Title

Future Air Conditioning Energy Consumption in Developing Countries and what can be done
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Abstract
The dynamics of air conditioning are of particular interest to energy analysts, both because of the high energy consumption of this product, but also its disproportionate impact on peak load. This paper addresses the special role of this end use as a driver of residential electricity consumption in rapidly developing economies.

Recent history has shown that air conditioner ownership can grow grows more rapidly than economic growth in warm-climate countries. In 1990, less than a percent of urban Chinese households owned an air conditioner; by 2003 this number rose to 62%. The evidence suggests a similar explosion of air conditioner use in many other countries is not far behind. Room air conditioner purchases in India are currently growing at 20% per year, with about half of these purchases attributed to the residential sector.

This paper draws on two distinct methodological elements to assess future residential air conditioner 'business as usual' electricity consumption by country/region and to consider specific alternative 'high efficiency' scenarios. The first component is an econometric ownership and use model based on household income, climate and demographic parameters. The second combines ownership forecasts and stock accounting with geographically specific efficiency scenarios within a unique analysis framework (BUENAS) developed by LBNL. The efficiency scenario module considers current efficiency baselines, available technologies, and achievable timelines for development of market transformation programs, such as minimum efficiency performance standards (MEPS) and labeling programs. The result is a detailed set of consumption and emissions scenarios for residential air conditioning.

Introduction – Residential Air Conditioning in Developing Countries

In the last eceee Summer Study, in 2005, George Henderson presented a paper entitled *Home air conditioning in Europe – how much energy would we use if we became more like American households?* (Henderson 2005) which considered the hypothetical (but imaginable) scenario that European households would adopt a similar air conditioning culture to that now exists in the United States. Air conditioning is affordable to most European households; therefore, Henderson's investigation focused on climate factors as the main determinant of annual household air conditioning consumption in an air conditioned Europe. This paper poses a complementary question with respect to the developing world, namely "how much air conditioning would developing country households use if air conditioners were affordable to them?". The second question is whether this transition is likely to happen over the next 25 years, and when.

Air conditioning gets a lot of attention within the energy analysis community, and for good reason. For the developing world, an emphasis on air conditioning is even more deserved for two related reasons. First, air conditioners in developing countries will probably be installed in households where electricity consumption is still fairly low. These households will use a lot of energy for lighting, a refrigerator, possibly a washing machine, almost definitely a television and probably some other entertainment products. In such a household, the addition of an air conditioner causes a big jump in the energy consumption. The second aspect, of course, is air conditioner's contribution to peak load. In California, one of the wealthiest economies in the world, this single enduse more than any other has challenged the power grid's ability to keep the lights on. How, then, may we expect developing countries to handle it? Many already experience chronic shortages of power. Far beyond the expense of energy generation, the capital required to add new capacity (and replace worn out distribution systems) will be a high barrier to meeting demand, which in turn has significant economic and social consequences.

Of course, air conditioning is not much of an issue in countries with cold climates. Neither has it yet become widespread in the poorest countries. The influence of affluence and climate on this specialized enduse makes it an interesting one to study in the context of developing countries. Table 1 highlights this issue. The table shows a grouping of the world's countries into regions convenient for this analysis, with per capita GDP and cooling degree days for each. The regions are listed in order of increasing per capita GDP, starting with India. The table shows a general anti-correlation of wealth with temperature. Almost all of the regions as so defined have higher cooling degree days than the last 3 regions, which together include the world's wealthiest countries (members of OECD). The exceptions are the countries of the former Soviet Union, and Eastern European countries. The regions are defined in this way to correspond roughly to the regions defined by IPCC in its Special Report on Emissions Scenarios (SRES). For this analysis, we have disaggregated some of the SRES regions to specifically deal with large developing countries (India, Indonesia, Brazil and Mexico – China is not considered separately because it constitutes almost the entire Centrally Planned Asia region), and combined others. Regions in bold are considered for the analysis of developing countries.

Table 1 Per Capita GDP and Cooling Degree Days by Region

Region	Code	Per Capita GDP in 2000 ($2000)	CDD
India	**IND**	**520**	**3120**
Sub-Saharan Africa	**SSA**	**642**	**2125**
Indonesia	**INDO**	**877**	**3545**
Centrally-Planned Asia	**CPA**	**1103**	**1180**
Other Asia	**SAS-PAS**	**1287**	**2965**
Former Soviet Union	FSU	1292	347
North Africa	**NAF**	**1527**	**1808**
Eastern Europe	EEU	3472	226
Brazil	**BRA**	**3917**	**2015**
Latin America	**LAM**	**3924**	**1669**
Middle East	**MEA**	**4878**	**1796**
Mexico	**MEX**	**6731**	**1560**
Western Europe	WEU	19556	335
OECD Asia + Korea	PAO	30155	842
North America	NAM	36186	812

The table suggests that air conditioning may be most "desirable" where it is least affordable. Therefore, predicting air conditioner uptake becomes a critical task, but, as we have found, not a simplistic one. A model for ownership will have to try to explain the trade-off between climate, and financial considerations.

The second question is what efficiency can do to address consumption growth associated with air conditioning uptake. If, in fact, we are about to witness an explosion in air conditioning, isn't this the best time to get robust efficiency policy implemented, in order to 'get in on the ground floor' to produce an efficient stock from the outset? Or will we find that even strong programs will not make a significant dent in the consumption growth in the absence of a technology breakthrough, and that building codes and passive cooling provides more hope.

The rest of the paper explores some of these questions, but does not answer them definitively. In particular, while the question "what can efficiency do?" is well-understood, the study of the future of Base Case consumption in developing countries leads to as many questions as it answers. In the sections that follow, we present what we consider to be a reasonable methodology, and return to the nagging questions in the Discussion.

