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Residential air conditioning in developing countries

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Abstract

The amount of energy needed to supply residences in developing countries with air conditioning (AC) was calculated for an energy-efficient base-case building, as well as for a number of alternative assumptions, using PEAR 2.1 (Program for Energy Analysis of Residences). For a warm and humid developing country climate, the result was 40-80 W_e/capita, when building envelopes, air conditioners, and other equipment were comparable to the most energy-efficient technology commercially available in Western Europe today and passive cooling and other energy-efficient cooling methods were used whenever possible. Further significant reductions of energy demand may be obtained with more efficient AC units now under development, but not through further improvements of the building envelope. The 1981 average electricity consumption for residential AC in 25 Palm Beach residences was 227 W_e/capita. To prevent electricity supply from becoming a constraint on development, it is important to improve building envelopes and appliances before AC is widely introduced in developing countries.

1. Introduction

1.1. Background

To substantially raise the standard of living for people in developing countries is partly a question of preventing electricity from becoming a constraint on development, because of environmental effects and the capital needed for new electricity production plants, supply networks, etc.

The capital required for a planned increase in total electricity production capacity in 70 important developing countries from 471 GW_3 to 855 GW_e during the 1990s was estimated by the World Bank [1] to be U.S. $745 billion in 1989. Of this amount, 38% would be hard currency, used for import. If the plans are realized, the World Bank expects the annual need of hard currency to be about 15 times the present level of its annual power lending. The possibility that the required capital will not become available appears very real.

According to United Nations (UN) statistics [2], the world-wide use of commercial primary energy in 1987 was 9.0 TW (TW year/year; W and W_e refer in the following to average power, unless otherwise stated) or an average of 1.8 kW/capita. Electricity use was 1.2 TW_e or 240 W_e/capita.

The developing regions of the world are here defined as Asia except the USSR and Japan, Africa, Middle and South America, and the Caribbean. In 1987 the use of electricity in these regions was 0.25 TW_e or about 64 W_e/capita. In industrialized regions the average electricity use was 800 W_e/capita. With 800 W_e/capita and a population of 5.0 billion (UN estimate for the year 2000 [3]), developing countries would use 4.0 TW_e.

According to Goldemberg *et al.* [4], the energy needed to provide people in a typical developing country with amenities comparable to those of Western Europe in the 1970s would be 1.0 kW/capita, if the average energy efficiency used were equal to that of the most energy-efficient technology commercially available or close to commercialization in the mid 1980s. Of the 1.0 kW/capita, 210 W/capita would be electricity. Technological leapfrogging is an important element of this devel-

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opment strategy. With such a strategy, energy would not necessarily become a constraint. However, the energy needed for space cooling was not included by Goldemberg *et al.* Would the picture significantly change if space cooling were included? This article presents a calculation of the amount of energy required to provide residences in developing countries with air-conditioning (AC).

1.2. Air-conditioning

The purpose of AC is to reduce indoor temperature and adjust humidity to a comfortable level. The comfortable temperature and humidity intervals form a comfort zone, although there is no general agreement over which levels are to be considered comfortable. The comfort zone presented by Ashok Kumar and Prasad [5] is shown in Fig. 1.

In conventional air conditioners, heat pumps are used. They remove heat without changing the amount of water in the air. With evaporative cooling the dry-bulb temperature is reduced, while absolute as well as relative humidity is increased. This demands much less energy. When both temperature and humidity have to be reduced, heat pumps are used to supercool the air, condensing water vapor into water which can be removed. Water can also be removed with drying agents. If a drying agent existed from which water could be mechanically removed, desiccation and evaporative cooling could form a cooling couple, which would demand less energy than conventional cooling. The cooling load can be reduced through a number of measures, such as ventilation, external shading, and proper building construction [6–8].

