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ENERGY USE IN BUILDINGS:
THE U.S. EXPERIENCE AND LESSONS FOR CHINA

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I. Introduction

This paper covers three topics concerning energy use in buildings. Its main focus is that of energy use in buildings in the United States. A second section describes some of the recent results of work by one the authors (BA) on energy performance of residential buildings in China. The third section contains suggestions for ways in which Chinese and U.S. researchers could establish fruitful collaborations on energy use in buildings.

II. Energy Use in U.S. Buildings

A. Overview

Buildings in the U.S. consume, according to the standard tabulations, more than 36 percent of total U.S. energy.[1] This means that buildings and industry, also at 36 percent, are by far the largest consumers of energy in the U.S. If the energy required to heat, cool, light, and ventilate industrial buildings were included in the buildings sector, buildings would be the largest U.S. energy consumer.

Building energy consumption in the U.S. amounts to a total of 26.8 Quads (one quad = 10^{15} Btu.) This compares with *total* commercial energy consumption in China of 21 quads. Thus, U.S. buildings, serving a population less than one-fifth that of China, consume more commercial energy than China uses for running its entire industry, transporting all people, materials, and products, pumping water, planting, harvesting, transporting, and harvesting crops, and all other uses.

The total bill for the 26.8 Quads is more than $170 billion per year, at 1985 energy prices. (Today the energy bill for buildings is higher than it was in 1985, in spite of the decline in oil prices, because of the relatively small use of oil and the large use of electricity in buildings.) This $170 billion is about $750 per person in the U.S., an amount three times greater than the per capita income of the average Chinese!

B. Trends in U.S. Building Energy Use

In 1973, residential buildings in the U.S. consumed 14.6 Quads. In 1985, residential buildings consumed 15.3 Quads, an increase of only 4.2 percent over a twelve-year period (or about 0.34 percent per year). During the twelve-year period *before* 1973, residential energy use increased 71 percent. Thus, the growth rate of energy use in the U.S. residential sector prior to the oil embargo was more than 13 times greater than after the embargo!

In 1973, commercial buildings consumed 9.5 Quads. In 1985, the consumption was 11.6 Quads, an increase of about 22 percent, or about 1.7 percent per year over this twelve-year period. In the twelve-year period prior to 1973, energy use in commercial buildings increased by 97 percent, or 5.8 percent per year. Thus, the growth in commercial building energy use also declined substantially after the embargo (annual growth was cut by a factor of 3.4), but the commercial building sector appeared to respond less than the residential sector to higher energy

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prices.

These reductions in energy growth in the building sector are smaller than for other sectors. As a result, buildings consume a larger fraction of total U.S. energy use today than they did at the time of the oil embargo: 36.3 percent today versus 32.5 percent in 1973. Since the embargo, industry has cut its energy use by 4.5 Quads (-14 percent), transportation has increased by 1.5 Quads (+8 percent), and buildings have increased by 2.7 Quads (+11 percent). According to these statistics, it might well appear that buildings have been the laggard in reducing energy use, compared with other end-use sectors.

This is, we believe, not a correct conclusion. It is very important to recognize that buildings are very long-lived capital stock. A building will typically survive 75 to 100 years. Once a building is built, many worthwhile options for increasing energy efficiency in a cost-effective manner are gone. Thus, considering that the existing building stock turns over very slowly, the gains in energy performance in the U.S. building sector that have occurred during the past decade and one-half have been very substantial.

It is useful to look at the data on building energy use in a slightly different way. For the residential sector, the primary unit is the household. In 1973, the average household consumed 205.6 million Btu per year. In 1985, consumption was reduced to 176 million Btu per household per year. This 14 percent reduction occurred in spite of the fact that (1) electricity consumption increased in residential buildings, and the saturation of electric space heating increased, (2) the saturation of central air conditioners increased significantly (e.g., less than half of new homes in 1973 had central air conditioners compared with 70 percent in each of the last five years), and (3) saturation of other energy-using products increased as well.