Bottom Up Modelling of End Use Consumption and Efficiency Impacts

Strong efficiency policies for residential equipment used to be the near exclusive domain of industrialized economies, especially the United States, European Union and Japan. In the past decade or so, however, this situation has changed dramatically with the proliferation of policies, especially Standards and Labelling (S&L) programs. In the 15 years between 1990 and 2005, the number of such programs worldwide has increased from 12 to over 60 (Wiel 2005), including many developing countries. The growth in the number of programs indicates that developing country governments are increasingly concerned with controlling energy consumption, and also that they view the experience of programs in industrialized countries as having been successful. Indeed, there have been notable successes. For example, standards already written into law in the United States are expected to reduce residential sector consumption and carbon dioxide emissions by 8-9% by 2020 (Meyers 2002). Another study indicates that policies in all OECD countries will likely reduce residential electricity consumption 12.5% in 2020, compared if no policies had been implemented to date (Waide 2003). Studies of impacts of programs already implemented in developing countries are rare, but there are a few encouraging examples. Mexico, for example, implemented its first Minimum Efficiency Performance Standards (MEPS) on four major products in 1995. By 2005, only ten years later, standards on these products alone were estimated to have reduced annual national electricity consumption by 9% (Sanchez 2006). China also has a successful program which includes air conditioners among many products and passed an update for 2005, along with a very aggressive requirement to come into effect in 2009.

Despite these successes, and the increase in numbers of programs, most countries do not yet cover a wide variety of equipment, leaving an enormous potential for efficiency improvement. Quantifying how much could be saved worldwide is of increasing interest, especially as the environmental consequences of energy consumption come to be seen as a global issue. This need has led the authors, in partnership with CLASP[1], to develop an analysis package to estimate potential standard impacts over a wide range of countries, and across end uses and sectors. This package, called the Bottom Up Energy Analysis System (BUENAS) forecasts energy consumption of individual equipment types based on an econometric model utilizing macroeconomic parameters available for a wide range of countries. The analysis framework is shown in **Error! Reference source not found.**.

The analysis consists in four steps. Step 1 consists in modelling appliance ownership. The shipments and stock turnover for all these appliances are then derived from first purchases (due to increase in ownership and population growth) and replacements. Step 1 is described in detail in the section called *Forecasting Air Conditioner Ownership*. The second step of the analysis is to gather estimates of the average baseline unit energy consumption (UEC), and is the focus of the next section *Energy Consumption Forecasting*. Step 3, which estimates the unit efficiency targets achievable through energy efficiency policies is described in the subsequent section, called *Efficiency Scenarios*. This section also summarized the results of Step 4. In this step, total savings are calculated by combining the number of appliances sold in each year of the Base Case or Efficiency with the stock accounting model in order to arrive at total national end use energy consumption in each case.

Due to the modular nature of the package, various types of analysis can be performed. These can focus on a single end use over a range of countries, or they can be country or country sector analyses using individualized end use parameters[2]. The first published use of the model was a global analysis of the efficiency potential for refrigerators (McNeil 2006). Another contribution to this year's Summer Study concerns all enduses in the residential sector in India (Letschert 2007). This paper is a single end use analysis (air conditioners), concentrating on particular regions (developing countries).

[1] Collaborative Labelling and Standards Program – Information available at www.clasponline.org

[2] LBNL and CLASP have developed a separate product, the Policy Analysis Modeling System (PAMS) to consider a single enduse in one country. PAMS is available for download at http://www.clasponline.org/policy.php.

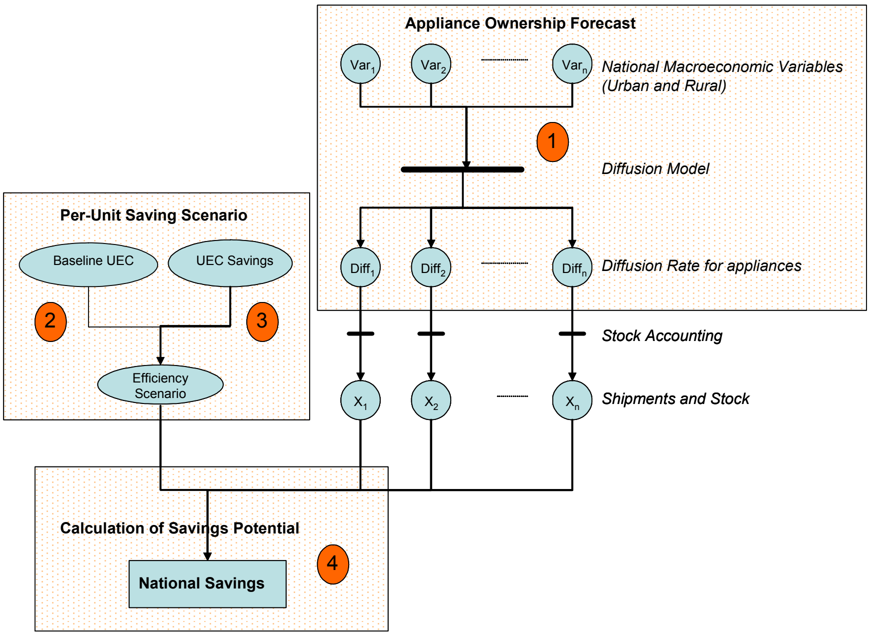

Figure 1 BUENAS Flowchart

Forecasting Air Conditioner Ownership

The first step in forecasting energy consumption and efficiency-related savings is to make a prediction of the future market for appliances. This entails forecasting sales and stock increases from increased ownership and population growth. For mature markets, where ownership levels are near saturation, sales are largely driven by replacements, population increase, and ownership of multiple appliances. For developing countries, on the other hand, stock and shipments will be dominated by the dynamics of affordability. Not surprisingly, our research finds a strong correlation between household income and appliance ownership. This is particularly true for refrigerators and for inexpensive appliances like TVs and fans. For TVs, the major barrier to uptake is electrification rates – most electrified households have at least one television. Refrigerators on the other hand, represent a major purchase, and even households with good access to electricity may find them unaffordable. Refrigerator ownership shows a steep curve of saturation versus income indicating that even low income households will acquire a refrigerator (McNeil 2006). With other end uses, an 'appliance ladder' can be observed, where households sequentially purchase a washing machine, water heater, electronic and small kitchen appliances, and finally, an air conditioner.

Modelling of air conditioner ownership is distinct from the modelling of other appliances for several reasons. Air conditioning is a major investment for most developing country households, and one which they can easily survive without, so we expect an S-shaped curve described by a logistic function. The crucial question, as discussed below, will be the threshold point – at what level of income does ownership 'take off' and how quickly thereafter does it approach saturation?

The second obvious difference between air conditioners and other appliances is the climate dependence. A reliable model will have to take climate into account. Cooling Degree Days are the most natural variable to include as the climate variable in an air conditioner ownership model.