In developing countries, residential AC alone could consume much more electricity than the current total consumption. In 1981, when the electricity consumption for AC was measured in 25 residences with AC in Palm Beach, Florida, the average was 227 W_e/capita or 5.3 W_e/m^2 [9]. In these residences the average floor space per capita was 70% more than what is assumed for developing countries in this paper. On the other hand building technology is less

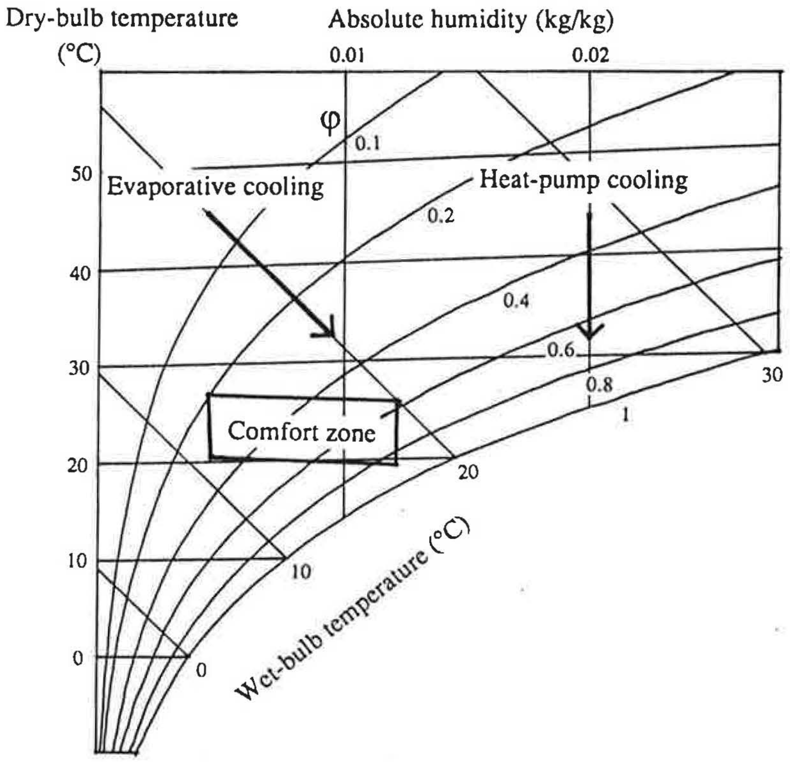

Fig. 1. A Mollier diagram for humid air, showing the comfort zone used by Ashok Kumar and Prasad [5]. With evaporative cooling the wet-bulb temperature is ideally constant, while relative humidity, φ, increases. With heat-pump cooling, temperature decreases while absolute humidity is constant.

advanced in developing countries. With 227 W/capita, five billion people in developing regions would use 1.1 TW_e for residential AC.

2. Method and assumptions

For the calculation of the energy demand, a microcomputer program called PEAR 2.1 (Program for Energy Analysis of Residences) [10] was used. It calculates the yearly energy demand for cooling and heating in residences, based on the results from a large number of simulations using the numerical model DOE-2.1A. These simulations were made using climate data for a number of U.S. locations, among them Miami in southern Florida.

2.1. The climate

The energy demanded for AC depends on the climate. For the calculation, ten cities were chosen, following an estimation of the Third World population distribution in the year 2000 [11–14]. Based on this estimate, the climate of each of the cities was assumed to be representative for the climate of a tenth of the Third World population. The cities are Beijing, Shanghai, Hong Kong, New Delhi, Calcutta, Mangalore, Jakarta, Dagoretti in Kenya, Lagos, and Rio de Janeiro. Seven are Asian, since it is estimated that slightly more than 70% of the Third World population will live in Asia by the year 2000 [12]. Eight cities are situated at or near coastlines, where the population generally is most concentrated, one at a large river, and one in the mountains. Dagoretti was chosen not only to represent Africa but also to represent the people living at a high altitude.

Beijing has a low average yearly temperature, which means that the ground can be used for cooling storage [7, 11]. In arid climates, like that of New Delhi, evaporative cooling and cooling by night radiation can be used [7, 11, 15–17]. Dagoretti is rarely very warm, and cooling requirements can be greatly reduced through ventilation and use of construction with high thermal capacity. Due to these factors, 30% of the population was assumed not to need conventional AC at all.