The improved energy performance of the residential sector on a per household basis is a result of a large number of factors. These factors include two that have little to do with energy conservation or efficiency *per se*: the decline in the average household size during this period (from 3.1 to about 2.8 persons per household, a significant reduction) and a substantial population shift to the southern and southwestern regions of the U.S. (resulting in the movement of the average house to milder climates).

However, there have been significant conservation and efficiency measures introduced into the U.S. residential sector: (1) the thermal integrity of new houses in much improved over 1973 houses, (2) a large number of existing houses have had energy audits and have installed energy retrofits, (3) the energy efficiency of many new appliances (especially refrigerators, freezers, furnaces, and central air conditioners) have increased significantly, (4) people are using appliances less than in the past, and (5) people are overheating houses less in winter, overcooling less in summer, and practicing night setback of thermostats. In addition to these factors, it is worth noting that almost all appliances (except central air conditioners) had achieved a large saturation by 1973, so that higher percentage saturations did not contribute to increased energy use. (See Levine, 1985, and Meyers, 1987, for more details and quantitative information about the efficiency improvements and conservation measures that have occurred in residential buildings.[2,3])

The improvements in thermal integrity of new houses have been substantial since 1973. In 1973, an average new house installed ceiling insulation of K-2.5, equivalent to a thickness of about 10 cm of insulation. By the early 1980s, the average value of ceiling insulation had increased to almost K-5, double the thickness and insulating values of the 1973 levels.* Thickness of wall insulation in new houses increased by 40 or 50 percent from 1973 to the early 1980s. In 1973, three-quarters of all new houses were constructed with single-glazed windows; by 1980, more than half of all new houses had double glazing.[4] More recently, houses have been constructed with low emissivity glazings, further reducing heating loads in winter.