Data and Variables

The initial approach in developing an econometric model for air conditioning saturation was to follow the method used for other appliances, that is, to combine macroeconomic variables – income, urbanization and electrification – with a climate variable (CDD) into a single linear regression in order to determine the role of each.

Climate Maximum Saturation

Surprisingly, in a simultaneous fit of CDD and income, climate was not a highly significant variable because the warmest (and often poorest) countries do not show a statistically significant saturation signal. Therefore, another approach was taken. Following the example of Henderson, we take individual regions in the United States as an example of universal availability (affordability) of air conditioning. More precisely, we assume that the saturation rates in the United States are the absolute maximum for a given CDD value. Henderson shows data, including CDD and air conditioner saturation (including both room units and central systems) for the nine U.S. Census Divisions, plus the four largest states (California, Texas, New York and Florida), as provided by the U.S. Energy Information Administration's Residential Energy Consumption Survey (RECS) for 2001. The data show a clear trend, with the coolest regions (Pacific and California) having saturation rates of about 40%, and the warm, humid regions nearly saturated. Henderson references a study which made a fit to U.S. data based on 39 individual cities (Sailor 2003). The relation is

$$Saturation = 0.944\text{-}1.17 \times e\text{-}^{0.00298*CDD}$$

In the Sailor study, cooling degree days were based on hourly data, as opposed to the RECS values, which use daily average temperatures to calculate CDD. Therefore, we refit the RECS data using the functional form from Sailor. Because saturation approaches 100%, and in order to allow for linear transformation, we replaced the constant 0.944 with 1.00. Finally, we recalculated CDD using data from major cities in each region, and removed 3 regions which appear to show anomalous behaviour[3]. The modified RECS data are shown in ***Error! Reference source not found.***. The two curves produced by refitting the above functional form to the data are very similar, but the R^2 from the regression on corrected data is 0.93 for corrected data, vs. 0.53 from the uncorrected RECS data. We chose to use the former fit which gives a relationship of

$$Saturation = 1.00\text{-}0.949 \times e\text{-}^{0.00187*CDD}$$

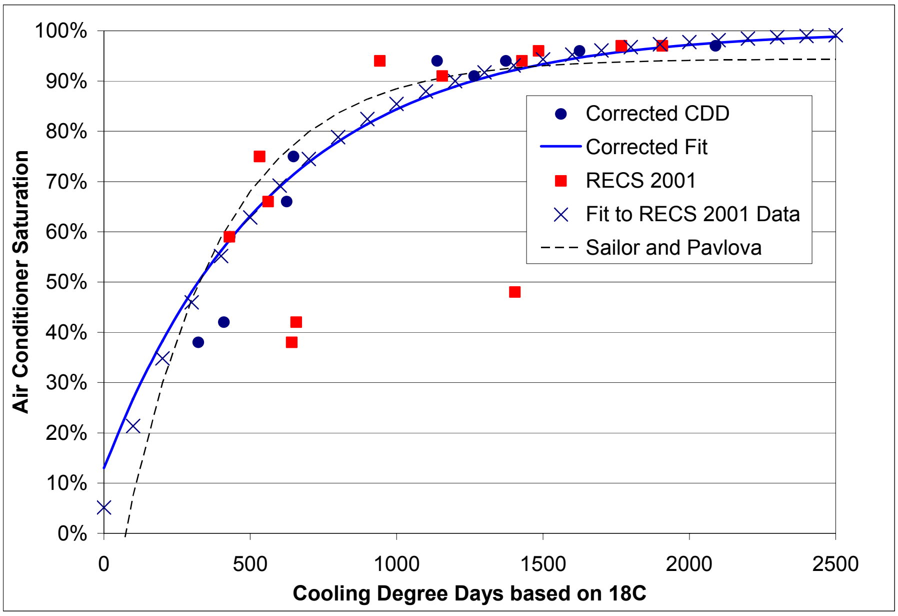

Figure 2 Air Conditioner Saturation vs. CDD for U.S. Regions

The saturation model assumes that developing country air conditioner ownership will approach the Climate Maximum given by the above relationship, but never exceed it. Saturation is expected to scale with this parameter, according to

$$Saturation = Availability(Income) \times ClimateMaximum\ (CDD),$$

where *ClimateMaximum* is a function of CDD, and *Availability* represents the affordability of air conditioning to households, and is a function of household income.

Determining National Cooling Degree Days

The determination of CDD for each country is worth mention. National CDD is necessarily an approximate measure of climate, due to the climatic variation within countries. Not even a population-weighted average will take into account the non-linearity involved in combining warm and cool regions in a national saturation. For the purposes of this analysis, however, national CDD is deemed sufficient. We use national CDD provided in a report by the World Resources Institute (Baumert 2003), which provides them for 171 countries.

Income

The analysis uses an estimate of household monthly income given by annual per capita GDP divided by twelve, and multiplied by the average number of people per household. This is a simplistic estimate, and not expected to precisely determine household income, but to provide a consistent methodology using data available for a wide range of countries. Income forecasting is performed according to a growth rate in per capita GDP, and adjusted to account for changes in household occupancy. Historical GDP estimates and forecasts were available from the

[3] The West North Central, East North Central and Mountain census divisions. Possible reasons for the anomaly are discussed in Henderson.

World Bank. Household size estimates were given by UN Habitat. Although we expect that distribution of income plays an important role in appliance ownership rates, neither saturation rates nor projections of shifts in income distribution were generally available, so we relied on average income estimates.

In order to take into account differences in the cost of living in poor countries, we used an estimate of per capita GDP adjusted for Purchase Power Parity (PPP) to characterize income. Estimates of PPP were provided by the World Bank for the years 1980-2000. For the projection of income, we used per capita GDP growth rates. As countries become wealthier, cost of living generally increases. We modelled this correction by plotting adjusted vs. non-adjusted per capita GDP in the year 2000 for 150 countries. We found that the relationship was very well described ($R^2 = 0.92$) by a power law given by:

$$GDP\ per\ capita_{PPP\ adjusted} = 20.9 \times GDP\ per\ capita_{unadjusted}^{\ 0.7088}$$

We therefore made a correction for PPP in the income forecast according to this relationship.