The remaining 70% was assumed to use conventional AC as their only cooling method. They were assumed to live in a typical developing country climate (TDCC), for which the dry-bulb temperature was defined as the average over the dry-bulb temperature of Shanghai, Hong Kong, Jakarta, Calcutta, Mangalore, Lagos, and Rio de Janeiro. The relative humidity was defined in the same way. The climates of the seven cities are all humid and warm temperate to tropical, but Shanghai is cool enough to make AC unnecessary during a large part of the year [18]. As a consequence, the average energy demand for AC in the seven cities would be slightly higher than the energy demand for AC in the TDCC.

To calculate the energy required for AC, detailed weather data are needed. For the TDCC no such data are available. The tropical climate of Miami was used to approximate the TDCC. Measured weather data for Miami are similar to data of the TDCC (see Table 1).

The summer temperatures are lower in the TDCC than in Miami, because the hottest month is not the same in all the TDCC cities. It does not affect the suitability of the Miami weather data. The suitability is affected by the fact that relative humidity is less in Miami than in the TDCC, particularly during the warmest months. This means that the exterior cooling load in the TDCC would be higher than the exterior cooling load in Miami. Other factors that may affect the suitability of the Miami weather data are the temperature distribution between day

TABLE 1. The long-term average temperature and relative humidity of the TDCC and Miami [18]. The values for the TDCC are calculated as the average over the values for Shanghai, Hong Kong, Jakarta, Calcutta, Mangalore, Lagos, and Rio de Janeiro. The monthly data for Lagos and Rio de Janeiro are displaced six months in order to make the warm season fall approximately at the same time at all cities

	Temperature (°)		Relative humidity (%)	
	TDCC	Miami	TDCC	Miami
Yearly average	23.9	23.9	78.8	72.3
January	19.6	19.4	76	74
February	20.0	19.9	77	73
March	22.1	21.4	78	70
April	24.3	23.4	78	69
May	25.9	25.3	79	71
June	26.2	27.1	82	72
July	27.0	27.7	82	72
August	27.2	27.9	82	72
September	26.4	27.4	81	75
October	25.1	25.4	78	75
November	22.7	22.4	77	71
December	20.4	20.1	76	74

and night and the number of hours with a clear sky. These were not examined.

2.2. The building

The energy demand for AC in a residence was calculated for a base case, for a case were each family was assumed to have its own single-family house, and for a number of other assumptions. The base-case assumptions are given below and in Table 2, together with the single-family case. The remaining alternative assumptions are given in the notes to Table 2 and in Table 3. When the effects of the alternative assumptions were calculated, one assumption was changed at a time while the rest were the same as in the base case, except for the case with a single-family building, when a number of assumptions had to be adjusted for consistency.

The single-family building was a one-storey house. Otherwise the building was a two-storey house with average height of the walls of 5 m and perimeter length of 52 m.

If the exterior walls of the building have high thermal capacity, coolness may be stored in them from night to day. This contributes to decreasing the energy demand for AC. The thermal capacity of the exterior walls of the building was assumed to be 280 kJ/m^{2}K.

3. Results

3.1. The base case

The result given by PEAR for the base-case building in the TDCC was 5008 kWh$_e$/year. This result had to be adjusted for the interior cooling load, which in PEAR is fixed at a level 4.25 MWh/year less than the base-case assumption. Assuming that cooling is necessary during 75% of the year and that interior heat generation is roughly constant throughout the year, the base-case energy demand in the TDCC became 5920 kWh$_e$/year. With 12 people living in the house and 300 m^2 floor space, the energy demand was 56 W$_e$/capita or 2.3 W$_e$/m^2. This may be compared with the 227 W$_e$/capita or 5.3 W$_e$/m^2 used in the 25 Palm Beach residences, since the climates of Palm Beach and Miami are similar.

Since 30% of the people in developing countries were assumed not to need a significant amount of energy for AC because of low average temperature during the year, low average and maximum daily temperatures, or arid climates, the average over the whole population was 39 W$_e$/capita.

3.2. Alternative assumptions

The results with alternative assumptions are given in Table 3. In the single-family case, the energy demand per capita was 22% higher than in the base case. This was calculated using the assumptions for the single-family building in Table 2 and the same method as above.