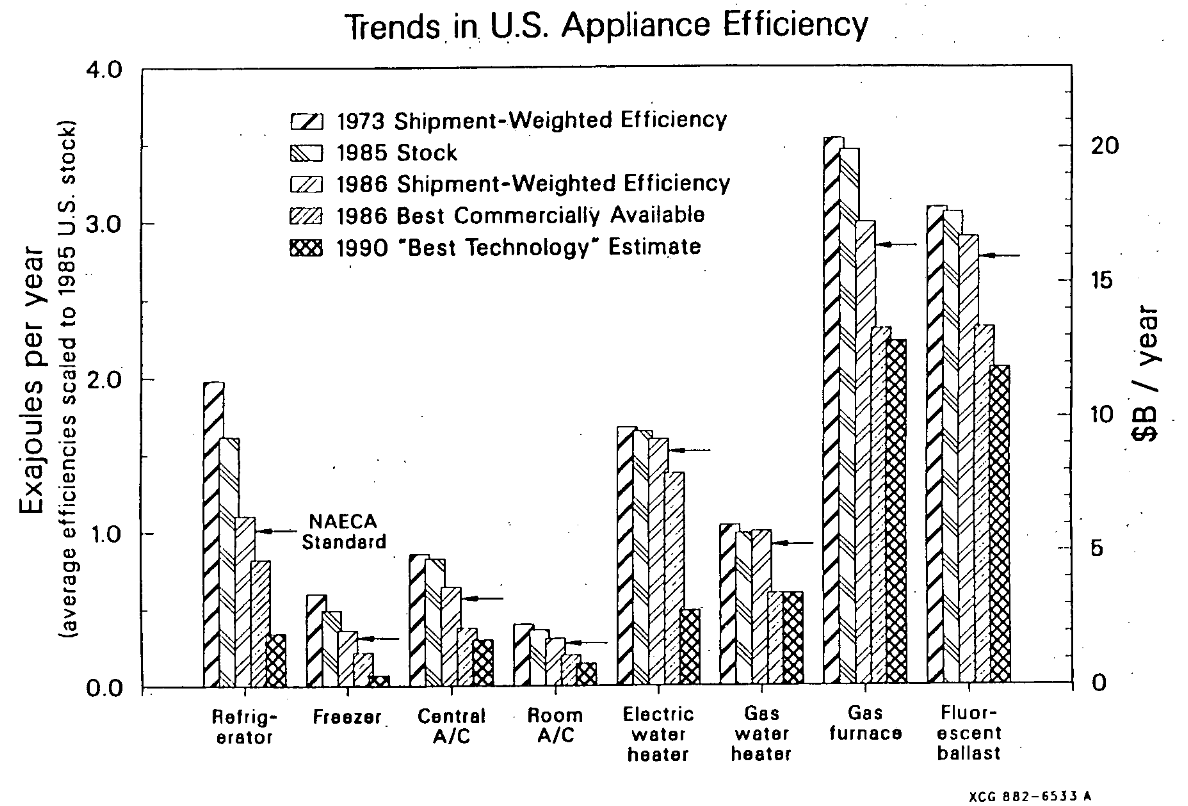

Figure 1.

In addition to these large improvements in the thermal integrity of new houses, the efficiency of major energy-consuming appliances has improved as well. Figure 1 presents data on the energy consumption of the 1985 stock of appliances if they all had the efficiency of (1) the typical new appliance sold in 1973 [left-most bar], (2) 1985 stock [second bar], (3) the national energy efficiency standards in the U.S., as mandated by the National Appliance Energy Conservation Act (NAECA) of 1987 [third bar], or (4) most efficient technology, currently available [fourth bar] or likely to be available in 1990 or somewhat thereafter [fifth bar]. This Figure demonstrates that substantial efficiency improvements have taken place in many of the household appliances since 1973, that under NAECA additional improvements are in the offing, and

*The units for insulation K-values are m^2 K/W.

that current and future technology could lead to much greater efficiency gains.[5]

New commercial buildings in the U.S. also showed significant gains in energy efficiency. Figure 2 presents a great deal of information about the energy use of new commercial office buildings from 1950 to 1985.[6] This Figure demonstrates a dramatic reduction in the intensity of energy use in new, large, office buildings. At their peak in the early 1970s, a typical large office building consumed about 500 kBtu per square foot per year. By the middle 1970s, thanks to the "voluntary" U.S. standards (established by the professional association of refrigeration, heating, and cooling engineers and adopted by essentially all state governments in the U.S.), the typical new, large, office building had reduced the intensity of energy use by 60 percent! (The reductions in energy use from the average office building stock in 1979 were about 30 percent.)

