Preliminary Results from a Bottom-Up Analysis to Determine Residential Energy Consumption in the Emerging Economies of the World

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ABSTRACT

Studies forecasting the future demand for energy in developing countries often employ a top-down approach whereby total residential energy consumption or total fuel consumption is compiled by government agencies or utilities and projections are made for future demand based on some assumption of overall growth in different sectors of the economy. Such studies, while useful in predicting the future demand for energy, do not help identify where the best opportunities for efficiency improvements lie. This report employs a bottom-up approach. To quantify the benefits of more efficient appliances, we have looked at specific end-use appliances, their saturation levels, unit energy consumption and sales in specific countries of interest. Such data are very difficult to obtain and we were able to gather sufficient data for our analysis for China only. Residential electricity consumption by end-use is calculated for refrigerators and air conditioners in China under 3 efficiency scenarios. There is much you cannot know from a top-down approach. For example, this analysis suggests that for air conditioners in China, standards can help control rate of growth in energy use of CO_2 emissions but cannot bring emissions of CO_2 back down to 1990 levels, or even 2000 levels. For refrigerators, very aggressive efficiency standards in China could maintain carbon emissions approximately at the 2000 level even with further increases in household saturation.. This is not possible for air conditioners because achievable efficiency improvements would not be great enough to overcome the estimated rise in the total number of air conditioners in use.

Introduction

Even though the largest users of residential energy are the industrialized countries of North America and Europe, growth in energy consumption has been most rapid in developing countries. the 1995 World Energy Council Report (Table 1) shows an average annual growth rate of 5.7% for residential buildings energy use in developing countries as compared to 1.4% in OECD countries between 1971 and 1992 [World Energy Council, 1995]. Residential energy consumption in the emerging economies of Asia is rapidly increasing. The economic boom and the growing household wealth in the faster developing countries of this region has resulted in sharp increases in the ownership of household appliances. This trend has already resulted in very significant increases in electricity use and associated carbon dioxide emissions. This paper looks at a number of these emerging economies of Asia where growth in appliance ownership and power consumption are most notable. Improving the energy efficiency of appliances in these countries, by implementation of minimum efficiency standards or by other means, can be an effective measure to offset the rapid growth of electricity consumption. This can help mitigate global climate change by slowing the growth of CO_2 emissions. Figure 1 presents a historical view of residential electricity consumption for a select group of developing countries. It can be seen that residential electricity consumption in these countries has been steadily increasing over the last decade. In China, consumption in 1995 had increased by 274% over 1987. Similarly, India, Indonesia, Philippines and Thailand have also experienced growth in residential electricity consumption by 93%, 137%, 77% and 228% over their 1987 levels, respectively. These growth rates can be compared to that of a developed country like the U.S., where residential electricity consumption increased by 23% between 1987 and 1995. In the last decade, carbon emissions due to fossil fuel consumption in China, India, Thailand, Philippines and Indonesia increased by 40%, 77%, 205%, 64% and 94% relative to the 1987 levels, respectively (Figure 2). In comparison, world carbon emissions have risen by 8% and those of the U.S. by 14% over their respective 1987 levels.

Table 1. World Residential Primary Energy Use by Region

Region	1971 (EJ)	1980 (EJ)	1990 (EJ)	1992 (EJ)	Avg. Annual Growth Rate 1971-1992
OECD	28.3	32.8	36.5	38	1.4%
Developing Countries	4.9	8.8	15.0	15.7	5.7%
EE/FSU	8.1	12.9	15.1	12.8	2.2%
World	41.3	54.4	66.5	66.5	2.3%

Source: *Energy Efficiency Improvement Utilizing High Technology: An Assessment of Energy use in Industry and Buildings*, World Energy Council, 1995 [World Energy Council, 1995]