Other Variables

In addition to income and climate, other variables are likely to affect air conditioner ownership, notably electrification and urbanization. We have found these variables to be useful in modelling uptake of other appliances, such as refrigerators and washing machines. Use of these variables posed a difficulty in modelling air conditioning, however, because of their high degree of correlation with income. Only the wealthiest households in poor countries can afford air conditioning, and these households are almost always urban, and electrified. In addition, high income countries where air conditioning is common usually have universal electrification, and are highly urbanized. Ultimately, we found that these variables may be useful for describing large datasets, but there was not enough air conditioner data to justify their use.

Saturation Data

In our research on other appliances, we have found that saturation data is most likely provided by generalized household surveys. Refrigerator and television ownership rates in particular tend to be provided in census data, or, more often, in standard of living surveys. There is less data for air conditioners in developing countries, because it is still rare, and yet to be considered an essential item. Finally some data are provided by dedicated surveys to evaluate energy consumption.

Table 2 summarizes saturation values in the gathered data, along with the variables defined above. They cover a wide range of incomes and CDD values. The United States is included as a national value instead of in terms of individual regions, in order to not overly bias the sample. Also, countries for which data were available in multiple years appear only once in the dataset.

Table 2 Country Air Conditioner Saturation and Model Variables

Country	Year of Survey	GDP/hh/Mo. (US$)	GDP/hh/Mo. PPP Adjusted (US$)	Cooling Degree Days	Climate Maximum	Saturation	Availability
Nicaragua	2001	$403	$1,122	1533	100%	0.5%	0.5%
Albania	2002	$501	$1,093	3342	66%	2.1%	3.2%
India	1999	$201	$1,093	3120	99%	2.1%	2.1%
Sri Lanka	1999	$337	$1,312	2319	100%	2.1%	2.1%
Indonesia	1997	$308	$1,216	466	100%	2.7%	2.7%
Honduras	2001	$429	$1,108	3187	91%	3.2%	3.5%
Egypt	2003	$682	$1,293	3249	95%	3.4%	3.6%
Ghana	1997	$96	$950	1265	100%	4.5%	4.5%
Philippines	2003	$464	$1,567	3559	100%	5.0%	5.0%
Paraguay	1992	$610	$2,531	1611	95%	5.0%	5.3%
Brazil	1996	$1,119	$2,062	221	99%	7.2%	7.3%
Panama	2000	$1,370	$2,094	3001	100%	8.8%	8.9%
Thailand	2000	$646	$2,353	2742	100%	10.8%	10.8%
China	2000	$277	$1,102	881	81%	12.0%	14.9%
South Africa	2002	$950	$4,472	739	76%	15.0%	19.7%
Mexico	2003	$2,265	$3,772	3280	76%	17.4%	23.0%
Syria	2002	$618	$1,837	723	76%	17.4%	23.0%
Spain	2001	$3,858	$4,833	734	76%	29.0%	38.1%
Australia	1998	$4,364	$5,814	542	52%	40.0%	76.8%
Italy	1996	$3,816	$4,856	365	52%	40.0%	76.8%
Canada	2003	$4,863	$5,927	263	42%	41.7%	99.0%
Singapore	2003	$8,805	$6,505	850	100%	72.0%	72.1%
United States	2001	$7,675	$7,028	3280	100%	72.0%	72.1%
South Korea	2000	$3,007	$3,616	974	85%	85.0%	100.3%

The last column in Table 2 is the estimated availability, that is, the saturation divided by the climate maximum. For the warmest countries, there is little difference between saturation and availability, because the model indicates that air conditioning is applicable throughout the country. For cooler countries, such as Canada, saturation and climate maximum are very close to each other, meaning that the low saturation rate in Canada is due to the climate, not because Canadian households cannot afford it.

Modeling Income Dependence

Error! Reference source not found. shows the availability parameter from the table plotted versus income. We expect availability to follow income according to a logistic *S*-curve with a long delay before a rise in uptake. Therefore, we define the availability according to:

$$Avail = \frac{1}{1+\gamma \exp(\beta \times \text{Inc})}$$

where γ and β are to be determined by linear regression analysis. The logistic equation can be recast as a linear function by taking the log and rearranging:

$$\ln(\frac{1}{Avail}-1) = \ln\gamma + \beta \times \text{Inc}$$

The results of linear regression on this relation are shown in Table 3

Table 3 Regression Results – Availability of Air Conditioning versus Income (PPP adjusted GDP/hh/mo.)

Observations	24			
R^2	0.740			
	Coefficients	*Standard Error*	*t Stat*	*P-value*
ln γ	4.838	0.465	10.394	5.9E-10
β	-1.055	0.133	-7.922	6.9E-08

The data fit in this way shows an *S*-curve, with very gradual increase at low incomes (**Error! Reference source not found.**). The curve fits well to most countries with income of between $1000 and $2000,which show less than 10% availability. The curve does not reach 20% availability till about $3300, after which point it climbs steeply. One notable exception is seen in the data to the rule that low income countries have very low air conditioning ownership rates – this is China, which has a per household monthly GDP of only $1102 dollars, but a saturation of 12% and an availability of 14.9%. The particular case of China, and the relevance of the Chinese experience is treated in the Discussion.

