



Technological Alternatives to Reduce Acid Gas and Related Emissions from Energy-Sector Activities in Northeast Asia November, 1996

Recommended Citation

David Von Hippel, "Technological Alternatives to Reduce Acid Gas and Related Emissions from Energy-Sector Activities in Northeast Asia November, 1996", Uncategorized NAPSNet Special Reports, November 23, 1996, <https://nautilus.org/uncategorized/technological-alternatives--o-reduce-acid-gas-and-related-emissions-from-energy-sector-activities-in-northeast-asia-november-1996/>

1.Introduction and Background

Of the many environmental concerns currently facing the nations of Northeast Asia, the problem of "acid rain" or "acid precipitation" presents perhaps the most potent combination of immediate and ongoing impact and regional scope. "Acid rain", (as described in more detail in other papers in this series) is a general, though not entirely accurate, term used to describe a complex set of processes. "Acid gases"-principally oxides of sulfur (SO_x) and nitrogen (NO_x) are emitted to the air during the combustion of fossil fuels, as well as from some natural processes. In the atmosphere, acid gases can combine with water vapor or water droplets to form sulfuric and nitric acids. These acids are transported by prevailing winds, and eventually fall back to earth (or to the ocean) as rain or snow. Acid gases can also be adsorbed to particles in the atmosphere, and fall as to the ground as "dry deposition" with particles or as ions, becoming acidic when wetted.

The effects of acid rain vary considerably with the vegetation, soil types, and weather conditions in a given area. Under some conditions, the addition of sulfate and nitrate to the soil helps replace lost nutrients, and aids plant growth. In other instances, however, acid deposition can cause lakes and streams to become acid, damage trees and other plants, damage man-made structures, and help to mobilize toxic compounds naturally present in soil and rocks. The countries of Northeast Asia have already begun to experience some important impacts of acid rain. Forest health in some areas of the Koreas, China, and Japan has already revealed evidence of degradation that points to acid rain.¹ Man-made materials such as zinc-plated steel have drastically shorter-than-normal lifetimes in south China, and irreplaceable cultural landmarks made of limestone and other substances are being degraded at an accelerating rate.²

While natural sources account for a significant, though uncertain, fraction of the atmospheric sulfur and nitrogen oxides, human sources appear to be the major cause of recent declining trends in the pH.^a of rainfall. While some industrial sources of emissions, particularly the smelting of metal, can be important sources of sulfur oxides, the energy sector accounts for a large fraction of these

emissions. Sulfur oxides are produced during combustion of coal, which contains varying amounts (0.5 to 5 or more percent) of sulfur, and during combustion of oil products, particularly the heavier grades. These fuels are commonly used in large industrial facilities and in electric power generation in all of the countries of the region, and coal is also a very common domestic fuel in North Korea (DPRK), China, and Mongolia. Nitrogen oxides are produced at varying rates by all types of fossil and biomass fuel combustion; the nitrogen in the NO_x produced during combustion is derived both from nitrogen in the fuel and from the molecular nitrogen (N₂) that makes up nearly four-fifths of the air we breathe. Gasoline-powered autos, trucks, and buses are major emitters of NO_x, as are many utility and industrial combustion devices.

Though acid deposition *can* be a local phenomenon, particularly in urban areas and in areas near a large point source of emissions, the extent to which acid gases are carried by prevailing weather patterns makes acid rain a truly *regional* issue, one that frequently crosses national boundaries. Although, for example, a large fraction of the emissions in Northeast Asia both originate and fall to earth in China, there is substantial inter-country transport of acid gases. As the majority of the growth in emissions in the next two decades will likely be in China, a substantial regional, if not international, cooperative effort will be required to reduce emissions before the level of environmental damage becomes overwhelming. This paper provides information on the costs and effectiveness of alternative methods for reducing emissions of acid gases. The intent is that this background information can serve to illuminate the areas of technology transfer that are most likely to a) be most cost effective, and b) present appropriate opportunities for inter-regional cooperation on the "acid rain" issue.

1.1. The Acid Gas Emissions and Acid Precipitation Situation in Northeast Asia

Previous papers in this series have presented a detailed picture of the acid gas emissions and acid precipitation patterns in Northeast Asia. A very brief overview of this situation is presented below to demonstrate the need and opportunities for measures for reducing acid gas emissions.

Table 1-1 provides estimates of the emissions of both sulfur and nitrogen oxides for five of the countries of Northeast Asia for 1990. Emissions from China, particularly from area sources,^b dominate the regional picture of SO_x emissions. For nitrogen oxide emissions, China's emissions still dominate, but Japan and South Korea produce a much larger portion of the total. RAINS-Asia reference-case projections, in which no improvement in emissions controls is assumed, show SO_x emissions from all countries of the region with the exception of Japan nearly tripling between 1990 and 2020, yielding total regional emissions in 2020 of almost 71 million tonnes.

TABLE 1-1: Estimated Emissions of Acid Gases in Northeast Asia in 1990 (thousand tonnes)^c Indications from the current pattern of SO_x transport are that while virtually all of the sulfur oxides falling to earth in China originate in China, emissions from other countries constitute from 15 percent (South Korea) to over 60 percent (DPRK) of the total deposition in some of the other countries of the region.³ A review of the soil types in the region most subject to acidification shows that key agricultural areas in Southern and Eastern China, in North and South Korea, and in Japan are at risk.^e

The potential huge growth in regional emissions, coupled with the regional nature of atmospheric transport of acid gases and the sensitivity of key ecosystems to acidification, makes acid rain in Northeast Asia a problem that a) must be responded to forcefully and soon, and b) must be addressed at the regional level, as well as nationally and locally. The remainder of this document presents and compares some of the technologies and other measures that could be used to reduce regional risks from acid rain, and suggests some cooperative strategies to get widespread regional implementation of appropriate measures underway.

1.2. Plan of Document

Given the situation for acid rain in Asia as outlined above (and described in greater detail in other papers in this series), the need for options to mitigate acid gas emissions is clear. The remainder of this paper provides a description of these options, including:

- A sampling of the available mitigation technologies by type (*Section 2*), covering emissions control and burner technologies that result in cleaner exhaust gases, fuel improvement technologies that leave less sulfur in the fuel, fuel switching technologies that avoid or reduce the use of sulfur-containing fuels, and energy-efficiency technologies that reduce fuel use generally.
- A comparison of various technologies and measures for acid gas emissions reduction (*Section 3*), providing information on the cost and effectiveness of selected options, and the estimated life-cycle cost per unit emissions reduced, relative to a specified reference technology.
- A set of suggestions (*Section 4*) as to fertile areas for regional and international collaboration, and suggested mechanisms and initiatives that could be pursued to catalyze (figuratively) the implementation of acid gas reduction measures in the countries of Northeast Asia.

2. Technologies for Reduction of Acid Gas Emissions

There are a number of different technologies and measures that can be used to mitigate future emissions of acid gases in the countries of Northeast Asia. The text below provides a definition of the classes of emissions reduction technologies and strategies applicable to the region-especially to China and North Korea-plus a sampling of the important specific technologies and measures available. The key questions to consider when evaluating emission reduction technologies, and touched on briefly in each of the examples below, include the following:

- Is the technology useful for new facilities, in "retrofit" (added on to an existing plant) applications, or both?
- What are the costs of the facility, including capital, ongoing O&M (operating and maintenance) costs, fuel costs (if any), and other costs? What fraction of the costs are for goods and services that must be imported?
- What is the effectiveness of the technology or measure in reducing emissions? What is its impact in terms of disposal or solid and liquid wastes, or on emissions of other air pollutants?
- How applicable is the technology or measure availability in the region? Is it, or is it likely to be, broadly available?
- Is the technology or measure, as applied in Northeast Asia, likely to produce other direct or indirect monetary benefits, or involve other direct or indirect *monetary* costs? If so, how important are those costs likely to be?
- Will the use of the technology present other direct or indirect *non-monetary* benefits and costs? For example, does the application of the technology or measure help toward solving or reducing environmental impacts beyond acid gas emissions? (Note that this topic will be discussed in greater detail in another paper in this series.)

Four classes of technologies and measures are discussed below: "end-of-pipe" and burner modification emission control technologies, fuel processing technologies, fuel-switching measures, and energy-efficiency technologies and measures.

2.1. "End-Of-Pipe" and Burner Modification Emissions Control Technologies

The first group of measures for reducing acid gas emissions considered here are those that either "scrub" oxides of sulfur or nitrogen from the exhaust gas following fuel combustion, or modify the way that fuel is burned to reduce emissions. The attempt here is to summarize the types of technologies available. For each type of technology, there are typically a number of different options and variants.

2.1.1. End-Of-Pipe Measures for Utility and Industrial Applications

Three of the main technologies for controlling SO_x emissions from utility boilers, large industrial boilers, and large industrial furnaces and kilns all involve the injection of a sulfur-absorbing substance into the exhaust gases (flue gases) from the boiler.⁴ These technologies are most commonly used on boilers fired with coal, but could also, in some cases, be used on units fueled with high-sulfur residual oil. SO_x removal technologies for devices smaller than utility or industrial scale are uncommon.

In the first of these technologies, known as **"duct injection"**, flue gases are cooled, typically using water as a coolant, to an appropriate "approach temperature", then routed to an absorber unit. In the absorber, a solution of calcium hydroxide ($\text{Ca}(\text{OH})_2$) is sprayed into the flue gases. This calcium "sorbent" reacts with SO_x in the gases to form calcium sulfate (CaSO_4) and calcium chloride (CaCl_2). These reaction products, together with fly ash (particulate matter from the gas stream) and unreacted sorbent, are removed from the flue gases by settling and by the use of a fabric filter.⁷ The reaction products are disposed of, and unreacted sorbent can be recycled back to the absorber. Duct injection can be used in two configurations. In the "pre-ESP" configuration, duct injection takes place before the exhaust gases are routed to an electrostatic precipitator⁹ (for particulate matter removal). Pre-ESP sorbent injection can remove 30 to 70 percent of the SO_x in the flue gas. Post-ESP injection, in which injection occurs after the exhaust gas has passed through the ESP, can achieve 80 to 90 percent removal. A diagram of the latter process is provided in Annex 1 (Figure A1-1). Direct injection technologies are now in the demonstration and early commercialization phase. They are relatively low-cost, and can be retrofitted to existing plants. The lack of demonstration units in developing countries, however, means that the technologies are unlikely to make much of an impact in China or North Korea before the year 2000.