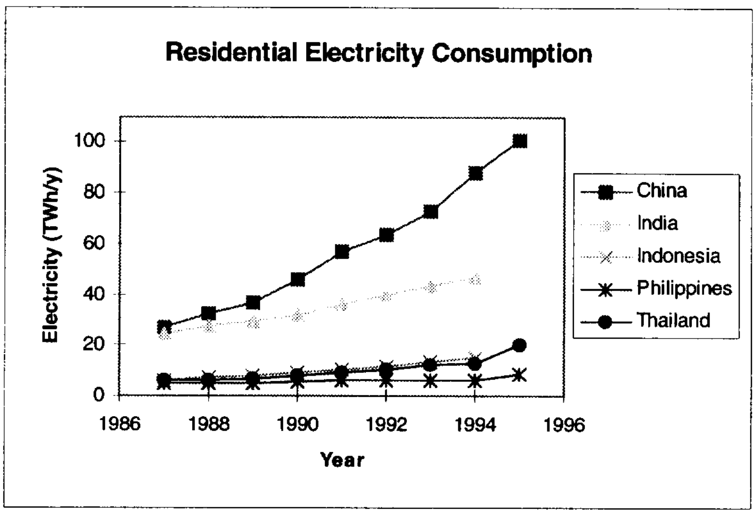

Figure 1. Residential electricity consumption in selected developing countries
Source: IEA Statistics 1995 and 1996.

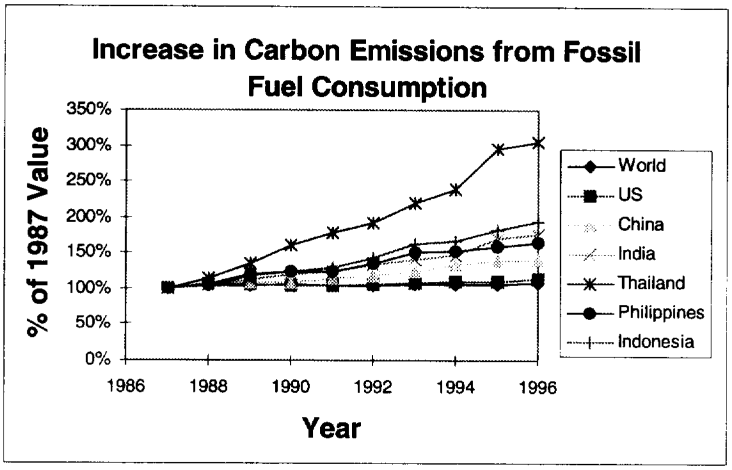

Figure 2. Carbon emissions of a selected developing countries and the U.S.
Source: International Energy Annual 1996 [EIA, 1998]

Another way to look at residential energy use is to look at the energy consumed per household. Figure 3 presents a comparison of average household energy use characteristics for selected countries. Electricity consumption, delivered modern energy consumption (electricity, natural gas, oil, etc) and delivered total energy consumption (sum of modern and traditional) are shown except for Brazil and Mexico, for which data on traditional energy were not available. Traditional energy is for the most part derived from burning biomass (wood and agricultural waste products). Since US households use the most residential energy, the graph has been normalized with the US per-household energy use set at 1.0. Per-household electricity consumption in China is currently only 3% of that in the US, while total modern energy use in Chinese households is about 11% of the U.S. level. However, it is important to note that the total primary energy use (modern and traditional) for Chinese households totals about 35% of US households. This demonstrates dependence of households in China on traditional forms of energy. With further economic development, an increasing proportion of this traditional energy will be replaced by electricity or other modern forms of energy. This holds true for other developing countries like India and Thailand, where dependence on traditional energy is high, particularly in rural areas.

A number of studies have forecast world energy use under various technology and economic scenarios. One such study, conducted by the Intergovernmental Panel on Climate Change (IPCC), took into account the effect of technological advancements as well as measures such as mandatory and voluntary energy efficiency standards to forecast carbon emissions from energy consumption in residential and commercial buildings around the world [IPCC, 1996]. This study estimated that, in 2020, codes and standards could achieve about a 20% reduction in annual building energy use relative to the base case. Even with codes and standards, the projected energy use in 2020 would be about 9% higher than in 2000. In this paper, we analyze energy savings potential on an end-use basis.