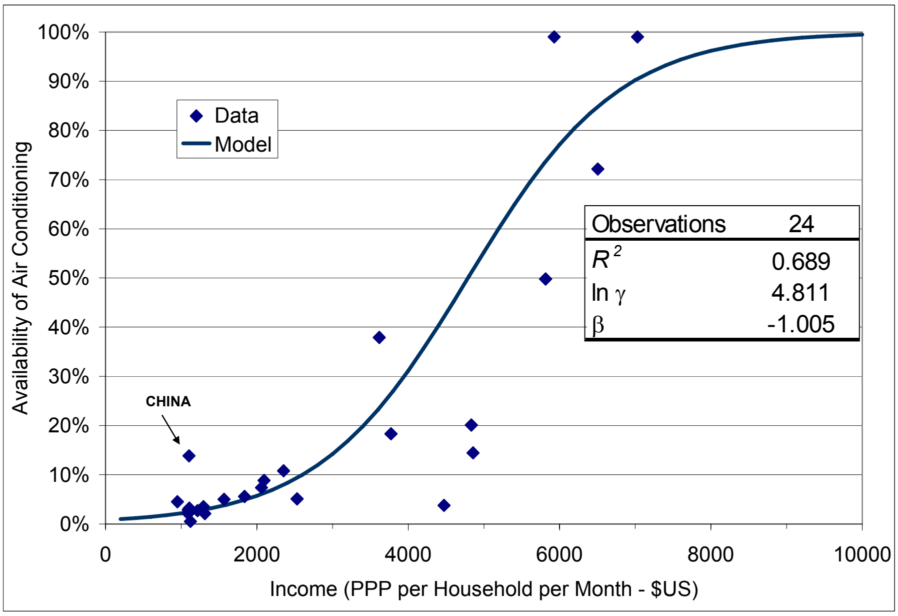

Figure 3 Air Conditioner Availability vs. Income

Forecasting Saturation

Using the models described above for *Climate Maximum* saturation and *Availability*, calculation of saturation for any given country is a simple multiplication of the two factors, which are in turn determined by CDD and monthly income, respectively. CDD is assumed not to change with time[4]. Income growth is calculated in a simplistic manner according to average annual per capita GDP growth rates determined from SRES data corresponding to the A1 scenario (Rapid Economic Growth / Low Population Growth). The growth rates are 1.6% for the industrialized regions (WEU, PAO and NAM), 5.5% for the developing Asian regions (IND, INDO, SAS-PAS,CPA), and 4.0% for the remainder of the developing world and transition economies.

The results of the saturation forecast are shown in **Error! Reference source not found.**. The graph shows that the regions with the highest current saturations will rapidly continue towards widespread use of air conditioning. Mexico stands out. By 2030, the model predicts that over 80% of Mexican households will own an air conditioner, up from about 20% in 2005[5]. This means that air conditioner ownership grows at about twice the rate of economic growth in that country. In terms of the model, this rapid growth is understood in terms of the Mexican economy reaching the threshold of affordability for air conditioners. The rest of Latin America (BRA and LAM regions) will also increase their ownership rates by factors of 2.0 (Brazil) to 3.6 (other Latin America). Second to Mexico in percentage growth is the SAS-PAS region, which includes non-India South Asia, and non-Centrally planned economies of South East Asia, such as Thailand and Malaysia, and Taiwan.

Interestingly, although already fairly high, the Middle East Region (MEA) shows continued growth as ownership in wealthy Gulf States and Saudi Arabia saturates, and there is significant uptake in moderate income countries like Iran, where air conditioner ownership is predicted to grow from about 15% to 65%. Likewise, significant ownership growth occurs in the SAS-PAS region and North Africa, where diffusion rates will exceed 20% by 2030.

Saturation rates remain low in Sub-Saharan Africa, Indonesia and India as income in these countries is not expected to exceed the threshold of affordability. Nevertheless, fractional growth in India and Indonesia is large, with the growth in the number of households using air conditioning growing at 13-14% per year, corresponding to a factor of 5 increase over the forecast period. Growth rates in Sub-Saharan Africa are expected to be much less, at about 6% per year. Finally, saturation rates in the Centrally Planned Asia region are underestimated because Chinese saturation level is not well-modelled. This discrepancy is included in the Discussion below.

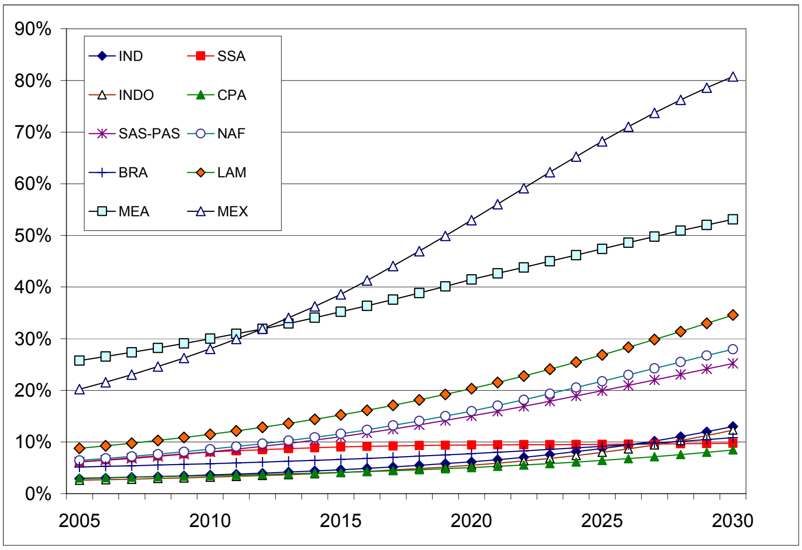

Figure 4 Air Conditioner Saturation by Region 2005-2030

Energy Consumption Forecasting

Steps 2 and 3 of BUENAS involve estimating country or region specific UECs for a Base Case (baseline technology) and Efficiency Scenario (high efficiency technology). Once the unit energy values are established, a scenario is constructed by assuming that high efficiency units become the norm in a specified year, as a result of efficiency programs. These scenarios are then combined with the stock accounting module to calculate penetration

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[4] This assumption is of course no longer an obvious one. One aspect of the analysis is that it lends itself well to studies of the impacts of climate change on air conditioner ownership and use. These are not included here, however.

[5] The availability model slightly overestimated air conditioner saturation rates in Mexico in 2003. For this reason, we readjusted the PPP correction for Mexico in the forecast in order match the 2003 data point.

rates, and the resulting stock efficiency in each year. Stock consumption in each scenario is summed and compared in Step 4.

Baseline UEC

In terms of unit energy consumption, air conditioning again distinct from other appliances. For lighting, refrigerators and washing machines, the main determinant of per unit energy consumption is the type and size of appliance used (as well as dwelling size and number of household members), and of course efficiency. For air conditioners, climate plays the dominant role. Not only will countries in a warm climate have a higher potential for air conditioner ownership, households that own them will also use them more often. As in the case of saturation, we model UEC according to CDD and income. The dependence on climate is obvious, but there is a significant dependence on income as well. Wealthier households will be less likely to be sparing in air conditioner use in order to keep utility bills low. More significantly, however, wealthy households may purchase larger units, and/or own several units[6]. Ownership of air conditioners is formulated in terms of whether air conditioning is used or not; the use of multiple units is taken into account in the UEC model.