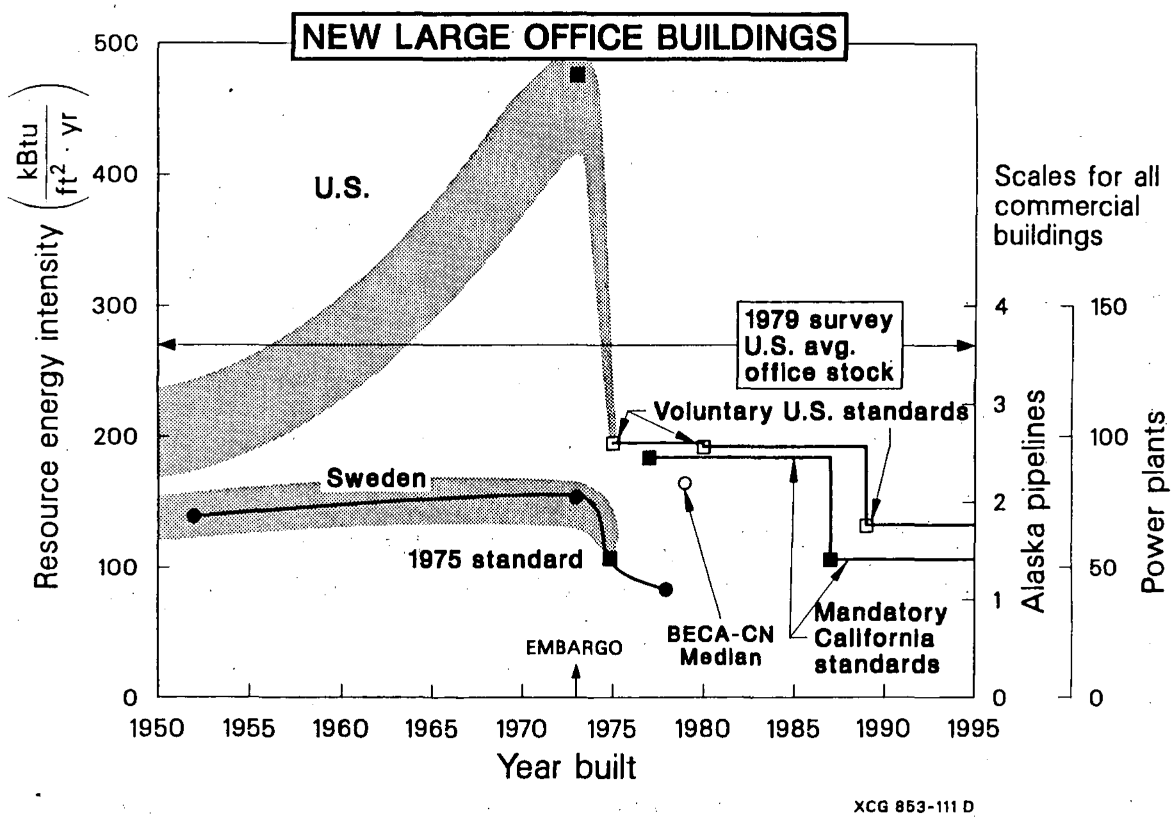

Figure 2.

Sweden is included in the Figure to demonstrate that the Swedes, running buildings in a much colder climate, had already achieved these energy intensities years before the U.S. started paying attention to energy use in buildings. The Figure also makes clear that future voluntary standards, also expected to be promulgated by the professional societies and adopted by state governments, can reduce energy use even further.

With these dramatic reductions in energy use intensity in new office buildings since the peak in the early 1970s, it is useful to ask why energy consumption in commercial buildings has continued to increase (albeit at a much slower growth rate than in the past) since 1973. Some factors that have worked to increase energy intensity in new commercial buildings (compared with results for office buildings) include: (1) many non-office commercial buildings have taken fewer steps to increase energy efficiency, (2) various miscellaneous energy uses (e.g., computers) have increased substantially in the existing stock of commercial buildings, (3) building energy retrofit activity has been emphasized much less in commercial than residential buildings (with the exception of federally-supported programs for schools and hospitals), (4) commercial buildings are often thought of as being much more complicated than residential buildings, with the result that common sense measures to save energy (including changes in behavior) are often not taken, (5) commercial building space has been growing more rapidly than housing, and (6) commercial appliances have not increased in efficiency as much as residential appliances (with the exception of lighting systems).

Thus, it is likely that commercial energy consumption will continue to increase at a rate somewhat faster than residential energy use in the U.S. The opportunities for successful energy retrofit programs (e.g., promoted by electric utilities) are substantial.

C. The Future

Overall, the energy efficiency of new residential and commercial buildings in the U.S. could increase by 25 to 50 percent through cost-effective investments at current energy prices. In spite of the large reductions in energy use that have already taken place through efficiency improvements, much more can be done in the future. The view, once widely held, that energy conservation would yield benefits for only a short time appears not to be valid. As time marches on, so does new, energy-efficient and cost-effective technology for buildings.

The critical issues affecting the future energy efficiency of the U.S. building stock and newly constructed buildings are: (1) will the marketplace invest in efficiency at suitable levels, (2) will the research efforts aimed at developing more efficient technologies continue, and (3) will the federal and state governments develop and implement new programs and policies to promote energy efficiency in buildings? The answers to these three questions are crucial determinants of the energy use of the next generation of U.S. buildings. As we have noted, buildings are the largest energy-consuming sector in the U.S. As such, the answers to these questions will profoundly influence the balance between energy supply and demand in the U.S. in the years to come.