A second technology that makes use of sulfur-absorption is the "wet scrubber" or "flue gas desulfurization" (FGD). This technology is widely used in developed countries. In wet scrubbers, flue gases enter a large reaction vessel, where they are sprayed with a water slurry containing about 10 percent lime (calcium oxide, or CaO) or limestone. The calcium compounds react with the SO_x in the flue gas, forming calcium sulfate and calcium sulfite, which are collected, thickened (by removing water and filtration), mixed with fly ash and stabilized with additional lime, and disposed of in landfills. A diagram of this process is provided as Figure A1-2. Many of variants of wet scrubber technologies exist, including, notably, the "limestone with forced oxidation" process (which uses air to oxidize more of the calcium sulfite to calcium sulfate for easier removal) and the Chiyoda Thoroughbred process, which uses a streamlined process design. Wet scrubber technologies remove 80 to 90 percent of the SO_x in flue gases. They are well-proven devices, applicable to new plants and in retrofit installations, and available from a number of developed-country suppliers, including Japan. Wet scrubbers are relatively costly, however, and will require a substantial amount of foreign exchange until the developing countries of Northeast Asia can produce the technology domestically.

"Dry scrubbers", or spray dryers, are a third type of sorbent-based SO_x removal technology. Here, a slurry of quicklime mixed with water (calcium hydroxide) is atomized and sprayed into a tower, where it mixes with hot exhaust gases. The calcium hydroxide reacts with SO_x in the exhaust gases

as the droplets dry, resulting in the production of a dry calcium sulfate/sulfite by-product, which is collected in the bottom of the spray dryer and in equipment used to collect particulate matter (ESP or baghouse). A diagram of this process is shown in Figure A1-3. Dry scrubbers can remove 70 to 90 percent of the SO_x in flue gases. The technology has been used with low-sulfur coals in the United States and Japan, but needs to be demonstrated for high-sulfur coals. Dry scrubbers can be used in retrofit as well as new installations, cost slightly less than wet scrubbers, and are somewhat simpler to operate.

Options for the control of nitrogen oxides from utility and industrial facilities include primarily selective noncatalytic reduction (SNCR) and selective catalytic reduction (SCR) of NO_x to elemental nitrogen (N₂). In SNCR, a nitrogen-based chemical reagent—most commonly urea (CH₂CONH₂) or ammonia (NH₃)—is injected just after the exhaust gases exit the boiler (that is, when the gases are still very hot). SNCR can reduce NO_x emissions by 35 to 60 percent, can be used in new and retrofit installations, and have relatively low capital costs. SNCR has mostly been used with gas and oil-fired boilers and turbines, but has been demonstrated on coal-fired boilers in the United States and Europe, and has also been used on specific types of cement kilns.⁵ Concerns with the SNCR technology include possible ammonia contamination of fly ash (ammonia can cause odor problems), release of unreacted ammonia into the environment with treated flue gases, and production of (N₂O), a potent greenhouse gas, during the reaction of flue-gas NO_x with the injected reagents.

The SCR process is similar to SNCR, in that ammonia is reacted with the NO_x in the flue gas to yield (mostly) molecular nitrogen. The difference between the technologies, as their names imply, is that SCR makes use of a catalyst to accelerate the chemical reactions, and (thanks to the catalyst) can operate at lower flue gas temperatures than SNCR. The catalysts used in SCR are oxides of metals, typically vanadium and titanium. SCR has been widely used in low-sulfur coal and oil-fired power plants in Europe and Japan, but its use with medium- and high-sulfur coals is still in the demonstration phase. SCR can remove 70 to 90 percent of the NO_x in the flue gas, but is significantly more expensive than SNCR systems. Issues such as the impact of alkalis and arsenic (common coal contaminants) on catalyst life, the emissions of unreacted ammonia, and the conversion of SO₂ to SO₃ by catalysts (and the impact of that process on NO_x removal) all may have an impact on the applicability of SCR in Northeast Asia.

Post-combustion technologies for combined removal of sulfur and nitrogen oxides are currently under development. These processes are expected to provide SO_x and NO_x removal in the range of 80 to 90 percent. A variety of different technologies are in the research and/or demonstration process. The projected costs of these technologies are currently relatively high, approximately equal to the sum of the most expensive separate SO_x and NO_x removal systems currently commercially available. Table A1-1 in the Annex 1⁶ summarizes some of the advantages and disadvantages of the combined SO_x/NO_x removal processes currently under investigation. These processes will need to be demonstrated and commercialized first in developed nations before they are likely to be used in China and North Korea, a process that will take several years, at a minimum.

Table 2-1 presents capital and O&M cost estimates for the different utility and industrial-scale end-of-pipe SO_x and NO_x reduction technologies described above. As these costs are representative primarily of utility-scale applications, they are expressed in dollars per unit of electrical generating capacity and per unit of electricity generated. For industrial boiler and furnace applications, these costs could be converted to dollars per unit heat delivered by factoring in the relative efficiencies of electricity and heat generation. The converted costs would probably be on the low side of cost for industrial installations, due to economies of scale in producing and operating the larger utility-scale units.

TABLE 2-1: Cost Estimates for Post-Combustion SO_x and NO_x Reduction Measures

2.1.2. End-Of-Pipe Measures for Applications in Other Sectors

End-of-pipe or post-combustion methods for reducing SO_x and NO_x emissions are generally not available for use in the commercial/public and residential sectors (except as noted below). In the transport sector, the major technology for reduction of nitrogen oxide emissions is the *catalytic converter*. Catalytic converters have been used on passenger vehicles and light trucks sold in the United States since the early 1980's, and are now required in Japan and in many other OECD countries. Three-way catalytic converters, commonly used in the US, are designed to reduce emissions of carbon monoxide and hydrocarbons, as well as NO_x. These devices can reduce NO_x emissions by roughly 50-90 percent relative to uncontrolled emissions, and have costs on the order of one hundred to two hundred dollars per vehicle. Disadvantages of these devices include their use of expensive catalyst materials (including platinum, in some cases), and their susceptibility to fouling if poor-quality fuels are used. Catalytic converter technology can also be applied to stationary engines used to provide motive power, on-site electricity generation, or engine-driven cooling in commercial and institutional installations. These applications of catalytic converters could become more important if (for example) dispersed power generation or cooling fired with natural gas becomes more prevalent, in Northeast Asia.^h

2.1.3. Burner Modification Technologies for the Utility and Industrial Sectors

A number of different options are available or in the research and development phase for reducing SO_x and/or NO_x emissions by modifying the way that coal and other fuels are burned in utility and industrial boilers, furnaces, kilns, ovens, and combustion turbines. Among these are atmospheric fluidized-bed combustion (AFBC), pressurized fluidized-bed combustion (PFBC), coal gasification technologies, and low-NO_x burner designs.

AFBC boilers have been under development for many years, and are now commercially available (and in use) in a variety of industrial and utility sizes (up to 200 MW). This technology is apparently in wide use (although with smaller units) in China. In AFBC systems, pulverized coal is burned in a "bed" of circulating (or "bubbling", in a simpler alternative design) solid material that includes fuel, ash, and limestone. SO_x formed during coal combustion reacts with the limestone and is removed as a solid product (CaSO₄) with the coal ash. AFBC units therefore produce somewhat more solid wastes than conventional pulverized coal-type boilers (a common coal combustion technology), but the wastes are of a similar volume to conventional plants fitted with scrubbers. In addition, the wastes are generally less hazardous than scrubber sludges, and are considered suitable for some types of re-use (road construction, aggregate, cement production) in some countries. AFBC units reduce SO_x emissions by 70 to 90 percent relative to conventional boilers, and, because their operating temperature is lower than other boiler types,ⁱ also produce significantly less NO_x. AFBC units can also use low-quality fuels, such as lignite coal and wastes from coal cleaning (see below). The cost of AFBC units is somewhat lower (5 to 15 percent) than similar-sized conventional-coal plants fitted with scrubbers. Figure A1-4 compares a typical pulverized coal boiler with two types of AFBC units.

Pressurized fluidized bed combustion technology is a variant of AFBC where the boiler is operated at higher than atmospheric pressures, and where the exhaust gas is cleaned after exiting the boiler, then expanded in a gas turbine. PFBC technology offers higher efficiencies for electricity generation than AFBC, is easier to retrofit to existing powerplants (due to lower space requirements), and costs less than pulverized coal plants with wet scrubbers. It also offers high (more than 90 percent) SO_x removal, and low NO_x emissions. PFBC technologies are currently in the demonstration phase, including a demonstration plant in the design-construction phase in Japan.

Coal *gasification* technologies, including integrated gasification combined-cycle (IGCC) electricity generation plants, start by converting coal into a gas with a heating value 20 to 50 percent of that of natural gas (on a volumetric basis).^j The gas is then used as a fuel for furnaces, kilns, boilers, or other power generation equipment. In an IGCC unit, coal is first gasified in the presence of oxygen and steam. The gas thus produced is then cleaned of ash and sulfur compounds.^k After the gas is cleaned, it is burned in a combustion turbine. Hot Exhaust gases from the gas turbine are routed to a boiler to raise steam which turns a steam turbine-hence the name "combined cycle". The IGCC technology promises very high energy conversion efficiencies (up to 45 percent), up to 99 percent SO_x removal, low NO_x emissions, and adaptability to a variety of different grades of coal, including the high-ash coals that are encountered in China. IGCC plants are in the demonstration phase in Japan and other countries, and are expected to have capital costs about 20 percent higher than typical pulverized coal plants with scrubbers; \$1300 to \$1600 per kW.⁸ Figure A1-5 shows diagrams of three types of gasifiers and a schematic of an IGCC plant.

An additional option for SO_x reduction is the direct injection of sorbent (lime, limestone, or dolomite) into the combustion zone of boilers. This method works in a similar way to AFBC units and post-combustion scrubbers, but is less expensive (capital costs of 70 to 120 US dollars per kW, and O&M costs of 0.3 to 0.7 cents per kWh), easier to operate and maintain, and is suitable for retrofit applications. Unfortunately, the SO_x removal efficiency of this technology is lower than some of the other alternatives (30 to 60 percent), and sorbent injection may adversely affect other boiler and pollution control processes.