The UEC model makes use of 37 data points, some of which were taken from the same sources as the ownership rates shown in Table 2. Values of CDD were taken from the WRI report (Baumert 2003) when the data corresponded to a country average. In cases where the data represented a particular locale (like a city), CDD were recalculated according to weather data from the Weatherbase website (www.weatherbase.com), which gives monthly temperatures. In order to take into account daily temperature variations from monthly data, we used the method originally defined in (Erbs 1983)[7]. A linear regression of the data resulted in the following relationship:

$$UEC\ (kWh) = 0.345*Income + 1.44 * CDD - 823$$

The R^2 value of the regression is 0.67. Both the household income and cooling degree days are highly significant variables. A result of the income dependence is that baseline UEC is not static, but increasing with time (with income).

Base Case Electricity Consumption

In order to forecast total electricity consumption from air conditioners, the formula for UEC developed in the last section is used to calculate unit consumption in each country in each year, given by

$$UEC^0{}_c(y) = UEC^0\ (Income_c(y), CDD)$$

The total electricity consumption is then given by the product of UEC, saturation and number of households:

$$E^0{}_c(y) = UEC^0{}_c(Income_c(y), CDD) \times Saturation_c(Income_c(y), CDD) \times HH_c(y)$$

Country consumption is then summed in order to give regional totals. The results of this calculation are shown in **Error! Reference source not found.**. Overall, the model predicts that developing country air conditioner consumption will increase from 115 in 2005 to 757 TWh – and increase of a factor of 6.8 overall. There is significant variation in the growth factors, from 3.8 in Brazil to about 11.9 in Mexico. The rest of Latin America increases by about a factor of 10. The SAS-PAS region encompassing much of South and South-East Asia also sees a factor of 8 increase.

For comparison, the forecast of residential space cooling consumption in the United States (DOE-EIA 2006) is plotted on the same chart. Consumption in the United States was still rising in the early years of the decade, but EIA predicts that it will level off and stay constant, most likely due to complete saturation, and efficiency standards that are integrated in the model. The comparison shows that the developing world will catch up to the U.S. in the next few years, but it will continue to grow rapidly, thus far surpassing the U.S by the end of the forecast.

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[6] In principle the use of central air conditioning is also modeled as equivalent to multiple room units, but this is not of great significance as the use of central systems in homes is rare outside of the United States.

[7] According to this method, CDD is derived from average monthly temperature by

$$CDD_m = \sigma_m (D_m)^{1.5} [h/2 + \ln(e^{-ah} + e^{ah})/2a],$$

where:

D_m = Monthly Degree Days
$h = (T_a-18)/[\ \sigma_m (D_m)^{1/2}]$,
$a = 1.698 (D_m)^{1/2}$,
$\sigma_m = 1.45 - 0.29 T_a + 0.664\ \sigma_y$
T_a = Average Monthly Temperature

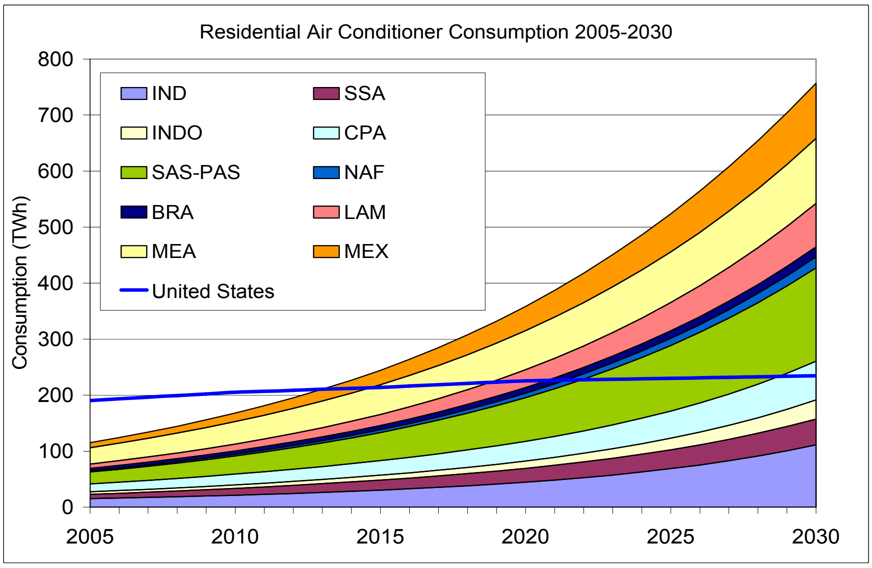


Figure5 – Projection of Base Case Residential Air Conditioner Consumption by Region 2000-2030

Efficiency Scenarios

In the sections above, we have mentioned several challenging aspects to air conditioning energy consumption modelling. Happily, there is also a simplifying aspect, namely that room and mini-split air conditioners are relatively generic worldwide compared with refrigerators and washing machines, for example, which have widely varying configurations and features across markets. In particular, efficiency ratings for air conditioners are well-defined by established international test procedures[8]. Efficiency scenarios can therefore be framed according to a common technical basis.

Unit Efficiency Improvement

We take the baseline UEC (Step 2 of BUENAS) to be the time-dependent UECs defined in the previous section. This does not explicitly take into account relative levels of efficiency for each country. Instead we create High Efficiency UECs in terms of relative improvement over the baseline, which yields a relatively good estimate in terms of overall percent savings. In order to evaluate the potential for efficiency improvement, we define the baseline efficiency, high efficiency level, and implementation dates for each region. Efficiency improvement evolves in three phases. Phase 0 includes improvements made to date, before 2005. These include programs in China, Mexico and Brazil. We include this as a separate phase, instead of within the baseline, to include savings from all developing country programs. The Base Case should therefore be understood as the state of affairs if little or no action had been taken outside of industrialized countries. Baseline efficiency, and higher efficiencies introduced in the scenario are given in Table 4. A graphical representation is shown in Figure 6.