III. Energy Use in Residential Buildings in China

A. Overview

One of us (BA) is, with Mr. Lang Siwei of the China Academy for Building Research, co-leader of a project concerning "design of new energy-efficient buildings in moderate and cold climatic zones in China, including utilization of passive solar energy."[7] The purpose of the studies has been to improve the indoor thermal and moisture conditions in unheated residential buildings and to reduce the energy consumption in heated residential buildings, in both cases by an improved building envelope. The approach taken has been to perform parametric studies for a number of places in China using the JULOTTA code for building energy analysis.[8]

For purposes of the study, China was divided into three principle heating zones, following the map in Figure 3. Cities such as Harbin, Xining, Beijing, and Jinan are located in the central heating zone. Nanjing and Shanghai are in the transition zone, where central heating is not applied but some local heating can be used. Wuhan, Hangzhou, and Guangzhou are in the non-heating zone.

For the transition zone, the key question is the improvement of comfort conditions. For example, in an unheated occupied middle-story apartment in Nanjing, calculations indicate that the monthly minimum temperatures are about 4°C and the average temperatures in January are +8°C. It is clearly desirable to increase the temperatures in these buildings, if economic conditions so admit.

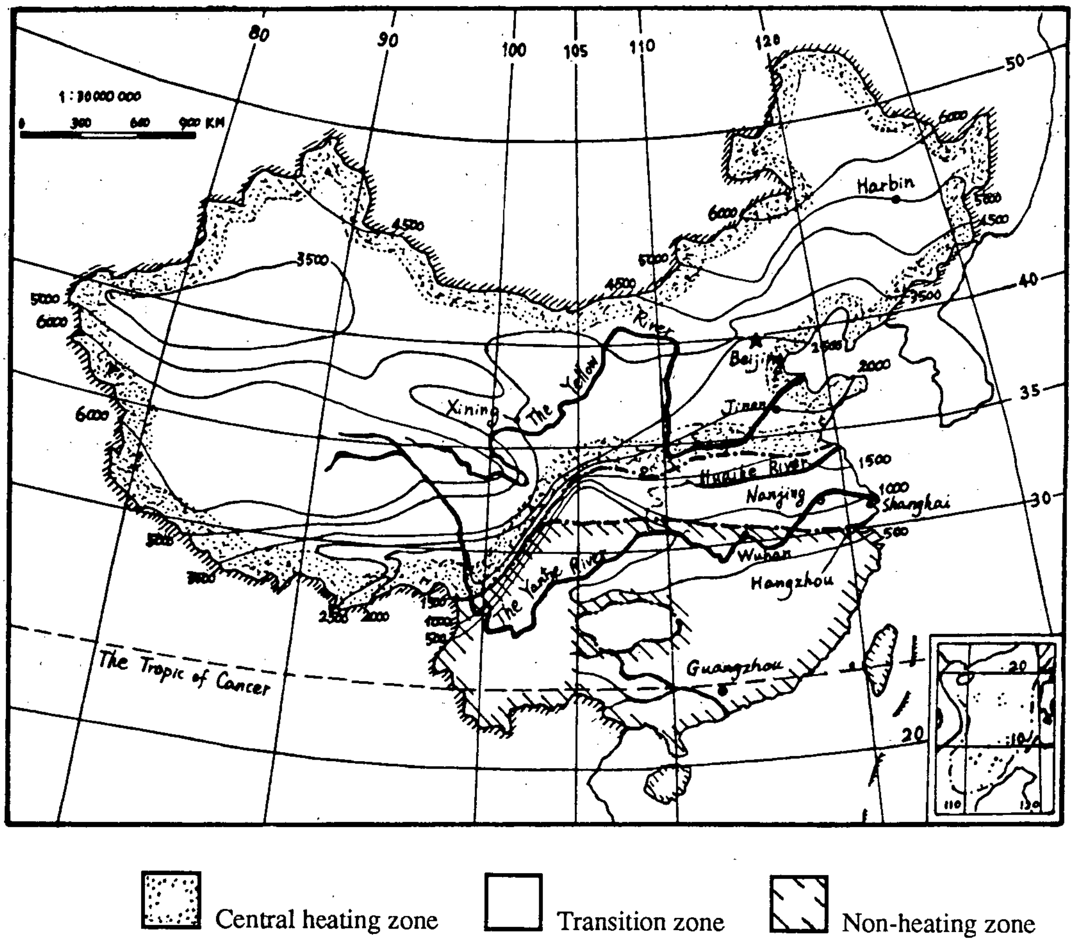

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Figure 3. Map of China showing 3 Heating Zones

Although people can bear very low indoor temperatures during the winter (particularly if they are of short duration and occur at night), improved living standards include better indoor conditions. It is often assumed that temperatures should not fall below +12°C more than 100 to 200 hours per year for reasonable comfort conditions to be met. This limit, +12°C, seems from a

Western point of view to be very low, but is an essential improvement compared with current conditions in the transition zones in developing countries such as China.

For buildings with central heating, the cost of the heating system is an essential part of the total building cost. If the heating system can be excluded (i.e., a passively-heated building), the cost of the heating system can be used to improve the building envelope without increasing the total building cost. We investigate this issue for buildings in the central heating zone, with the purpose of moving the border between the transition and the central heating zones northwards.

The possibility of passive climatization was studied for one city in the transition zone (Nanjing) and two cities in the central heating zone (Beijing and Xining). The design variables to achieve passive design included increasing: (1) insulation of exterior walls, (2) areas of south-facing glazing, (3) thermal mass of interior walls, and (4) reduction of air infiltration.