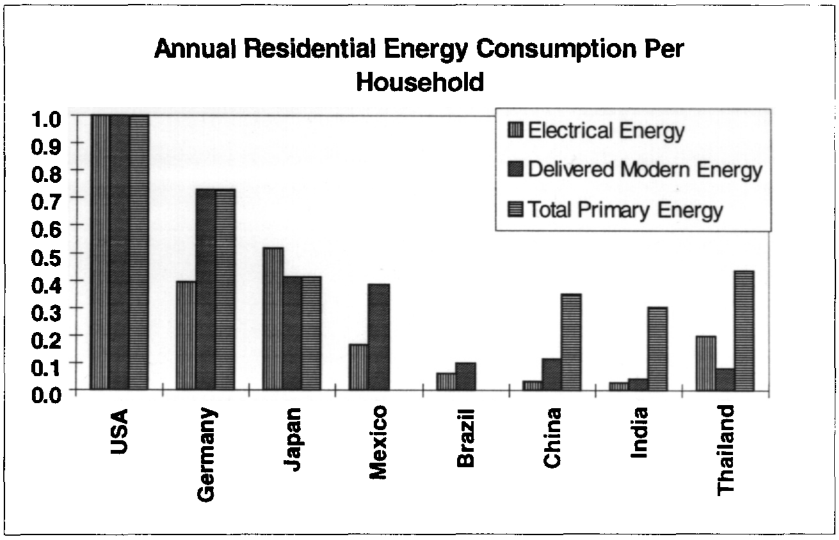

Figure 3.. U.S. residential energy use is compared to several other countries.
Source: *China Statistical Yearbook* [China State Statistical Bureau, 1997], *Non-OECD Energy Balance* [IEA, 1997], *OECD Energy Balance* [IEA, 1997].

Methodology & Data Sources

Studies forecasting energy demand for developing countries often (there are exceptions -see Shrestha, 1998) employ a top-down approach whereby statistics of total residential energy consumption or total fuel consumption are collected by government agencies or utilities and projections are made of future demand based on assumptions of overall growth in different sectors of the economy. Such studies, while useful in predicting the future aggregate energy demand, may ignore important sectoral trends and usually are not useful in identifying where the best opportunities for efficiency improvements lie. This report summarizes the results of a bottom-up approach. To quantify the benefits of more efficient appliances, we have looked at specific end-use appliances, their saturation levels, unit energy consumption and shipments in specific countries of interest. Residential electricity consumption by end-use for refrigerators and air conditioners in China is calculated under 3 efficiency scenarios. When combined with cost data, these results can help interested parties determine the costs and benefits of undertaking various kinds of programs aimed at increasing appliance efficiency.. This could be particularly useful under the Kyoto Protocol, which requires industrialized countries to reduce their collective emissions of greenhouse gases by 5.2% by 2012. The Protocol grants the industrialized countries a certain degree of flexibility in how they achieve and measure their emissions reductions. In particular, a "clean development mechanism" would enable industrialized countries (with cooperation from developing countries) to finance emissions-reduction projects in developing countries and receive some portion of the emissions credits for doing so. The bottom-up approach used in this study (if data allow it to be applied to enough countries) will allow the interested industrialized and developing countries to identify emission reduction programs that would deliver the best results. In this section, we summarize the data collected, their sources, and the methodology used in the analysis. Residential electricity consumption, using the bottom-up approach, is calculated in the Results section and scenarios incorporating different trends in saturation and efficiency improvements are then studied to assess the benefits of various emission reduction strategies.

A spreadsheet model was developed to calculate total energy use by appliances. Energy use in the urban or rural sector in any year is calculated by the following equation:

Energy Use = Households x Saturation x UEC

where the households and saturation levels pertain to a given sector and country, and UEC (Unit Energy Consumption) is the annual energy consumption of an appliance. The total energy use for the appliance is the sum of the energy use in rural and urban sectors. Presently, UECs for rural sectors are not available as field measurements (the few that are available) are often carried out in cities.

We are in the process of acquiring data from China, India, Thailand, Philippines and Indonesia. When complete, these data will include appliance saturation, unit energy consumption, shipments and the present stock of the major electricity-consuming appliances in the urban and rural sectors of these countries. These data, along with demographic data, are necessary to accurately estimate residential electricity consumption by end use as well as forecast future electricity demand. However, some of these data are not readily available and in many cases do not exist. The lack of data is a limiting factor in this analysis and also highlights the need for studies to gather such data from developing countries.

China

The historical saturation data for key appliances in China are presented in Figures 4 and 5. It can be seen that the saturation rates of color TVs, refrigerators and clothes washers (CW) are higher in urban than in rural China, and that room air conditioner (A/C) saturation is rapidly increasing in urban China. In Shanghai and Guangdong province for example, A/C saturation has already reached 50%. In rural China, the saturation rate of A/Cs is under 1%. For black and white TVs, saturation is decreasing rapidly in urban China and leveling off in rural China, as color TVs become more popular.