For the control of NO_x in industrial installations such as cement kilns, possible technologies include combustion control to optimize kiln performance while minimizing NO_x emissions,^l conversion of kilns to low-NO_x burners by applying indirect or staged combustion, and recirculation of exhaust gases.⁹ Low-NO_x burners for utility or industrial boilers can be used in new or retrofit installations, although the costs for retrofit applications are two- to three-fold higher. The effectiveness of low-NO_x burners in reducing emissions of nitrogen oxides varies by the type of technology applied, but range between 30 and 70 percent for an investment of \$1 to \$50 per kilowatt. Low-NO_x burners are used in virtually all new boilers in industrialized countries, and could be applied at minimal incremental costs in countries like China and North Korea if the technologies were made available.¹⁰ Low-NO_x burners are also generally available for boilers and furnaces fired with oil products or natural gas.

2.1.4. Combustion Modification Technologies for Other Sectors

"Low-NO_x" and similar burner types are available on some types of residential and commercial gas-fired appliances (mostly water heaters and furnaces) in OECD countries, but are still not in common use. Other technologies, such as radiant burners for residential and commercial water heaters, promise higher energy efficiencies and dramatically reduced NO_x emissions (up to 80 percent), but are not yet commercially available.¹¹ These technologies may be of use in Japan and South Korea in the near- to mid-term, but are unlikely to have a great impact in China or North Korea until gas use (and, subsequently, gas appliance use) in those countries increases substantially.

For internal combustion engines-mostly in the transport sector but in small utility, industrial, and commercial/institutional applications as well-much work has been done on combustion modifications to reduce NO_x and other emissions. These modifications include "lean-burn" engines, computerized engine control systems, and a host of other proven and under-development technologies. Given the recent and probable growth in personal vehicle use in Northeast Asia (for example, in South Korea and China), adoption of these types of technologies by vehicle manufacturers (particularly in China) could have a considerable impact on future regional NO_x emissions from the transport sector.

2.2. Fuel Processing Technologies

As the sulfur oxides emitted during fuel combustion are derived from sulfur compounds present in the fuel, SO_x emissions can be reduced by "cleaning" the fuel of sulfur before it is burned. Reducing the sulfur content of fuels is the most practical (sometimes the only) method of reducing sulfur emissions from area sources such as commercial/institutional, transport, and domestic-sector use of coal and oil products. Options for reducing the sulfur content of fuels include physical cleaning of coal, changes in oil refining, and changes in sources of raw and refined fuels.

Physical cleaning of coal is carried out around the world. Approximately 20 percent of the raw coal mined in China, for example, undergoes physical cleaning.¹² Physical cleaning of coal involves grinding to pulverize the coal and detach non-organically bound mineral particles from the coal itself. The mineral particles are then separated from the crushed coal by a variety of physical methods, which can vary by the installation (and the degree of cleaning desired). These methods include screening, air classification (for example, with cyclone separators), and "froth flotation" devices that take advantage of the different properties of coal versus mineral impurities when crushed raw coal is exposed to water. The removal of ash through coal cleaning can be up to 60 percent, with retention of 85 to 98 percent of the heating value of the coal. As only the sulfur associated with the mineral fraction of the coal is removed (and not the fraction organically bound to the coal), overall sulfur removal is only 10 to 40 percent, and varies with the coal type. The cost of coal cleaning is usually 1 to 5 US dollars per tonne. Cleaned coal burns better than raw coal, and the use of cleaned coal lowers cost for boiler maintenance, enhances the efficiency of particulate emissions control devices, and can lower coal transport costs (if cleaning is done at the mine mouth). Coal grinding, however, is energy-intensive, and some of the energy in the coal (as noted) is lost during cleaning. A number of advanced coal cleaning technologies, including advanced physical cleaning, aqueous-phase pre-treatment, selective agglomeration, and organic-phase pre-treatment (using non-aqueous solvent) are under development, but none have been widely commercialized.¹³

Short of fuel switching (as discussed below), the use of cleaned and briquetted coal may be the only way to substantially reduce SO_x emissions from domestic coal consumption (for cooking and heating) in China, North Korea, and Mongolia.

A host of oil refinery improvements can be made to reduce the sulfur contents of refined products such as gasoline, and more importantly, diesel and residual oil. These improvements are often specific to the particular refinery modified and the type of crude oil feed used, and cannot be detailed here. In some cases refinery improvements to reduce the sulfur contents of fuels may be made at the request of offshore refinery investors who would like to have the option of trading higher-quality fuels in export markets.^m

A final generic solution to reducing the sulfur content of fuels is to choose the source of the fuel. In some cases this may mean concentrating on extracting domestic low-sulfur fuel resources first, reserving the higher-sulfur resources for when refining or control technologies are more mature. In other cases, some of the countries of Northeast Asia (particularly, for example, Japan, Taiwan, and Chinese Taipei) may choose to purchase imported fuels (coal and crude oil) that are particularly low in sulfur, although higher in price than higher-sulfur alternatives.

The RAINS-Asia software system for modeling current and future SO_x emissions in the region uses price premiums (and thus costs, assuming a free market for energy commodities) of low-sulfur fuel products over higher-sulfur alternatives. These costs (in 1990 US dollars) are given in Table 2-2.¹⁴

TABLE 2-2: Price Differentials for Low-Sulfur Fuels

2.3. "Fuel-Switching" Technologies

A class of options for reducing acid gas emissions that goes a step beyond using low-sulfur fuels is switching to fuels that contain little or no sulfur. This broad class of options includes using different fuels and technologies for electricity generation, in the industrial sector, in the commercial/institutional/domestic sectors, and in the transport sector. Options for each of these applications are presented briefly below.

2.3.1. Fuel Switching Technologies for Electricity Generation

The major fuel-switching options for electricity generation in Northeast Asia include natural gas-fired technologies, nuclear electricity generation, and a variety of technologies for generation of electricity from renewable fuels.^p

Natural gas-fired electricity generation technologies are available in a wide variety of different sizes and configurations. They are available for baseload, intermediate, and peaking duty, and include both boiler and combustion turbine technologies. A particular technology, combined-cycle gas power plants, has been touted as a "bridge" between the electricity generation stock of today and a (substantially) fossil-free generation mix in the more distant future.¹⁵ Combined-cycle gas plants are commercially available, have relatively low capital costs, and are significantly more efficient than standard coal-fired power plants. As the sulfur content of natural gas is typically insignificant, switching from coal or heavy-oil-fueled generation to natural gas-fired options effectively eliminates SO_x emissions. NO_x emissions vary with the type of natural gas burner used and the type of emissions control technology applied, but are often lower (and/or less expensive to control) than emissions from coal plants.

The major concern with natural gas technologies in Northeast Asia, however, is not the cost or availability of the generation technologies that use gas, but the cost of procuring the gas itself. A number of different pipeline proposals have been made that would bring gas from the Russian Far East, Siberia, Turkmenistan, or even the Middle East to China, the Koreas, and Japan. Each of these proposals face formidable political hurdles, and each would be very expensive, on the order of 10 to 20 billion US dollars. The importation of gas to the countries of Northeast Asia as liquefied natural gas is already a common practice, but expansion of LNG imports is also not inexpensive. New LNG terminals are difficult to site, and cost on the order of one-half to one billion US dollars. LNG tankers cost on the order of a quarter-billion dollars each. The expansion of gas imports by pipeline or tanker will also require the expansion of natural gas distribution networks in the countries of the region. The ultimate questions determining the extent to which natural gas can be used to reduce acid gas emissions are: "What will the total cost of delivered gas be?", and "When will gas be widely available, particularly in China and North Korea?".

Nuclear electricity generation is used extensively in Japan, South Korea, and Chinese Taipei; several commercial-sized plants are also started operating recently in China. As nuclear plants generate electricity without fuel combustion, they produce no SO_x or NO_x during operation, although some acid gases may be emitted at other points during the nuclear fuel cycle.^q Nuclear plants have relatively low fuel costs, but capital costs are high, and non-fuel operating costs are also typically significant. In addition to costs considerations, materials handling, safety, security, waste disposal, and political factors will all play significant roles in determining the suitability of nuclear electricity generation as an acid gas reduction alternative in the region.

Renewable technologies include **hydroelectric** facilities, **wind** power generation, **solar** power generation, and various types of combustion facilities fueled with **biomass**. Hydroelectric vary in size from the fraction of a kilowatt to hundreds of kilowatts for "micro" and "mini" units, to huge

facilities with capacities of many gigawatts. Advantages of hydroelectric technology include its use of a "free" local resource (low operating costs), its lack emissions of acid gases and other air pollutants, the long life of hydro installations, and the extensive use of local materials in the construction of hydro impoundments (dams). Disadvantages of hydroelectric plants include relatively high capital costs, long lead times for design and construction, potential disruption of water resources, potential fluctuations in output from year to year and season to season due to variations in river flow, and potentially large use of land.

Solar power plants on the utility scale have thus far been limited to a number of demonstration units, mostly in developing countries. Solar power plants for utility use include solar photovoltaic and solar thermal designs. **Solar photovoltaic devices** have been fabricated from a number of different substances and have been used in progressively larger applications for over 30 years. Solar photovoltaic panels-arrays of photovoltaic "cells"-currently serve markets ranging from portable electronic devices (with only a few square centimeters of cells) to multi-megawatt power plants with thousands of square meters of panels. The advantages of solar photovoltaic systems include no-cost fuel; applicability to a wide range of different applications (including rural electrification); low maintenance requirements; portability to other sites; opportunity for local input in assembling the solar modules and support structures, and for local employment in operations and maintenance; and no acid gas emissions. The disadvantages of the technology include high costs for the photovoltaic cells themselves, and often for the support structures and wiring that complete the solar modules;^r the diurnal and intermittent (in some locations) nature of the solar resource; and the need for storage of electric energy for use when the sun is not shining (thus the dependence of photovoltaic systems performance on the performance of storage devices, such as batteries).