B. Results of Analysis

For Nanjing, in the transition zone, the simulations show that a middle-story apartment can be expected to achieve temperatures of greater than +9°C in all but 100 hours with no heating system using a passive design. The indoor temperature does not fall below +8°C at any time during the year. This is accomplished by making the building envelope air-tight (infiltration rate of 0.5 air changes per hour), placing moderate levels of insulation in the walls (K-value of 1.15) and roof (K-3), and orienting a large single-glazed window area (10.5 square meters) facing south. Double glazing can raise the indoor temperature 2 to 2.5 °C. Reduction of the south glazing area to 3.3 square meters will lower the indoor temperature 0.5 °C. With relatively simple passive design measures, reduction in infiltration, and envelope insulation, the indoor conditions in Nanjing can be improved by +4°C.

For Beijing, in the central heating zone, the simulations showed that an apartment building can be expected to achieve temperatures of greater than +14°C in all but 100 hours with no heating system using a passive design. This design includes (1) well-insulated exterior walls (K-3) and roofs (K-6), (2) inner walls simulated with 100 square meters of 24 cm brick per apartment (a rather high thermal storage capacity), (3) 10.5 square meters glass area facing south, and (4) low infiltration (0.5 air changes per hour). The windows are single-glazed. If the inner walls are of bricks with less than 12 cm thickness, +13°C is achieved in all but 100 hours of the year. (Upper stories are very slightly colder.) These results should be compared with interior temperatures of +8°C achieved in all but 100 hours with relatively small south-facing windows (3.3 square meters) and much lower temperatures if the walls and roof are not insulated and infiltration is high (i.e., current practice). *The important finding from this analysis is that it is possible to design a passive residential building in the Beijing climate that meets comfort conditions significantly better than present ones.*

For a heated building in Beijing, the annual energy consumption can be reduced from 78 kWh/square meter (current practice: uninsulated building, single glazing, 1.1 air changes per hour, and 5.2 square meters of south-facing glass), to 33 kWh/square meter (moderate wall and roof insulation, double glazing and 10.5 square meters of south-facing glass), and to 11 kWh/square meter (as above but with infiltration reduced to 0.5 air changes per hour). Thus, the simulations suggest that, at current comfort conditions, the installation of a very few conservation measures can reduce annual energy use to 15 percent of typical current levels, for heated apartments in Beijing.