Table 2 shows the unit energy consumption (UEC), domestic sales, and stock of nine appliances along with their saturation levels for 1995. These are the only appliances for which such data were available. There may be large uncertainties associated with these data (eg., see note to Table 2 concerning refrigerator stock and saturation numbers). Table 3 provides information on population, number of households, and energy use in rural and urban China. On average, rural households have more members then urban households. Since UECs were available for urban households only, we made the assumption that rural households used the same amount of energy per appliance as urban households. This may be approximately true for some products (e.g., refrigerators and freezers) if the impact of climate is ignored however, it may be less accurate for other products such as televisions and air conditioners (even after normalizing for climate)

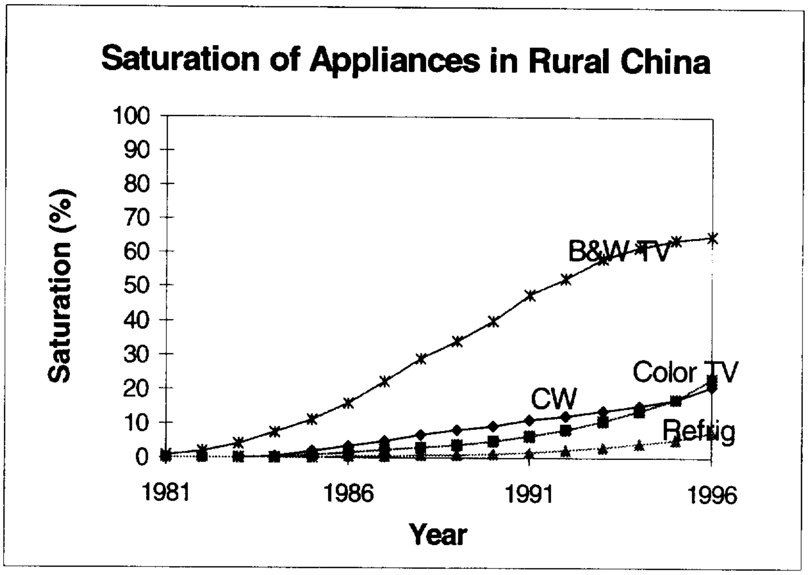

Figure 4. Saturation of selected appliances in rural China
Source: China State Statistical Bureau Statistical Yearbook 1996 [China State Statistical Bureau, 1996]

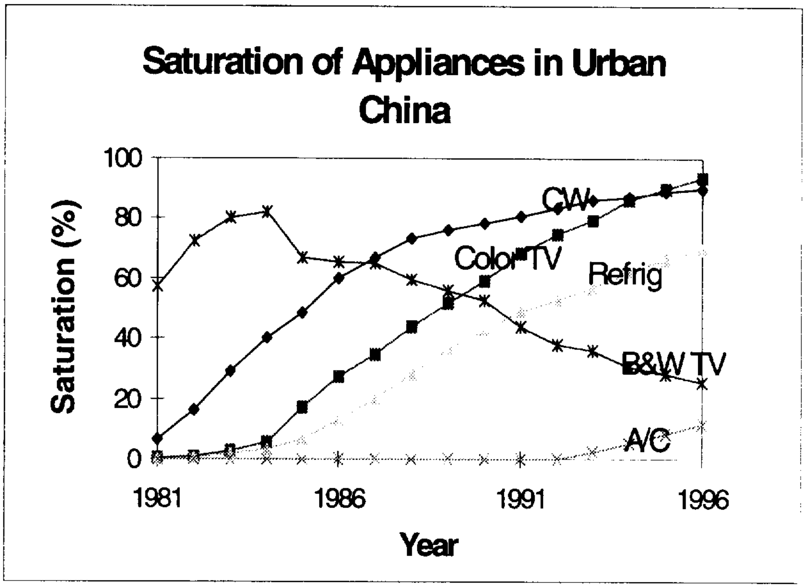

Figure 5. Saturation of selected appliances in urban China
Source: China State Statistical Bureau Statistical Yearbook 1996 [China State Statistical Bureau, 1996]

Table 2. Appliance data for China Households for 1995

Appliance	Saturations (%)		UEC*	Domestic Sales	Stock
	Urban	Rural	(kWh/y)	(Million Units)	(Million Units)
Refrigerators	66.0	5.2	408	8.32	57.58**
Freezers	2.9	0.0	387	2.85	3.02
Air Conditioners	8.1	0.0	297	5.16	8.42
Clothes Washers	89.0	16.9	55	8.95	124.30
Microwave Ovens	0.8	0.0	52	0.17	0.83
Televisions (B&W)	28.0	63.8	43	10.08	149.05
Televisions (Color)	90.0	16.9	124	12.87	125.37
Fans	167.0	89.0	20	NA	341.00
Rice Cookers	NA	NA	226	15.6	NA