Solar thermal-electric systems come in several types and sizes. The main varieties of systems are¹⁶ the parabolic trough, the central receiver type, and the parabolic dish type.^s Both the parabolic trough receiver and the central receiver solar-thermal systems are generally thought of as options for utility-scale (grid connected) systems. Like photovoltaic systems, solar thermal systems generally produce no acid gases.

The conditions for solar energy development in the countries of Northeast Asia are not as good as in other regions, due to high population densities and sometimes unfavorable weather patterns, but the solar electric technologies listed above could have an impact in many areas of the region.

The use of wind-powered devices to generate electricity has been increasing dramatically in recent years in both developed and developing nations. Accelerated adoption of the technology (and increased production of wind-power systems) has translated into improved reliability and lower unit capital costs. Commercially available wind turbines for electricity generation range in size from fractions of a kilowatt to nearly the megawatt range; the most common sizes are tens to hundreds of kilowatts.¹⁷ The advantages of wind power include use of a "no-cost" local energy source; relatively low maintenance requirements; potential for land used for wind power to be used for other purposes concurrently (farming or raising livestock, for example); and relatively few environmental impacts (including no acid gas emissions). The disadvantages of wind power stem mostly from the intermittent nature of the wind resource,^t and include the difficulty and cost of assessing the wind resource at a given site; limited experience in most areas in the maintenance of wind machines; the capricious nature of the wind, which translates into variable output at any given time in most locations, even if annual average output is reliable; the need, due to the varying nature of the electricity output of wind power systems, for either energy storage of some type (see below) or back-up power systems; and the high (relative to some conventional power generation options) capital costs of the technology. A number of areas in Northeast Asia region have very promising wind regimes, including the Gobi desert area of China and Mongolia.

As biomass fuels typically have minimal sulfur content, their use in power plants of conventional or advanced types yields relatively little SO_x, although NO_x emissions still occur. One promising alternative for biomass-fired electricity generation is the biomass integrated-gasifier/gas turbine-combined cycle (BIG/GT-CC) and related technologies. These systems can have efficiencies of 33 to over 40 percent, and can use local and waste fuels. BIG/GT-CC systems have relatively low capital costs, and provide baseload capacity in unit sizes less than 100 megawatts.¹⁸ The technology for these systems is now in the commercialization phase. Although electricity generation from biomass wastes could play a significant role in Northeast Asia (to the extent that these wastes are not recycled or used as a soil amendment already), significant development of generation based on "energy crops" in the region is probably unlikely in the near-term. High population densities in the region (as well as wars and other environmental disturbances) have burdened the agricultural and forest resources of most of the countries of the region to the extent that little suitable land for biomass fuel plantations is likely to be available in the next two decades or so.^v

Table 2-3: Representative Cost Estimates for Selected Central and Off-Grid Power Generation Facilities^w

2.3.2. Fuel-Switching Options for the Industrial Sector

Opportunities for fuel-switching in the industrial sector include conversion of industrial coal-fired boilers and furnaces to natural gas (or promotion of gas-fired equipment over coal-fired equipment for new installations), use of natural gas or electricity in place of coal for specific industrial processes, and greater use of waste product-fuels (for example, in the pulp and paper industry). General use of natural gas in industrial boilers and furnaces in place of coal virtually eliminates SO_x emissions. Converting existing combustion equipment from coal to natural gas is generally relatively inexpensive, and new gas boilers are less expensive (and typically smaller in size) than new coal boilers of the same capacity. Gas use in the sector, however, is constrained by the cost and infrastructural hurdles of supplying gas that were described above in the context of fuel-switching alternatives for electricity generation.

There are a large number of industrial processes where gas and electricity can substitute for coal or other fuels. Examples of the latter include:

- Substitution of electric arc furnaces for open-hearth furnaces in the iron and steel subsector;
- Use of all-electric kilns in cement manufacturing; and
- Microwave drying of products in the pulp and paper industry.¹⁹

Of course substitution of electricity for coal, while reducing local emissions of SO_x and other pollutants, is only likely to result in reductions in acid gas emissions on the national and regional levels if the electricity used is generated with low or no emissions of acid gases.

2.3.3. Fuel-Switching Options for the Commercial/Institutional and Domestic Sectors

As in the industrial sector, the primary fuel-switching options for applications in the commercial/institutional and residential sectors in Northeast Asia are conversion of coal-fired boilers, furnaces, and appliances (including cookstoves and space heaters) to natural gas or electricity. Reduction of SO_x emissions can also be achieved by replacing coal-fired cookstoves with stoves burning kerosene or liquid petroleum gas (LPG). The latter are typically more efficient than coal stoves, and produce reduced quantities of particulate matter, carbon monoxide, and other important local pollutants. The applicability of the residential-sector options, however, depend on the availability and price of the fuel and combustion technology, as well as on the cultural factors

such as cooking preferences.

2.3.4. Fuel-Switching Options for the Transport Sector

Fuel-switching options for the transport sector include continuing the transition (in China and North Korea) from coal-steam to diesel and electric trains and water vessels. For the road passenger and freight transport subsectors, fuel-switching options include switching to compressed natural gas and electric vehicles, or modifying engines to use biofuels (ethanol and methanol derived from biomass, or oils from oilseed crops, for example). The vehicles types for which conversions will provide the greatest reduction in SO_x emissions will be those that a) now use high-sulfur diesel fuel, and b) have high annual fuel use—namely long-haul trucks and buses. Reductions in NO_x emissions through use of alternative transport fuels will generally depend on the particular engine designs compared.

2.4. Energy Efficiency Technologies and Measures

A final class of methods for reducing acid gas emissions are energy efficiency technologies and measures. This class covers a wide range of technologies spanning all of the sectors. Energy efficiency technologies reduce acid gas emissions by reducing the amount of fuel—coal, oil, gas, electricity, or biomass—needed to provide a specific energy service. When the amount of fuel required is reduced, emissions of SO_x and NO_x are reduced at least proportionately. Some examples of these technologies and measures—organized by the sectors to which they apply—are listed here. Many more measures are listed in many different compendia and databases, including publications by the World Energy Council, the World Bank, the IPCC, IIASA, IEA/OECD, the California Energy Commission, and others.²⁰ The reader is referred to these sources for more detailed descriptions and cost information on particular technologies.

2.4.1. Energy Efficiency Technologies for the Utility Sector

Energy-efficiency technologies for the utility sector include electricity generation options with high conversion efficiencies, transmission and distribution improvements, and cogeneration. Two of the most attractive electricity generation technologies available now (or shortly) are coal-fired integrated gasification-combined cycle (IGCC) and gas- or oil-fired combined-cycle plants. These options have been described previously. Even higher conversion efficiencies are promised by *fuel cell* technologies. Fuel cells, which convert chemical energy to electrical energy without combustion, can operate on gaseous fuels (including natural gas, hydrogen, and producer gas from coal or biomass). Prototype fuel cell modules have been built that are approaching utility scale. Development of this technology bears watching, however, as fuel cells promise low emissions of NO_x and other pollutants, compact size, and very high energy efficiencies of energy conversion.^y

Reductions in electricity *transmission and distribution* (T&D) losses can help to provide more electricity without increasing fuel consumption. These measures are particularly applicable in China and especially in North Korea, where the T&D system has many serious problems and losses are high.^{21, z} Electricity T&D improvements would include better system control facilities, improved transformers, the addition of capacitance to the system, and other measures to improve power factors and reduce voltage fluctuations.²²

Cogeneration of heat and power is used in the utility sector in many countries, and has a long history. Heat is distributed for use as process heat in industries and/or for district heating of homes and other buildings. This is likely to be highly economic in many of the countries of Northeast Asia, where power stations are often close to cities, population densities are high, and wintertime space heating needs are significant.

2.4.2. Energy-efficiency Options for the Industrial Sector

The options for reducing energy consumption-and related emissions of acid gases-in the industrial sector are many and varied. Options for specific industrial subsectors are listed below, along with a list of more generic improvements useful in many different types of industries.

Specific options for the *Iron and Steel* industry include the continued replacement of open-hearth furnaces with basic oxygen furnaces (which can save 1 to 3 GJ per tonne of steel-about 5 to 15 percent relative to current OECD practice); increasing the use of scrap steel; the use of power recovery turbines on blast furnaces; the use of continuous casting of steel products (as opposed to ingot casting, in which steel ingots must be re-melted to produce products in their final form), and rolling of steel before it has cooled.

Options for the *Chemicals* manufacturing industries include the use of improved catalysts for key types of chemical reaction; improvements in distillation equipment; improvements in gas turbine efficiency; expanded process integration to conserve heat generated during reactions; insulating product pipelines to reduce heat losses, and use of membrane technologies for separation of reactants.

In the *Refining* industry (which will become increasingly important as China's consumption of petroleum fuels increases), energy efficiency options include pre-heating of crude oil feedstocks; use of reflux-overhead vapor compression; use of mechanical vacuum pumps; integration of heat use between distillation units; and improved catalysts.

In the *Pulp and Paper* subsector, options include continuous pulp digesters, alternative chemical and chemi-mechanical pulping processes, and alcohol-based solvent pulping; oxygen or ozone bleaching and delignification; chemical recovery, including freeze concentration or gasification of black liquor; wet-pressing of paper products, high-consistency forming, impulse drying, and microwave drying.

The *Cement* industry is an important subsector for many of the economies of Northeast Asia. Efficiency options here include measures to improve the efficiency of materials preparation such as waste-heat drying, differential grinding of limestone and clay, fluidized-bed drying with low-grade fuels; kiln combustion system improvements and modifications to reduce heat loss, the use of waste heat from product coolers, and the use of fluidized-bed kilns and all-electric or hybrid kilns; the blending cements so as to reduce the energy required for production; and modified product grinding equipment, including better control of particle size (for example, high-efficiency air classifiers.²³ Modifications in the way that buildings and other structures are constructed could save on use and wastage of cement and steel (as well as making the buildings themselves more efficient).

Generic options important in many (if not most) industrial subsectors in Northeast Asia include:

- The use of heat recovery (in many different sub-processes) for steam generation, and pre-heating of combustion air, including the use of ceramic recuperators
- Fuel-switching to natural gas (where available)
- Improved industrial boilers and furnaces, including improved fuel pre-treatment, using better refractory materials (special ceramics used as, for example, furnace linings) that last longer and have better insulating properties, computerized boiler control, and natural gas pulse-combustion boilers
- Modifications to reduce friction in piping, valves, and conveyance systems
- Using harder, longer lasting materials in cutting and grinding applications.