Table 4 Baseline and High Efficiency Levels by Year

Region	EER				Percent Improvement		
	Baseline	Phase 0	Phase 1	Phase 2	Phase 0	Phase 1	Phase 2
	2000	2005	2010	2015	2005	2010	2015
IND	2.34	2.34	2.7	3.2	0%	13%	27%
SSA	2.40	2.4	2.6	3.2	0%	8%	25%
INDO	2.40	2.4	2.6	3.2	0%	8%	25%
CPA	2.40	2.6	3.2	3.2	8%	25%	25%
SAS-PAS	2.40	2.4	2.6	3.2	0%	8%	25%
NAF	2.40	2.4	2.6	3.2	0%	8%	25%
BRA	2.34	2.84	3.2	3.2	17%	27%	27%
LAM	2.34	2.34	2.6	3.2	0%	10%	27%
MEA	2.40	2.4	2.6	3.2	0%	8%	25%
MEX	2.34	2.84	3.2	3.2	17%	27%	27%

* 2012 target MEPS

**1995 Baseline

[8] For the most part. ISO test procedures are generally used, and the rating is in terms of Energy Efficiency Ratio (EER), although the United States rates mini-splits according to Seasonal Energy Efficiency Ratio (SEER), the metric defined by USDOE for central systems.

China

China has implemented a series of MEPS of increasing stringency. As of 2000, the minimum efficiency was 2.45 EER[9]. A new standard passed in 2004 came into effect in 2005, requiring EER of 2.6 EER[10]. In addition, an aggressive "reach" standard was requires that units sold in China meet or exceed 3.2 EER by 2009. Because of China's influence as an exporter, we use Chinese levels as a proxy for several regions. Also, we take the Chinese reach standard as current best practice, and assume that all regions will reach this level by 2015, if not before.

India

The current baseline efficiency in India is taken from estimates made as part of India's standards and labelling program[11]. The standard, which takes effect in 2007 is not expected to initially remove many models from the market, but it will be ramped up significantly to the level of 2.7 by 2012.

Latin America (except Brazil and Mexico)

Recent work by CLASP has established a baseline for air conditioners in Central America to be 2.34 EER (CLASP 2007), corresponding to the previous level for window units established by the USDOE. Because the U.S. is a major trade partner in Latin America, we assume this as a baseline for all of Latin America, except Mexico and Brazil, which have strong efficiency programs.

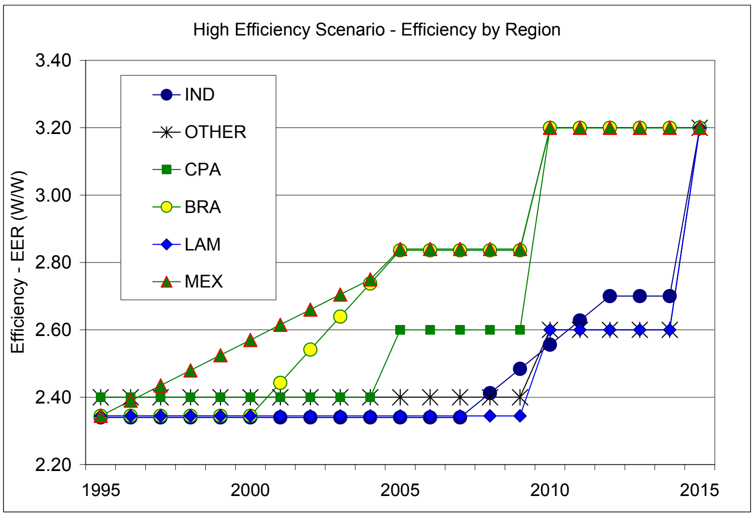
Mexico and Brazil

Mexico implemented MEPS for air conditioners in 1995 harmonized with the U.S. standards prevailing at the time, and subsequently set more stringent requirements. By 2005, the baseline for window units was at 2.84, equivalent to the most recent U.S. standards. The Brazilian program to date has been very successful in terms of labels, and the Government of Brazil is pursuing the addition of MEPS to the program. According to data published by the Brazilian testing agency[12], the average Brazilian air conditioner has an EER of 2.84[13]. Due to the success of the programs to date, we assume that both Mexico and Brazil will reach the level defined by the Chinese reach standards by 2010.

Other Regions

Efficiency programs for air conditioners are not well-developed for the most part in Sub-Saharan Africa, Indonesia, developing Asian countries[14], North Africa or the Middle East. Therefore, we assume that the baseline efficiency is similar to the Chinese 2000 standard[15], and that these levels will persist till 2010. The high efficiency scenario proposes that these countries will develop standards equivalent to Chinese standards, but with a 5-year lag time.

Figure 6 Evolution of Efficiency Values (EER) from 1995-2015



[9] We use the rating for split systems with cooling capacity between 2500 and 4500 W.
[10] Split systems < 4500 W
[11] For window units, BEE estimate based on industry data.
[12] Data from INMETRO, available at http://www.inmetro.gov.br/consumidor/tabelas.asp
[13] Split systems, average of models (not sales weighted).
[14] Thailand, the Philippines and Singapore are exceptions.
[15] This may be an overestimate for some regions, where 'dumping' of inefficient products, and mass importation of older used products is common.

Stock Accounting

Unit energy consumption scenarios are combined with ownership projections via a stock accounting model in order to generate consumption figures for the entire stock for each region and year. New product sales (shipments) are generated either by new households or households purchasing an air conditioner for the first time, or by replacements of worn-out equipment. In our model, first purchases are the difference in total stock (saturation times number of households) from one year to the next. After equipment enters the stock, it is retired and replaced according to a simple retirement function with a mean lifetime of 15 years. Products are assumed to last at least 10 years, after which the probability of retirement gradually increases until it reaches 100% at 20 years, the maximum air conditioner lifetime. Each retirement generates another replacement shipment.

Energy Savings Results

Once the components of ownership forecasting and unit energy scenarios (Steps 1-3) are completed, bringing them together in order to estimate total savings is relatively straightforward (Step 4). In the Efficiency Scenario the energy consumption of the entire stock in region *r* in year *y* is given by

$$E_{r,y} = E^0_{r,y} \frac{\sum_{j=1}^{20} \left(\frac{EER^0}{EER} \right)_{r,y-j} \times Surv(j)_y}{\sum Surv\ (j)}$$

This equation represents a weighted average of efficiency for products shipped in the previous stock. The efficiency efficiency factor EER^0/EER is determined by the scenarios in Table 4. For example, the expected improvement over the baseline in Indonesia after 2010 is 8% and 25% after 2015. Therefore, the efficiency factor is 1.0 through 2009, 0.92 from 2010 to 2014, and 0.75 thereafter. Efficiency factors are weighted by the probability of survival *Surv,* which is in turn determined by the retirement function. The denominator is a normalization factor equal to the percentage of all products purchased in the last 20 years that remain in the stock. **Error! Reference source not found.** shows the results of the projection of the Efficiency Scenario by region. The Base Case total is shown for comparison.