*These UEC figures are from a 100 household survey conducted in 3 cities (Beijing, Shanghai and Guangzhou) and are representative of urban appliance usage. Rural usage may be different for some products.
** The stock of refrigerators is calculated by adding production and net imports each year to the 1992[1] stock of 39.41 million refrigerators. This number does not match the number obtained by multiplying the 1995 refrigerator saturation rate by the number of households.
Sources: *China State Statistical Bureau Statistical Yearbook 1996* [China State Statistical Bureau, 1996], *Energy Efficiency Opportunities in Chinese Building Sector* [Nadel 1997], *The Sino-US CFC-Free Super-Efficient Refrigerator Project Progress Report* [EPA, 1997].

Table 3. China's Demographics and Residential Energy Use for 1995

	Population (Millions)	Households (Millions)	Energy Use* (PJ)
Urban Sector	351.7	104	1910.6
Rural Sector	859.5	188	9064.7**

* 1994 values for residential energy
** includes 7266.4 PJ of traditional energy
Source: *Energy Efficiency Opportunities in Chinese Building Sector* [Nadel, 1997]

[1]*China Industrial Statistical Yearbook 1993* reports a total refrigerator stock of 39.41 million in 1992. This is the last year in which refrigerator stock figures were published.

Other Asian Countries

India is the second most populous country in the world, after China. As is the case with China, sustained increases in the saturation level and use of appliances in India could have a significant effect on the global environment as demand for electricity soars. Based on a 1993 survey, the saturation rate of appliances (refrigerators clothes washers and televisions) in India is fairly low, relative to China (NCAER,1993).

In the last decade, carbon emissions from fossil fuel consumption in Thailand has more than tripled. Thailand households in general own more appliances than households in India or China and are more electricity intensive. In 1993, for example, the saturation rate of refrigerators in the Thai urban sector was 88%, compared to 22% in India and 57% in China. The saturation levels of refrigerators and air conditioners in the urban and rural sectors of Thailand are forecast to continue increasing (Egan, 1997).

Data for the Philippines and Indonesia are very sparse and not presented here. A significant amount of effort will need to be expended to acquire sufficient data for even preliminary end-use forecasting for countries other than China.

Results

At present, we have produced forecasts of electricity consumption for two products (refrigerators and air conditioners) in China. One of the main factors in determining residential energy consumption is the saturation and use of appliances in new and existing households. For this analysis, the number of households (both urban and rural) is assumed to increase by 0.5% annually. That is the average growth rate over the time period 1990-2050 estimated by the China State Planning Commission in 1995, Although the rise over the period 2000-2020 is likely to be somewhat greater than 0.5%, we have used it for that period too. Figures 6 and 7 show our assumptions about the change in future saturation levels of appliances in China's urban and rural residential sectors. These assumptions are based on discussions with several energy researchers located in China. It is also assumed that new households have the same saturation rates as existing households. In urban China, color TVs and refrigerators are projected to exceed 100% saturation while the saturation rate of black and white TVs is expected to fall rapidly. Clothes washers are projected to rise slowly from about 90 to around 100% saturation and air conditioners from about 10% to about 50% saturation by 2020. In rural China, saturation levels are generally rising but are lower than in urban China owing to lower purchasing power and electric power supply constraints.