- Expanded use of cogeneration of heat and power
- High-efficiency electric motors and electronic adjustable-speed drive systems
- High-efficiency lighting systems
- Computerized process optimization, control, energy management, and environmental management (that is, pollution emission sensing and control) systems
- Good housekeeping and minimization of materials waste, including pre- and post-consumer recycling of raw materials.

2.4.3. Commercial/Public/Institutional and Domestic Sector Options

Options for improving energy efficiency in the commercial/public/institutional sectors of the countries of Northeast Asia primarily address energy use in buildings. Options for the reduction of coal, gas, and electricity use include:

- *Boiler and furnace improvements*, including hardware modifications such as burner upgrading (or replacement) and addition of control systems, and "human" measures such as improved operator training to increase the efficiency of operation and maintenance.
- High-efficiency *lighting* systems, including high-efficiency fluorescent and compact fluorescent bulbs, reflectors, and ballasts.
- The use of high-efficiency *air conditioning* equipment, including improved *motors and drive* systems (applicable to many other types of equipment as well), and improved compressors.^{aa}
- *Building envelope* improvements such as improved insulation, weatherstripping, and windows.
- The use of *cogeneration* for larger institutional users such as hospitals and colleges.
- Higher-efficiency *domestic appliances*, including refrigerators, room air conditioners, and clothes washers.²⁴

2.4.4. Energy Efficiency Options in the Transport Sector

The transport sector is likely to command much larger shares of the national energy budget in China and North Korea as those countries, develop, following the pattern of Japan, South Korea, and Chinese Taipei. Energy-efficiency options in the transport sector can be separated into personal passenger transport efficiency options, mass transit efficiency improvements, freight transport efficiency options, and "mode-shifting".

For personal passenger transport, a wide variety of engine and transmission modifications, modifications to reduce vehicle weight, and changes to reduce air and rolling friction have been proposed²⁵, ²⁶. These changes have made it possible to reduce the energy intensity of automobiles by a factor of two or more compared to present conditions.^{bb} The impact of these types of technologies could be huge in Northeast Asia, due primarily to the explosive growth in the Chinese transport sector. China's stock of small passenger vehicles (not including motorcycles) increased more than two-fold between 1987 and 1992. If that rate of growth is sustained, there could be 100 million small passenger vehicles in China in 20 years-and even at that rate China would have significantly fewer vehicles per capita than South Korea does today,^{cc} and less than a fifth as many vehicles per capita as are currently in the United States. Improving the energy efficiency of the average Chinese vehicle by 50 percent (by adopting technologies for high efficiency vehicles now, as the Chinese auto industry builds productive capacity) would translate into a huge reduction in future energy use and

NOx emissions. Assuming 100 million passenger vehicles, 15,000 km per vehicle/year, and a decrease in energy intensity from the present 10 (or so) liters per 100 km to 5 liters per 100 km yields a savings in energy consumption of roughly 100 million tonnes of oil per year. (By way of comparison, China's total oil production in 1994 was slightly under 150 million tonnes.) This example is certainly not intended to suggest that China will, can, or should increase its passenger car fleet in this way; it is intended only to point out the potential for energy efficiency improvements in the sector, particularly if current trends hold.

For mass transit of passengers, substantial efficiency improvements in bus engines and transmissions are possible. Traffic flow modifications, such as dedicated bus lanes, are ways of increasing the efficiency of bus transit without changing equipment. Rail transport efficiencies can be increased by improving maintenance of trains and tracks (including wheel lubrication), eliminating reducing constrictions to traffic flow ("bottlenecks") where trains must slow down or stop outside of stations, using higher-horsepower engines, optimizing train size and traffic flow (including computer control).²⁷ Opportunities for rail sector improvements that focus on infrastructure are large in both China and North Korea, both of which have rail systems that are currently overburdened. These improvements in rail efficiency are also applicable to rail freight transport systems.

Freight transport by road can be made more efficient through a number of different measures, including engine-drive-train modifications^{dd} (some of which are also applicable to agricultural-sector equipment), improved aerodynamics, construction of improved roads,^{ee} optimizing the distribution of truck sizes (tonnes of freight capacity per unit) in the truck fleets of China and North Korea, moving toward use of more diesel and less gasoline trucks (China), and moving freight via rail rather than road wherever practical. Improving the octane rating (a measure of fuel quality) of gasoline produced by refineries is another method of reducing fuel consumption by cars and trucks.

A final category of transportation energy efficiency measures considered here is the broad category of mode-shifting. Mode-shifting includes policies that encourage the development of certain transport subsectors-such as urban and inter-city mass transit by train and bus-while discouraging other options such as low-occupancy use of passenger cars. Other possibilities for countries in which urban and peri-urban areas are rapidly developing include planning of neighborhoods and transit systems so as to maximize convenience for pedestrian and bicycle traffic, as well as access to efficient mass-transit systems.

3. Comparison of Technologies-Estimated Cost-Effectiveness for Emissions Reduction

The comparison of the cost-effectiveness of the sometimes vastly different technologies for reducing acid gas emissions discussed in the previous section is subject to (at least) two methodological difficulties. First, technologies presented above are geared to provide different types of energy services, and thus cannot be compared side-by-side. Second, substantial uncertainties exist in many of the parameters that must be used to evaluate the technologies, including variations in current cost and performance across applications in different locations (and with different fuels), and in terms of future trends in cost and performance. The general approach adopted here is to evaluate each measure or type of measure relative to some reference technology that provides that same energy service-producing a kilowatt-hour of power, manufacturing a tonne of steel, cooking a meal, or moving a tonne of freight from one place to another. The difference in cost between the acid gas reduction technology or measure and the reference technology is then divided by the difference in SOx or NOx emissions between the two alternatives to provide a measure (albeit an incomplete one) of the cost-effectiveness of acid gas reduction. For the sake of simplicity, the attempt here is to focus

on a small set of technologies and measures applicable to China, using China-specific costs and efficiencies (where available) for reference technologies and measures, and Chinese fuel prices and fuel specifications, including sulfur content. The assumptions used in preparing these estimates, plus the results of sensitivity analyses (in addition to those presented below) are contained in detail in Annex 2 to this paper; some key assumptions are listed below.

3.1. Technologies Compared, and Key Assumptions

In estimating the cost per unit of acid gas emissions reduced or avoided, a selection of technologies were chosen in each of five categories: "End-of-pipe" SO_x and NO_x emissions controls, burner modifications, coal cleaning and refinery upgrades, fuel-switching alternatives, and energy-efficiency measures. 1990 US dollars were used as the currency unit throughout, and real discount rates of 10 percent (utility and industrial sectors) and 12 percent (other sectors) were used to annualize capital costs. In most instances, average coal prices were assumed to be approximately \$1.33 per GJ (although Chinese coal prices vary significantly from place to place, sector to sector, and over time), and the base cost of liquefied natural gas was assumed to be \$4.00 per GJ at the dock. The average sulfur content of Chinese coal, estimated from RAINS-Asia results (and thus a weighted average over all Chinese coal use) was taken to be 1.04 percent.

3.2. Methods of Comparison

The evaluation of the cost-effectiveness of these technologies for acid gas emissions reduction has necessarily involved a considerable number of assumption. These are detailed in the workpapers provided as Annex 2. In some cases, sensitivity analyses have been performed to demonstrate the impact of changes in key and uncertain parameters. Some of the key approaches used for the five groups of technologies were as follows:

- For "*End-of-pipe*" technologies, most of the options listed in Section 2.1.1 were compared, in retrofit and new applications, with existing and new (respectively) coal plants without SO_x and/or NO_x controls. New coal plants were assumed to have a net heat rate (after accounting for in-plant use of electricity) of 10.29 MJ/kWh, corresponding to an efficiency of about 35 percent. Where a range of cost or performance estimates were used, a mid-range value was typically chosen. The one transport sector technology addressed, 3-way catalytic converters, was evaluated relative to a similar vehicle without a converter.
- All of the technologies in the *burner modification* category were applied to utility coal combustion, relative to standard existing or new coal plants.
- The options in the *fuel improvement* group include coal cleaning-evaluated at a range of costs per tonne processed and removal efficiencies-and several low-sulfur coal and petroleum fuel options. Prices and related costs per tonne of sulfur removed for the low-sulfur fuels relative to higher-sulfur varieties were taken from the database for the RAIN-Asia modeling system.
- The *fuel-switching* options considered include several renewable and non-renewable electric utility generation options-all evaluated relative to a standard new coal plant-and switching from coal-fired domestic cooking stoves to gas-fired stoves, with pipeline LNG as the fuel.
- Finally, a number of different *energy-efficiency* options were evaluated for the utility, industrial, commercial/public/institutional (buildings) and domestic sectors, and the transport sector. Here each option was evaluate relative to either an existing technology to be retrofitted (utility boilers, for example) or a standard new technology to be improved upon (such as automobiles).

In preparing the comparisons, an attempt was made to evaluate the acid gas control or reduction

technology on an even footing with reference alternative technologies. This included (for example) recognizing that some of the technologies save fuel, or require more fuel, than the baseline technologies against which they were measured, and accounting for this difference in fuel use as a credit or cost to be factored in with differential capital, O&M, and other costs.

3.3. Cost-Effectiveness Results

The acid gas emissions reduction measures presented above are, as stressed previously, only examples of the many different options theoretically available to China and to other countries in Northeast Asia. For energy-efficiency options in particular, this analysis has only barely touch the "tip of the iceberg" of the many options available. While many of the comparisons necessarily are over-simplified, they serve to indicate the pattern of emissions reduction costs encountered among the various classes of measures.

