.

CONCLUSIONS

Air pollution from electricity generation can be addressed at all stages of the energy cycle—from resource planning through operations. Pre- and postcombustion technologies are sufficiently mature, and the industry is nearing transition to highly efficient next-generation combustion technologies. However, the electric utility industry remains dependent on fossil fuel for electricity generation.

As the consumption of energy, electrical or otherwise, increases, the growth of CO_2 emissions continues irrespective of conventions, treaties, and debate in the public media. Even after many of the industrialized countries committed to reduce their CO_2 emissions under the FCCC, most of them failed to achieve their own goals. There is scientific evidence that global warming is unavoidable. However, the degree of this warming can be slowed down if prudent action is taken by all parties, but most importantly, by the ones who can afford the most and have some historical obligations due to their past emission practices.

It is true that a few developing countries will gradually surpass some of the highest CO_2 emitters of the late twentieth century, and the level of atmospheric CO_2 concentration affects all countries. It is, however, judicious for the industrialized countries to take unilateral actions to reduce their CO_2 emissions, at least so that they can take the moral high ground in the debate on who has been responsible for global warming and who will make how much sacrifice to reverse the trend.

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AIR POLLUTION CONTROL. See Electrostatic precipitators.