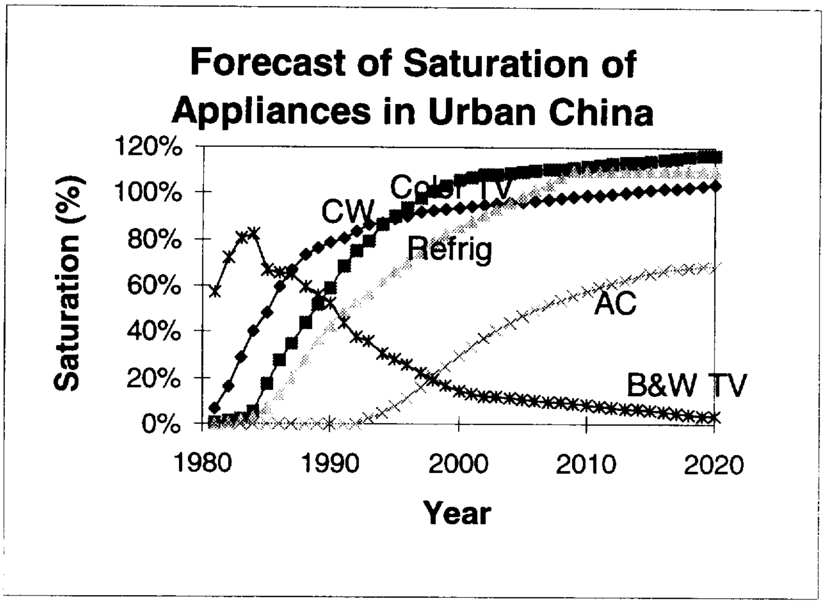

Figure 6. Forecast of appliance saturations in urban China.

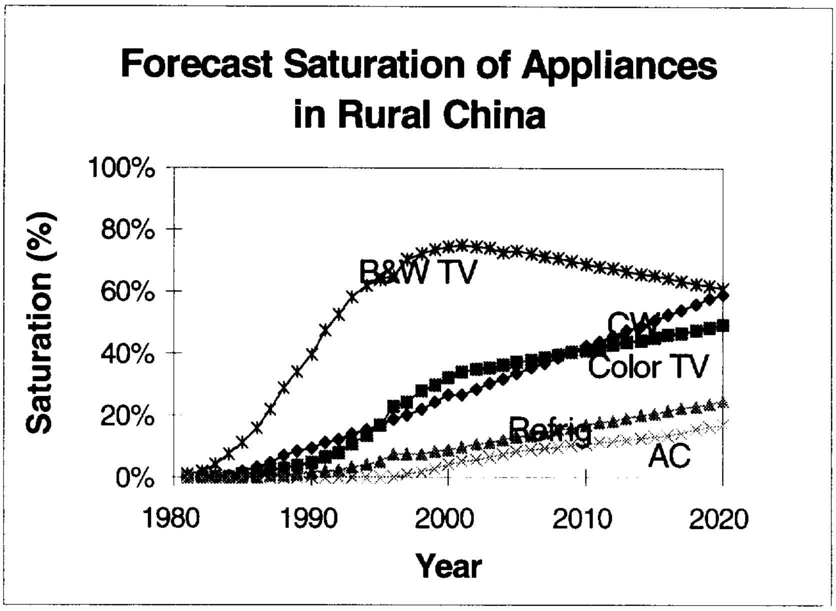

Figure 7. Forecast of appliance saturations in rural China.

Refrigerator Energy and Emissions Forecast

Based on the forecasts of refrigerator saturation levels in the urban and rural sectors, projected refrigerator energy consumption and associated carbon emissions under different scenarios are shown in Figure 8. These forecasts assume a base case UEC of 408 kWh/y [EPA, 1997] and a refrigerator life of 15 years for typical 220 liter refrigerator-freezers. The UEC is based on measurements in 100 households [EPA, 1997]. In the base case, efficiency is assumed to be frozen; we are assuming that any improvements that occur without government intervention are offset by increases in the size of refrigerators and in energy-using features such as automatic defrost. An emissions factor of 0.339 kg carbon/kWh of electricity used on site has been assumed to convert electricity consumption into carbon emissions. The carbon emissions per unit of electricity used is high for China because approximately 80% of electricity generation is coal based; as a result, about 1/3 of CO_2 emissions in China come from power generation.

A new efficiency standard implemented in 2000 was assumed in the calculations of the efficient cases (Case I & Case II). While the efficiencies represented by Cases I and II are technically achievable, we are not suggesting that they will actually be implemented as standards by 2000. These are just illustrations of what savings are achievable with such efficiency improvements. Case I assumes 293 kWh/y UEC from year 2000 onwards. At least one refrigerator manufacturer in China is currently producing energy-efficient units that use 293 kWh per year. Adopting such a standard would result in a 22% reduction in cumulative energy use from 2000 to 2020, from 1107 TWh to 868 TWh, a savings of 239 TWh. Under this scenario, total refrigerator energy use increases by 8.2 TWh/y, or 24%, between 2000 and 2010, compared to the base case increase of 19.9 TWh/y, or 56%. In the base case scenario, refrigerator energy use by 2010 would reach 55.2 TWh/y (a 450% increase from the 12.2 TWh/y level of 1990), whereas in the efficient case, energy use by 2010 would be 42.6 TWh/y or 350% higher than the 1990 level.