Table 3-1 presents the results of the cost-effectiveness evaluations detailed in Annex 2. Three yardsticks of cost-effectiveness are used. The first two, respectively, are simply the relative net cost of emissions reduction expressed as dollars per tonne of SO_x and NO_x. These costs are not additive; they can be thought of as the costs one would want to compare if one were interested in reduction of sulfur oxides or nitrogen oxides separately. These metrics are less adequate if one is interested in aggregate acid gas emissions reduction, and wishes to compare across types of options suitable for reducing SO_x emissions, NO_x emissions, or both. The right-hand column of Table 3-1 represents an attempt to evaluate reduction of the two emissions as a single index. Taking into account the relative equivalents of acid formed when SO_x and NO_x react with water (two and one per molecule, respectively), plus the relative molecular weights of SO_x and NO_x, the index is expressed in terms of dollars per thousand moles (kmol) of acid precursor emitted. This index is far from perfect, in large part because SO_x and NO_x do not behave identically in the atmosphere.^{ff} Nonetheless, it is one way of evaluating technologies that substantially reduce the emissions of both species-energy-efficiency technologies, for example-next to technologies that remove primarily one of the two acid gases.

TABLE 3-1

3.4. Discussion of Results

As shown in Table 3-1, the measures evaluated span a wide range of emissions reduction costs, with values for SO_x reduction in the range of -\$4,400 to +\$5,000 per tonne, NO_x reduction costs of -\$6,300 to +\$7,500 per tonne, and overall reduction in the range from -\$72 to +\$108 per kmol acid equivalent.^{gg} Here, a negative control cost implies (since all measures result in emissions reduction) that the net cost of applying the measure is negative, that is, applying the measure results in a cost savings even before its environmental benefits are considered.

Comparing results between categories of measures, end-of-pipe controls tend to be less cost-effective than burner modifications or coal cleaning, but refinery upgrades to reduce the sulfur content of vehicle fuels are relatively expensive. Switching to gas or to wind-generated power results in acid gas emissions reductions that are similar in cost per kmol of acid to burner modifications. Energy efficiency options provide the most cost-effective means of reducing acid gas emissions, with many of the examples shown having low or negative costs of emissions reduction per unit acid gas. This is particularly true if a credit for avoided generation capacity (that is, for avoided capital and fixed operating and maintenance costs) is provided for those measures that save electricity, in addition to the credit for avoided fuel use in electricity generation.

Several caveats should be kept in mind when reviewing the results above and in Annex 2:

- The analysis as shown depends on a number of assumptions, many taken from analysis done by other workers-where possible, including cost information from China-based analyses-but some no better than rough estimates. In some instances, the results of the analysis are quite sensitive to relatively small changes in input parameters. Many of these analyses could be refined with additional local data from the countries in Northeast Asia.
- Not all of the benefits, and probably not all of the costs, of some options have been captured. Many changes in industrial processes have the effect of reducing SO_x and/or NO_x emissions, but may be undertaken for reasons to do with enhanced profitability, reduced material use, meeting environmental standards for other effluents, or other reasons. For example, moving to continuous casting in steel-making dramatically improves the value of the product in addition to saving energy. This added value is not, however included in the cost calculation. Similarly, other environmental benefits (greenhouse gas reduction, for example) accrue to some of the technologies but are not captured in the analysis, while others (for example, FGD systems) have environmental costs (such as solid waste disposal) that have not been rigorously included.
- Some of the technical measures-boiler efficiency improvements and automotive engine improvements are cases in point-will likely reduce emissions (NO_x, especially) by a fraction greater than the fraction of fuel saved simply by allowing better control of combustion.
- In many cases the costs and benefits, as well as important parameters of the analysis such as fuel prices and fuel sulfur content, will vary considerably from place to place and application to application. An analysis like this can only hope to indicate general trends and patterns-location-specific project analyses are required to determine an optimal investment plan for acid gas emissions reduction.
- Similarly, this analysis has not attempted to evaluate the potential of measures such as urban and suburban planning to minimize the need for transport, materials recycling, and reduction of materials use and waste in manufacturing. Each of these (and many other similar measures) would reduce acid gas emissions and address numerous other environmental problems at the same time.
- The apparent attractiveness of energy-efficiency measures from a cost-of-emissions-reduction perspective was noted earlier. Why not, then, focus on these measures to the exclusion of other options? One key reason not to exclude other options, including burner modification and end-of-pipe control, has to do with the likely rapid future growth of the economies of the region, particularly China, South Korea, and potentially North Korea. This growth means that reduction in energy use through efficiency measures may slow, but will likely not stop, the growth in the need for new energy infrastructure, including power plants, and as a consequence reductions in energy use will not necessarily mean that older, dirtier plants run less or are retired. An effort to reduce emissions from existing facilities, as well as building new facilities to higher environmental standards, is therefore in order.
- Conversely, however, only a fraction of the SO_x and NO_x produced in the region comes from the "Large Point Source" group of facilities that are arguably best suited to end-of-pipe emissions control. This means that an effective effort to reduce acid gas emissions in the region must focus not only on these "big ticket" facilities, both existing and new, but also on the much smaller-sized equipment in the industrial, commercial, and transport sectors that produce, and will continue to produce, the lion's share of acid gas emissions.

4. Promising Areas and Initiatives for US-Japan and Regional Collaboration

Coal cleaning, burner modifications, switching to natural gas and wind power generation, and (particularly) energy efficiency improvements represent attractive options for the countries of the region to reduce acid gas emissions. As acid rain is a regional problem in Northeast Asia-and is

likely to become an increasingly important concern-regional coordination and support will play an important role in catalyzing the uptake of acid rain reduction measures.

4.1. Other Considerations in Choosing Acid Gas Emissions Reduction Measures

Before considering regional initiatives to aid in reducing acid gas emissions, it is necessary to review some of the practical considerations that can limit the uptake of certain measures and technologies by the countries of the region. These include:

- Are suppliers and vendors of the technology available in all of the countries of the region? For example, certain technologies may not be available to North Korea due to its current political isolation.
- Which measures are suitable for local manufacture, particularly in China and North Korea? Which will require inputs from the more developed nations of the region (and elsewhere) for the foreseeable future?
- Which technologies require a high foreign exchange input, and where could those funds come from in countries strapped for hard currency?
- Which technologies and measures will be socially acceptable, and fit within existing regulations and economic patterns?
- Some technologies may not be applicable in some areas due to resource or land-use constraints.

4.2. Potential Types of Regional Collaboration

There are a number of generic strategies that could be promoted and/or facilitated by the regional international community to help to implement some of the emissions reduction options described in this paper. These strategies could include^{hh} (but are certainly not limited to):

- *Provide Information and General Training to Government Officials.* Getting initiatives such as industrial energy efficiency, and utility boiler emissions control programs, and fuel switching/renewable energy initiatives off the ground in the countries of the region (again, particularly China and North Korea) will be impossible without top officials embracing the concept. Consequently, the advantages and local/international opportunities provided by the measures and technologies covered here must be presented to top officials in a manner that is both forceful and forthright.
- *Provide Specific Information and Training to Local Actors.* Training of a very specific and practical nature must be provided to personnel at the local level. Examples here are factory energy plant managers, boiler operators in residential and commercial buildings, power plant and heating system operators, and new job classifications such as energy-efficiency and pollution control equipment installers, energy auditors, and environmental officials.
- *Encourage the Implementation and Enforcement of Energy and Environmental Standards.* Although the countries of Northeast Asia uniformly have general policies supporting energy efficiency and environmental sustainability, not all have well-defined, quantitative set of standards in place to codify these general policies. Where standards exist, furthermore, they may not be stringent enough to satisfy regional needs for acid gas emissions reduction. Once standards are set, it will be necessary to create the capability to enforce them by recruiting and training enforcement personnel and supplying them with the tools necessary to do their job (testing equipment and adequately equipped labs, for example) and the high-level administrative support needed for credible implementation of sanctions. Setting up these regulations and support structures is an area where international assistance may be valuable in some instance.

- *Establish Programs of Grants and Concessional Loans.* Experience in China has shown that such a program in itself can have a significant positive impact in overall sectoral energy efficiency.²⁸ The benefits of institutionalizing support for pollution control and energy efficiency, however, would go beyond those obtained through the various individual projects themselves. Creating government agencies or corporations with their own budgets would signal a strong commitment to acid gas emissions reduction on the part of the government, and would create a constituency within official circles for promoting environmental.ⁱⁱ Moreover, by establishing a pool of funds for which government ministries, sectors, and/or individual enterprises could compete, it would stimulate at all levels awareness of the potential, methods, and technologies for reducing acid gas emissions.
- *Modify Existing Incentives for Energy Efficiency and Pollution Prevention.* Depending on the structure of a country's economy, it may be possible to implement administrative measures (in non- or semi-market economies) or efficiency regulations and inducements (in market economies) that will help to spur the incorporation of appropriate technologies in new and existing infrastructure.
- *Promote Joint Ventures and Licensing Agreements.* The growth in the need for pollution control and energy-efficiency equipment, could be met by domestic production through joint ventures and licensing agreements between governmental or private organizations in China and North Korea and foreign firms (especially, for Northeast Asia, South Korea, Japan, and the U.S.) with the necessary expertise to produce the needed equipment. For example, a wide variety of efficient industrial equipment and controls—including adjustable speed drives, higher-efficiency electric motors, and improved industrial boilers—have already been introduced to China through commercial channels and are being or will be manufactured there.

4.3. Specific United States-Japan and Regional Initiatives Useful in Starting Collaborations to Reduce Regional Emissions

A variety of opportunities exist for the United States and Japan to contribute to the reduction of regional acid gas emissions in the ways described above (and others). In many cases, existing bilateral or multi-lateral programs or initiatives could be built upon and strengthened. Some potential starting points for United States-Japan and regional collaboration in reducing acid gas emissions in Northeast Asia might include:

- *Create a clearinghouse for summary and detailed information on acid gas reduction measures.* Access to up-to-date information on the types of technologies and measures available for acid gas reduction (including their costs, benefits, advantages, and disadvantages), how to contact technology suppliers, and existing experience in the region with various measures and technologies would help to facilitate the implementation of acid gas reduction measures. The United States and Japan (as well as other regional governments) could support the formation of such a clearinghouse, perhaps under the structure already set up by the APEC Energy Working Group for energy modeling activities. This effort should build on the substantial body of information already available (and noted previously in this document). The clearinghouse could also provide support, software, and guidance for more detailed country- (or sub-country) level assessments of opportunities for acid gas reduction measures. The clearinghouse would thus play a role in helping to provide information to decisionmakers and local actors, as well as in catalyzing technology transfer and the formation of joint ventures.
- *Create a trade liaison to promote the transfer of appropriate technologies.* The United States and Japan could set up a specific trade office designed to facilitate the process of linking firms with emissions reduction technologies to sell or license with firms and other organizations in the region that need the technologies. The liaison office could help to provide contact information, translation, dispute mediation, and assistance in obtaining financing to potential trading partners, thus

expediting the process of forging joint ventures and licensing arrangements.