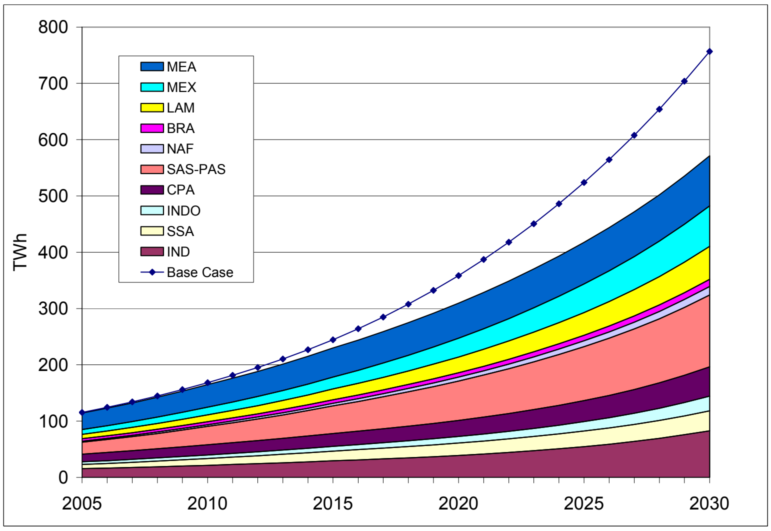


Figure 7 Projection of Efficiency Case Residential Air Conditioner Consumption by Region 2000-2030

Table 5 shows consumption and savings in individual years. A comparison can be made to our previous research on refrigerators (McNeil 2006). That study estimated developing and transition country[16] refrigerator consumption to be 308 TWh in 2005, increasing to 581 TWh by 2030. This means that current air conditioner consumption, at 115 TWh is less than 40% of refrigerator consumption, but will grow to be considerably higher at 757 TWh. This is not surprising considering that refrigerator ownership is already saturated in several of the regions, and. This would tend to suggest the view that air conditioning will emerge as the most important enduse in the future in developing countries. Energy savings by 2020 will be only half of the equivalent value for refrigerators, but will be higher (185 TWh vs. 155 TWh) in 2030. The savings in that year will exceed the total consumption estimated in 2005 by 60%.

[16] That study included Eastern Europe and the Former Soviet Union together with developing country regions.

Table 5 Energy Consumption and Savings by Region

Region	2005	2010	2020	2030	2010	2020	2030	2010	2020	2030
	Base Case				Efficiency Case			Savings		
	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh
IND	15	21	45	111	21	39	83	0.1	5.8	28.3
SSA	8	12	25	46	12	22	35	0.0	2.6	10.7
INDO	5	6	13	34	6	12	26	0.0	1.4	8.0
CPA	14	19	35	69	18	29	52	1.0	6.7	17.3
SAS-PAS	21	32	78	167	32	70	128	0.0	8.2	38.9
NAF	2	3	8	20	3	7	15	0.0	0.8	4.6
BRA	5	6	10	18	5	8	13	0.7	2.4	4.7
LAM	8	12	32	78	12	28	58	0.0	3.7	19.5
MEA	29	40	70	116	40	62	89	0.0	7.4	27.0
MEX	9	15	43	99	14	33	72	1.7	10.0	26.3
Total	115	168	358	757	165	310	571	3.4	48.9	185.4

Discussion

While there are many technical parameters and use patterns that vary between countries, we can be fairly confident about the unit efficiency improvements achievable. Savings in this range have been accomplished already in industrialized countries, and for other products in developing countries. Consumption level, and especially saturation rates seems much less certain, however. This is due to the unique nature of the evolution of uptake of air conditioning with income. **Error! Reference source not found.** clearly displays the issue at hand. In some sense, the general form of the curve seems believable enough – we would expect that for this particular appliance that mass uptake would be very slow at low incomes, but at some point a threshold is reached when air conditioning becomes affordable and becomes the norm seemingly overnight. This, phenomenon has indeed been witnessed, notably in China, where urban air conditioning saturation grew from 2.3% to 61% between 1993 and 2003[17], at a truly astonishing growth rate of 39% per annum. Another example is South Korea, where it grew by a factor of five in about the same period (KEPCO 2004). The crucial question is to determine the income at which takeoff occurs, and how fast the uptake proceeds thereafter. Unfortunately, there are not many examples of mid-income countries with available saturation data, which would give more confidence in the model. Mexico and Korea are perhaps the best evidence that we are gaining accurate insights. In terms of per capita income, however, most countries have a long way to go.

Then, of course, there is China. The apparent income of Chinese households seems far to low to explain the explosion in not only air conditioners, but other household appliances (and now automobiles). Of course, it's well known that GDP according to exchange rates greatly underestimates wealth in China. Even the PPP adjustment we applied does not eliminate the discrepancy between China and other poor countries. China also has experienced a mass urbanization. In addition, electrification has been nearly universal for a long time. Finally, the gap in wealth between urban and rural China is enormous and continually growing. This is not a unique feature to China, however. An analysis of these urban and rural sectors separately would probably be useful, but unfortunately the data do not allow it[18]. Each of these parameters suggest but do not adequately quantify what is a common understanding – that China has experienced a wholesale economic transformation that has generated 'first world' urban lifestyles in a matter of a short decade or two.

If the poorest countries studied in this paper also experience a China-like economic miracle, the projection we have presented may not be too conservative. Even if average incomes do not grow rapidly, dramatic increases in wealth of elites is already occurring. The real determining factor in air conditioner (and other appliance) ownership will be the size of the middle class, that is, the number of households achieving a moderate level of affluence. This is an area of research we hope that we and others will pursue, because the stakes for energy consumption are high, as we hope at least to have shown.

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[18] In fact, the authors contributed another paper to this year's Summer Study, which provides precisely this type of analysis for India. That analysis finds significantly higher growth in Indian air conditioner saturation during the same forecast period.

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