A more stringent efficiency standard has also been analyzed (Case II). This standard would mandate the production of refrigerators that consume no more than 220 kWh/yr. Prototypes of refrigerators using about 255 kWh/yr have already been tested [EPA, 1997]. If such a standard took effect in 2000, total refrigerator energy use would remain fairly constant over the period 2000-2020. Such a standard would result in a 36% reduction in cumulative energy use over the period, from 1107 TWh to 714 TWh, an energy savings of 393 TWh. In this scenario, refrigerator energy use increases by a total of 0.6 TWh/y, or 1.8% between 2000 and 2010, whereas in the base case scenario, the total increase would be 19.9 TWh/y or 56%. In the base case scenario, by 2010 refrigerator energy use would reach 55.2 TWh/y (a 450% increase from 1990) whereas in the efficient case energy use by 2010 would be 34.5 TWh/y or 280% higher than 1990.

Figure 8 also shows the carbon emissions due to the forecasted refrigerator electricity use in the three scenarios above. The more stringent scenario results in stabilizing carbon emissions at almost the 2000 level. Cumulative carbon emissions for the base case and the two efficient cases are 375, 294, and 242 million metric tons of carbon, respectively. Efficiency case II results in savings of 7 million metric tons of carbon in the year 2010 alone, compared to the total increase of 12.5 million metric tons in carbon emissions for China between 1995 and 1996 (from 792.3 to 804.8 million metric tons [EIA, 1998]).

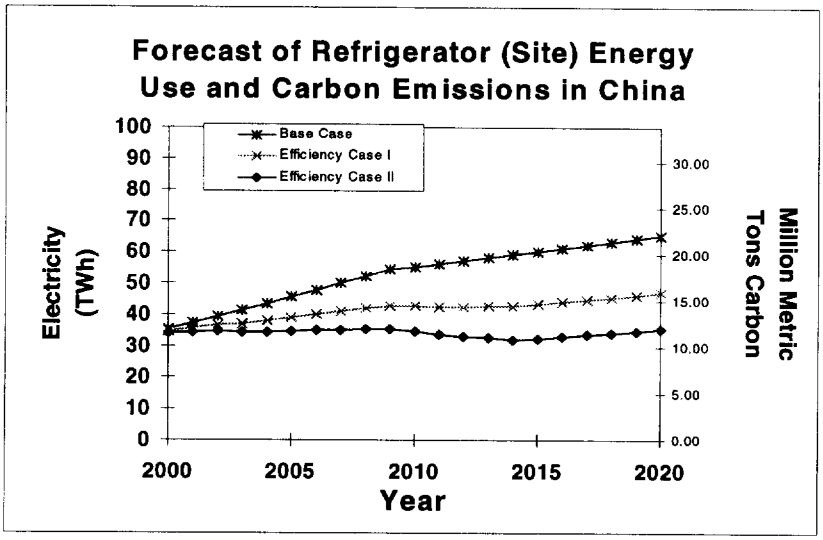

Figure 8. Three scenarios for refrigerator energy use and the resulting carbon emissions in China.

Air Conditioner Energy and Emissions Forecast

Based upon the forecasts of air conditioner saturation levels in the urban and rural sectors, projected air conditioner energy consumption and associated carbon emissions are shown in Figure 9. This forecast assumes a constant base case UEC of 450 kWh/y [EPA, 1997] and a life of 15 years for a 2.7 kW capacity air conditioner. The UEC is based on surveys of 100 households in three Chinese cities. The weighted average of all the units surveyed indicates a power draw of of 1.04 kW for 433 hours per year. In the 100 household survey [EPA, 1997], the average yearly usage for the southern city of Guangzhou was reported as 183 hours. This was presumed to be too low given the wealth and climate of the city and instead 540 hours (3 hours a day for 180 days) was assumed in calculating the weighted average of yearly usage. The choice of 540 hours is similar to the hours of use in other urban cities (e.g., Bangkok) of similar wealth and climate. A new study is in progress to measure air conditioner energy consumption in 150 households in China. In the base case, efficiency is assumed to be frozen.