- *Promote and sponsor study tours and in-country training activities.* The United States and Japan could sponsor study tours by appropriate Chinese and North Korean officials and industrial representatives for the purpose of learning methods of environmental management and acid gas emissions reduction. This should be augmented by in-country training activities involving local actors (ideally, those involved in day-to-day environmental management decisionmaking) and regional and international experts.
- *Promote and assist in applications that demonstrate promising technologies.* This would include providing equipment and expertise to do pre- and post-project monitoring of acid gas emissions. Assisting in technology demonstration projects would help to open the doors for technology transfer arrangements and to develop technical and regulatory expertise in the host country. Such assistance could also include providing seed money for grant and loan programs operated primarily by the host country.
- *Help to fund and organize regulatory infrastructure in China and North Korea.* The United States and Japan could help to fund, through grants and loans, the establishment and equipping of laboratories and other facilities necessary for the enforcement of environmental and energy-efficiency regulations, including regulations on acid gas emissions. This is a way of assuring that the regulatory infrastructure (including rule-making, monitoring, and enforcement) is in place to move forward with acid gas emissions reduction in China and the DPRK.

4.4. Technology Transfer Issues

As indicated throughout this paper, technologies do exist that, if widely and promptly applied in Northeast Asia, could go a long way toward reducing emissions of acid gases (and their subsequent impacts) in the region. Additional technologies are in the demonstration and commercialization phase. Transferring these technologies to the countries that need them in a manner that is both affordable and agreeable to all parties will likely be the limiting step in their adoption. In technology transfer, issues such as the political isolation of North Korea from potential trading partners (notably the United States and South Korea), technology patent conflicts between industrialized nations and China, and the practice of transferring sub-optimal or outdated technologies^j could, if not resolved, slow down the rate at which appropriate technologies are transferred. Cooperation between the United States, Japan, and the other countries of the region to resolve these sorts of issues will help to spur the implementation of acid gas emissions reduction measures.

In order for technology transfer to be effective on an ongoing basis, care must be taken to supply not only the "hardware"-provide and install the technology products, but also the human "software" that will assure that the technologies transferred continue to provide acid gas reductions at an optimal level for years to come. This means that any technology transfer arrangement must include a strong component of training of local actors (as noted above), including plant operators, installers, maintenance personnel, and regulatory personnel. These people must also be provided, on an ongoing basis, with sufficient tools, materials, information, and access to advanced training to allow them to use the technologies properly and to adapt and improve them to suit local conditions. Technology transfer projects in Northeast Asia should therefore explicitly include resources for initial and ongoing training, as well as training of trainers,^{kk} to assure that the technology transferred is used and spread in the host nation.

- a. "pH" is a measure of the acidity (hydrogen ion concentration) in a substance. The pH scale runs from 1 to 14, with 1 being very acid, 7 being neutral (the pH of pure water), and 14 being very alkaline. As the pH scale is a logarithmic one, the acidity of a sample with pH 3 (for example), is ten times that of a sample with a pH of 4. A normal pH for rainwater is about 5.6.
- b. "Area sources" denotes emissions of sulfur oxides from sources other than power plants, large industrial facilities, and other "Large point sources".
- c. Figures in this table were drawn from Hayes and Zarsky (1995) and from a table provided by David Streets of Argonne National Laboratory (see earlier paper in this series). Both sources used results from the RAINS-Asia project. Return to Table 1.1
- d. Zero values in this column for Mongolia and (particularly) for North Korea probably reflects a lack of information about the sources of sulfur oxides in those countries, rather than the actual lack of large point sources. Large point sources, as defined for the RAINS-Asia model, are identified large fossil-fuel-fired power plants and industrial sources that have electricity generation capacity of greater than 500 MW, have fuel input capacity of greater than 1500 MW (thermal), produce greater than 20,000 tonnes of SO_x per year, or produce greater than 5000 tonnes of NO_x per year. Return to Table 1.1
- e. The sensitivity of soils to acidification does not, of course, relay the complete picture of where acid precipitation could cause the most damage. Vegetation types, topography, and land use also play important roles. For example, areas with soil types that are most sensitive to acidification may not (and often do not) have vegetation that is similarly at risk.
- f. Fabric filters for utility and large industrial use are usually an array of bags, made out of fiberglass or other heat-stable material, mounted in a metal housing through which exhaust gases pass. This technology is also known as the "baghouse".
- g. Electrostatic precipitation is a frequently-used technology for controlling emissions of particulate matter. ESP units use electrically charged plates to collect particulate matter from the flue gas.
- h. Circumstances that would favor dispersed generation might include difficulty in siting large power plants; deregulation of gas pricing (Japan, South Korea, Chinese Taipei) leading (potentially) to lower gas prices for large users; difficulty in securing reliable power supplies from the central grid (China, North Korea); or difficulties in attracting private financing for larger power projects (China).
- i. NO_x formation during combustion is a function of combustion temperature. The higher the combustion temperature (generally), the more NO_x will be formed.
- j. Coal gasification technologies, in fact, pre-date the use of natural gas: piped gas used in homes and businesses in many US and European cities was initially "coal gas".
- k. Options for gas cleaning include cooling the gas before cleaning, which reduces efficiency, and hot-gas cleaning, in which gas is cleaned at high temperatures and pressures. The latter technology results in improved IGCC efficiency, but is still in the early demonstration phase.
- l. Control technologies, including the application of computerized control and sensor systems, help to provide improved efficiency as well as optimal environmental performance in industrial and utility boilers.
- m. This is not likely, however, to be the case for China, at least in the next few years. Although a

number of investors have expressed interest in financing and operating refineries in China, the Chinese government has thus far restricted access by foreign firms to the Chinese retail market, which has made refinery investment in China much less attractive to offshore investors. In the next decade or so, however, China will have to face the necessity of using a higher-sulfur crude slate (including more Middle East imports) in its refineries (as domestic demand outstrips production, and the availability of Asian low-sulfur crudes declines), and will at that time likely need foreign assistance to build/modify and operate refineries that can handle the more corrosive high-sulfur input. (David Fridley, Lawrence Berkeley National Laboratory, personal communication.)

n. Dollars per gigajoule of fuel energy and per percent of sulfur reduced compared to the original fuel. One gigajoule (GJ) is one billion (10⁹) joules. For purposes of comparison, 34 kg of (standard) coal or 31 liters of gasoline have an energy content of about one gigajoule. Return to Table 2.2

o. Calculated (by the original source) assuming that 5 percent of fuel sulfur remains in the ash after combustion. Return to Table 2.2

p. Oil-fired electricity generation technologies are already used in Northeast Asia, but the working assumption here is that large-scale replacement of coal-fired generation with new oil-fired generation is unlikely due (in part) to the importance of using oil in other sectors.

q. As reactor fuel for the countries of Northeast Asia comes, to a large extent, from other regions, SO_x and NO_x emissions from nuclear fuel cycle activities actually taking place in the region are probably minimal.

r. For most developing countries, acquiring these components will involve the use of foreign exchange funds, as most photovoltaic cells must be imported. It should be noted that there is significant promise, however, for cost reduction in solar photovoltaic cells, but attention must also be paid to standardizing and reducing the costs of the "balance-of-system" components, including the modules in which the cells are embedded, wiring harnesses, electricity storage systems, support structures, and mounting devices and techniques. This need was noted by the APEC Energy Data Expert Group in Basic Guidelines for New Energy Introduction, prepared by the Japanese Government for the "Council of Ministers for the Promotion of Comprehensive Energy Measures", December 16, 1994.

s. One variant of this design with promise for rural electrification applications uses a Stirling-cycle engine to convert heat into mechanical motion. Stirling engines promise low maintenance, but the technology is not yet fully commercialized.

t. Grids that include wind generators must make provision for this variability by providing either back-up generation resources (such as inexpensive gas-fired resources) or energy storage of some type.

u. The forest resources of the Korean peninsula, for example, were substantially destroyed before and during the Korean War.

v. Reforestation programs are active in many of the countries of the region, including both China and North Korea, but wood from the reforested areas is more likely to go toward the needs of the pulp and paper and construction industries, rather than to fuel power plants.

w. Costs and efficiencies for most options from page 67 of Johansson, T.B., H. Kelly, A.K.N. Reddy, and R.H. Williams, "Renewable Fuels and Electricity for a Growing World: Defining and Achieving the Potential", Chapter 1 in Renewable Energy: Sources for Fuels and Electricity, edited by T.B.

Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams, Island Press, Washington, D.C., USA. Note that these costs represent a blend of currently available technology and projections for technologies now in the commercialization phase. As a consequence, the cost figures shown here should be taken as representative estimates only. Costs for biomass gasifiers from Stassen, H.E., (1995), *Small-Scale Biomass Gasifiers for Heat and Power: A Global Review*, World Bank Technical Paper no. 296, Energy Series, The World Bank, Washington, D.C., USA. Costs for diesels are from Ramani, K.V., (1993), *The Asian Development Bank's Approach to Rural Energy Development in the 1990's*, Draft policy paper. Costs for hydro are from Shanker, A. and G.G. Krause, "Decentralized Small Scale Power Systems", Chapter 4-3 in Saunier, G. editor (1992), *Rural Electrification Guidebook For Asia and the Pacific*, Asian Institute of Technology, Bangkok, Thailand, page 254, and from Zhi Xiaozhang and Deng Bingli, *Small "Hydro Power Development for Rural Electrification in China"*, Chapter 5-5, same volume.

x. Estimates for the costs of nuclear generating facilities are from Page 18 of Wu Changlun et al, editors, *China: Issues and Options in Greenhouse Gas Control, Alternative Energy Supply Options to Substitute for Carbon Intensive Fuels*, Subreport Number 5. The World Bank, Industry and Energy Division, Washington, D.C., USA. December 1994. Estimates of fixed O&M costs are based on a range of different estimates provided. Variable O&M costs are for fuel only (quoted in the source at 440 Yuan/kW, 4.7 Yuan/\$, and 6000 hours of operation per year.

y. For example, Ramani (Ramani, R.V., "Approach to Rural Electrification", Chapter 5 in *Rural Energy Planning: A Government-Enabled Market-Based Approach*, edited by K.V. Ramani, A.K.N. Reddy, and M.N. Islam, Asian and Pacific Development Centre, Kuala Lumpur, Malaysia. 1995), page 178 cites the possibility of 57 percent overall efficiency for coal plants using integrated gasifier/fuel cell systems by the year 2025.

z. DPRK estimates place transmission and distribution losses of electricity at 16 percent of net generation (electricity leaving the power plant), although this figure may well be low.

aa. The use of air conditioning in non-residential buildings is likely to become much more important as development in China (in particular) continues.

bb. The environmental group Greenpeace recently commissioned the construction of a car, based on a popular European subcompact model (the "Twingo"), that achieved fuel consumption of between 3.26 and 3.75 liters per 100 km, about half of the 6.7 liters per 100 km consumed by the original vehicle.

cc. The motor vehicle fleet in South Korea as of 1995 included just over six million passenger cars and 1.65 million "private" (non-commercial) trucks. With 44.85 million people as of 1995, this works out to about one passenger car per 7.5 people, or about one car or truck per 6 persons (Korea Energy Economics Institute (KEEI), *Yearbook of Energy Statistics*, 1996. KEEI, Seoul, Korea, 1996.)

dd. The truck fleet in North Korea, for example, is based on a 2.5 tonne truck of 1950's era Soviet design that is notoriously inefficient.

ee. Note, however that construction of improved roads is a double-edged sword, as new superhighways-while allowing higher efficiencies--typically attract traffic and spur increased use of motor vehicles.

ff. The residence time of NO_x in the atmosphere, if it does not combine with water, is substantially shorter than SO_x-on the order of a day or less versus several days. As a consequence, it may not be transported as far as SO_x in its dry form. In addition, ammonia (NH₃) complicates the relative

transport and deposition of SO_x and NO_x through its interactions with both molecules, and with water vapor and droplets. This may be important in Northeast Asia, where industrial and agricultural sources of ammonia (rice paddies are an example) are probably substantial. (Dr. Charles Blanchard, Envair, Albany, CA, USA; personal communication).

gg. The very high cost per tonne sulfur oxide emissions shown for SCR technology is omitted from this range. SCR removes a small amount of SO_x in the process of NO_x emissions reduction.

hh. Adapted from Von Hippel and Hayes, 1995.

ii. Bringing together a large number of relatively small-scale demand side projects under the umbrella of a single program, for example, may also go some way towards mitigating the bias towards large-scale projects.

jj. The export of used engines and vehicles from Japan to other countries in the region is an example here.

kk. That is, training of local experts who can then proceed to train their compatriots in the use of the technology.

1. Hayes, P., and L. Zarsky, "Acid Rain in a Regional Context", in Science and Technology Policy Institute and the United Nations University's Joint Seminar on "The Role of Science and Technology in Promoting Environmentally Sustainable Development. Science and Technology Policy Institute and The United Nations University, Seoul, Republic of Korea, June, 1995.

2. Hamburger, J., China's Energy and Environment in the Roaring Nineties: A Policy Primer. Prepared for the United States Environmental Protection Agency and the United States Department of Energy by Pacific Northwest Laboratories Advanced International Studies Unit, Washington D.C., USA. 1995.

3. Hayes and Zarsky, *ibid*.

4. Tavoulareas, E.S., and J-P. Charpentier, Clean Coal Technologies for Developing Countries. World Bank Technical Paper Number 286, The World Bank, Washington D.C., USA. 1995. This volume is the source for much of the information on utility and industrial technologies presented in section 2.1 and 2.2.

5. United States Environmental Protection Agency (USEPA), Alternative Control Techniques Document-Nox Emissions From Cement Manufacturing. Emission Standards Division, United States Environmental Protection Agency, Office of Air and Radiation, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, USA. March 1994. Report number EPA-453/-94-004.

6. From Table 3.3, Tavoulareas and Charpentier, 1995, *ibid*.

7. Based on figures in Chapter 3 of Tavoulareas and Charpentier, 1995, *ibid*.

8. Tavoulareas and Charpentier, 1995, *ibid*.

9. USEPA, 1994, *ibid*.

10. Tavoulareas and Charpentier, 1995, *ibid*, page 18.
11. California Energy Commission (CEC), Energy Technology Status Report, Appendix B: Detailed End Use Technology Evaluations. California Energy Commission, Sacramento, CA, USA. June, 1991.
12. Sinton, J., editor, China Energy Databook 1996 Edition, Revised January 1996. Lawrence Berkeley National Laboratory, University of California, Berkeley, California, USA. LBL-32822.Rev.3. UC-900. 1996.
13. Tavoulareas and Charpentier, 1995, *ibid*, pages 13 - 15.
14. From D. Streets et al, "Emissions and Control", work in progress in RAINS-Asia: An Assessment Model for Acid Rain in Asia. April, 1995. Table 4.14.
15. Ishitani, H., and T.B. Johansson, Editors, "Energy Supply Mitigation Options". Chapter 19 in Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Published for the Intergovernmental Panel on Climate Change (IPCC) by Cambridge University Press, New York, NY, USA. 1996.
16. De Laquil, P., D. Kearney, M. Geyer, and R. Diver (1993), "Solar-Thermal Electric Technology". In Renewable Energy: Sources for Fuels and Electricity, edited by T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams. Island Press, Washington, D.C., USA. Chapter 5.
17. Moreno, R., Guidelines for Assessing Wind Energy Potential. World Bank Industry and Energy Department Working Paper, Energy Series Paper No. 45. Reprinted September 1991. The World Bank, Washington, D.C., USA.
18. Williams, R.H., and Larson, E.D. (1993), "Advanced Gasification-Based Biomass Power Generation". In Renewable Energy: Sources for Fuels and Electricity, edited by T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams. Island Press, Washington, D.C., USA, and Williams, R.H. (1995), Exploiting the Sugar Cane Cogeneration Potential in Quangxi Province. Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, USA.
19. World Energy Council (WEC), Energy Efficiency Improvement Utilizing High Technology: An Assessment of Energy Use in Industry and Buildings. Report and Case Studies. World Energy Council, London UK. 1995.
20. WEC, 1995, *ibid*; B.G. Tunnah, Wang Shumao, and Liu Feng, editors, China: Issues and Options in Greenhouse Gas Control, Energy Efficiency in China: Technical and Sectoral Analysis, Subreport Number 3, and W.A. Ward and Li Junfeng, Team Leaders, China: Issues and Options in Greenhouse Gas Control, Energy Efficiency in China: Case Studies and Economic Analysis, Subreport Number 4. The World Bank, Industry and Energy Division, Washington, D.C., USA. December 1994; Intergovernmental Panel on Climate Change (IPCC), Inventory of Technologies, Methods, and Practices for Reducing Emissions of Greenhouse Gases. Technical Appendix to Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses. Published for the IPCC by Argonne National Laboratory, Illinois, USA. 1996; Sch(fer, A., L. Schrattenholzer, and S. Messner, Inventory of Greenhouse-Gas Measures: Examples from the IIASA Technology Data Bank. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. WP-92-85, November, 1992; Organization for Economic Co-operation and Development/International Energy Agency (OECD/IEA), Energy Technologies for Reducing Emissions of Greenhouse Gases, Volumes 1 and 2. OECD/IEA, Paris, France, 1989; CEC, 1991, *ibid*.; Office of Technology Assessment (OTA), Industrial Energy Efficiency, OTA-E-560. Washington, D.C.,

UNITED STATES Government Printing Office. 1993.

21. Von Hippel, D., and P. Hayes, The Prospects for Energy Efficiency Improvements in the Democratic People's Republic of Korea: Evaluating and Exploring the Options. Nautilus Institute Report (Draft), Nautilus Institute for Security and Sustainable Development, Berkeley, California, USA.
22. Sathaye, J., Economics of Improving Efficiency of China's Electricity Supply and Use: Are Efficiency Investments Cost-effective? Lawrence Berkeley National Laboratory, University of California, Berkeley, California, USA. 1992.
23. Inventory of Technologies, Methods, and Practices for Reducing Emissions of Greenhouse Gases. Technical Appendix to Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses. Published for the IPCC by Argonne National Laboratory, Illinois, USA. 1996.
24. Nadel, S., J.A. Pietsch, and Shi Yingyi, The Chinese Room Air Conditioner Market and Opportunities to Improve Energy Efficiency; and Nadel, S., The Chinese Appliance Market: Current Status, Future Directions. The American Council for an Energy Efficient Economy (ACEEE), Washington, D.C., USA. 1996.
25. Gordon, D., Steering a New Course: Transportation, Energy, and the Environment. Union of Concerned Scientists, Washington, D.C., USA. 1991.
26. Greene, D.L., and D.J. Santini, editors, Transportation and Global Climate Change. The American Council for an Energy Efficient Economy (ACEEE), Washington, D.C., USA. 1993.
27. B.G. Tunnah, Wang Shumao, and Liu Feng, editors, China: Issues and Options in Greenhouse Gas Control, Energy Efficiency in China: Technical and Sectoral Analysis, Subreport Number 3. The World Bank, Industry and Energy Division, Washington, D.C., USA. 1994.
28. Liu, Z. P., J. E. Sinton, F. Q. Yang, M. D. Levine, and M. K. Ting, Industrial Sector Energy Conservation Programs in the People's Republic of China during the Seventh Five-Year Plan (1986-1990). Lawrence Berkeley Laboratory, Berkeley, California, USA and Energy Research Institute, Peoples Republic of China. LBL-36395. 1994.

View this online at: <https://nautilus.org/uncategorized/technological-alternatives-to-reduce-aci-gas-and-related-emissions-from-energy-sector-activities-in-northeast-asia-november-1996/>

Nautilus Institute

608 San Miguel Ave., Berkeley, CA 94707-1535 | Phone: (510) 423-0372 | Email:

nautilus@nautilus.org