Moving to a colder climate, Xining, the analyses show that one cannot come close to the comfort conditions with passive design and no heating system. For the building in Beijing that achieved a minimum temperature of 13°C, the minimum temperature in Xining is about 2°C. These passive measures and envelope insulation will, however, significantly reduce heating requirements in apartments in Xining.

IV. Opportunities for Cooperation

This paper highlights (1) improvements in the energy efficiency of the building stock that have taken place in the U.S. during the past fifteen years and (2) the potential for improvements in residential buildings in China.

We suggest that there are a number of areas where collaborative work among Chinese and U.S. (as well as other western) researchers would be highly desirable. These include:

- *establishing methods to gather data on energy use in buildings in China.*

  This would be an extremely valuable activity, as it is important to track building energy consumption over time to determine needed policy approaches. A number of different data bases would be valuable: an aggregate data base of energy use in residential and commercial buildings and more detailed regional data bases that provide more information about the causes of the changes in energy consumption. U.S. researchers could provide the benefit of their experience in the design of different data-gathering instruments.

- *assessing technologies to increase energy efficiency of buildings and energy-consuming equipment in buildings.*

  Numerous technologies have been developed in the industrialized West that improve energy efficiency, comfort, and economic performance of buildings. Advances in methods for identifying energy inefficiencies in buildings, improved insulation, more efficient appliances, air infiltration controls, more efficient lighting systems, and passive design are just a few examples of the technological improvements that have been made in the past 10 to 15 years. An effort to evaluate western technology for application to China and, where appropriate, to identify ways to establish the capability to manufacture and employ these technologies could be highly beneficial. A closely related issue concerns the development and transfer of technology to avert potentially injurious environmental impacts of energy production and use. A particularly important case that comes to mind is the need for refrigeration that does not make use of chlorofluorocarbons (CFCs). As China's economy expands, the sale of refrigerators is likely to expand enormously. Chinese refrigerators could have a very large impact on global climate, if measures are not taken to develop and employ refrigeration technologies that avoid the use of CFCs.

- *development of programs and policies to cost-effectively increase the energy efficiency of Chinese buildings.*

  There have evolved over the past decade a wide variety of programs and policies to effect energy savings in buildings in the U.S. and other developed countries. Of particular note in the U.S. have been (1) federal energy efficiency standards (either voluntary or mandatory), (2) state standards, (3) electric utility rebate programs to foster energy-efficient appliances, (4) electric utility energy audit programs for residential buildings, and (5) utility low-interest loan programs to foster energy conservation investments in residential and commercial buildings. These policies and programs are dependent on a substantial body of analysis, as well as the development and application of analytical tools and data.

  Lawrence Berkeley Laboratory is presently leading a major effort to develop policies to promote energy-efficient commercial buildings in five countries in Southeast Asia (Indonesia, Malaysia, Philippines, Singapore, and Thailand). One of the authors (MDL) is the principal investigator of this project. The project involves education, collaborative research, cooperation with the private sector, and technical and policy studies, with the purpose of developing and implementing energy standards for commercial buildings (as well as exploring other policy vehicles to improve energy efficiency). The other author (BA), as noted, is already engaged in a collaboration with Chinese researchers. These types of exchanges, significantly amplified, could be extremely valuable.

As China's economy grows, the need to use limited energy resources efficiently will, we believe, become increasingly apparent. The inefficient use of energy will (1) cost China valuable foreign exchange (as oil exports are reduced), (2) cost consumers yuan, as they overspend for energy (directly in houses and indirectly through more costly products), and (3) strain the capital resources of China, as large amounts of capital are needed to fuel the energy sector. As the developed countries have discovered, investments in energy efficiency pay off handsomely. We believe that some of the various approaches to spur such investments in energy efficiency in industrial countries may apply to industrializing countries like China. We also believe that the Chinese will develop indigenous methods of improving the efficiency of energy use. Collaboration, in both technical and policy studies, has the potential to be a very valuable undertaking.

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