A new efficiency standard implemented in 2000 was assumed in the calculations for the efficient cases (Case I & Case II). While the efficiencies represented by Cases I and II are technically achievable, we are not suggesting that they will actually be implemented as standards by 2000. These are just illustrations of what savings are achievable with such efficiency improvements. Case I assumes a 406 kWh/y UEC from year 2000 onwards. This translates into a COP (coefficient of performance) of 2.87, which is the minimum required by U.S. standards taking effect in the year 2000. Such a standard would reduce cumulative (2000-2020) energy use by 7.6% from 790 TWh to 730 TWh, an energy savings of 60 TWh. In the second efficiency case (Case II), annual air conditioner energy use falls to 398 kWh/y based on a COP of 2.93. This equates to the minimum efficiency level initially recommended for the U.S. room air conditioner standards in the year 2000. Implementation of this stricter standard would result in an additional 11 TWh of energy savings by 2020. Both Case I and Case II result in total air conditioner energy use in China growing by approximately 270%, compared to a growth of almost 300% without standards.

Carbon emissions in the base case and two efficiency scenarios were analyzed. Cumulative carbon emissions for the base case and the more efficient cases totaled 268, 247, and 243 million metric tons of carbon, respectively. Efficiency case II results in savings of 1 million metric tons of carbon in the year 2010 alone, as compared to the total increase of 12.5 million metric tons in carbon emissions for China between 1995 and 1996.

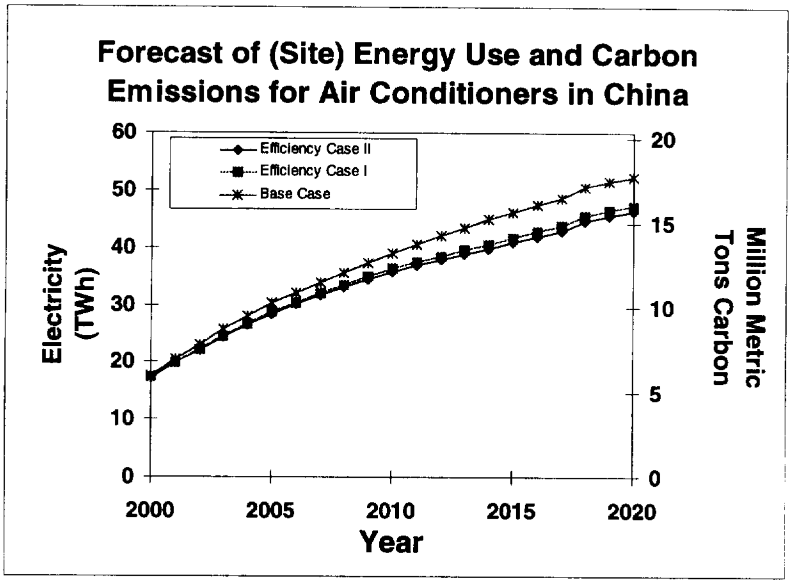

Figure 9. Three scenarios of air conditioner energy use and resulting carbon emissions in China.

Conclusions

It is clear that additional data collection on saturation rates, appliance sales, and the UEC of appliances is needed, particularly for India, Philippines and Indonesia. Unless such data are collected, it will not be possible to perform accurate estimates of energy and carbon savings from efficiency standards; this will hinder use of the clean development mechanism in the residential sectors of these countries.

Chinese data were adequate to perform end-use energy consumption forecasts for refrigerators and air conditioners. For refrigerators, very aggressive efficiency standards can maintain carbon emissions approximately at the 2000 level even with a continued rise in refrigerator saturation. Even with an aggressive program of efficiency improvement in air conditioners, however, a leveling-off of emissions before 2020 is not possible. Owing to the low level of air conditioner saturation in the 1990s, efficiency improvements after 2000 would not be great enough to offset the expected rise in air conditioner ownership and use.

We can compare our results for China to the predictions of the IPCC study. Overall, IPCC estimated that a 20% reduction in base case building energy use in 2020 was possible through codes and standards in buildings. In particular, mandatory equipment energy efficiency standards were estimated to achieve about a 13% reduction in residential building energy use in 2020. We have predictions for only two products in China. For air conditioners, we estimate a 10 to 12 % reduction in 2020 energy use. For refrigerators, we estimate a 28 to 46% reduction in 2020 energy use. For other large energy users, such as rice cookers and televisions, it may be more difficult to achieve as large a unit energy savings as we estimated for refrigerators. Therefore, the IPCC estimate of an overall 13% energy savings from mandatory residential equipment efficiency standards seems reasonable for China.

Acknowledgments

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