The effects of lower absorptivity and higher or lower total window area and air change rate were calculated directly with PEAR, using the same interior-load adjustment as in the base case. The effect of using AC units with higher cooling efficiency was calculated by assuming that the energy demand is inversely proportional to the efficiency. The effect of less-efficient appliances is a higher interior cooling load. The effects of lower window *U*-value and shading coefficient were calculated in ref. 11, using PEAR results and *U*-values and shading coefficients from ref. 10. The effects of higher or lower *U*-values of the roof and walls were found by extrapolation, using polynomial curves.

3.3. Uncertainties

There are several sources of uncertainty in this calculation. The largest uncertainty was introduced through the discrepancy between numerical models in general and reality. This discrepancy depends largely on the behaviour of the inhabitants. It is often in the order of $\pm 20\%$ [27].

From the results in Table 3, the likely effect on the result of the uncertainties regarding building envelope was estimated to be $\pm 5\%$. The effects of uncertainties of cooling efficiency, air change rate, number of families per building, and part of the population requiring conventional AC were each estimated to be $\pm 10\%$.

The discrepancy between PEAR and DOE-2.1 A is less than 10–15% [27]. The standard error was estimated to approximately $\pm 5\%$.

From the estimations above, an estimation of the standard error in the results was calculated to be $\pm 29\%$. This means that the average energy needed for AC in residences is 60 ± 20 W/capita in the TDCC and 40 ± 10 W$_e$/capita in all developing countries, provided that the most energy-efficient technology com-

TABLE 2. Assumptions used in the calculations. In PEAR, some values are fixed. These values are given in brackets when they differ from the base-case and single-family assumptions. The residential floor area was 25 m^2/capita and each household consisted of four persons, consistent with living conditions of Western Europe in the mid 1970s [4]

	Base-case assumptions	Single-family building
Climate	Miami	Miami
Households	3 (1) per building	1 per building
Inhabitants	12 (3.2) per building	4 (3.2) per building
Building floor space	300 m^2	100 m^2
Roof: *U*-value	0.18 W/m^2K[a]	0.18 W/m^2K
absorptivity	0.7[b]	0.7
Walls: *U*-value	0.23 W/m^2K[c]	0.23 W/m^2K
absorptivity	0.7[d]	0.7
Windows: area	18 m^2[e]	6 m^2
U-value	1.86 W/m^2K[f]	1.86 W/m^2K
shading coefficient	0.25[g]	0.25
Cooling efficiency (SCOP)	3.5[h]	3.5
Interior cooling load:[i]		
appliances, etc.	6910 (6255) kWh/yr[j]	2300 (5625) kWh/yr
inhabitants	5260 (1665) kWh/yr[k]	1750 (1665) kWh/yr
Thermostat set point	25.6 °C[l]	25.6 °C
Air change rate	0.6 AC/h[m]	0.6 AC/h

[a]According to Wirtshafter [19], a typical *U*-value of a roof in China today is 1.0 W/m^2K. The maximum U-value of roofs allowed in the Code of Practice for new buildings in Kuwait is 0.4 W/m^2K. According to Kellow [20], the code is 'rather generous in comparison with what can be achieved in economically optimum designs'. Wirtshafter [19] considers a *U*-value of 0.19 W/m^2K to be energy-efficient in the U.S. Alternative assumptions: 1.0 W/m^2K and 0.12 W/m^2K. [b]High absorptivity increases the heat gain and the energy demand, but it is very difficult to keep the absorptivity low in the high humidity of tropical climates [22]. Alternative assumption: 0.3. [c]The *U*-value of walls in typical Chinese residences today is 2.2 W/m^2K [19]. The maximum *U*-value allowed in Kuwait's Code of Practice is 0.57 W/m^2K [20]. For U.S. buildings a *U*-value of 0.21 W/m^2K is considered energy-efficient [19]. Alternative assumptions: 2.2 W/m^2K and 0.17 W/m^2K. [d]Alternative assumption: 0.3. [e]To decrease passive solar heat gain, the total glazed area can be small and windows can be mainly facing north (on the northern hemisphere) and not east or west. Here the gross window area was small: 6% of the floor area, while the standard in many Western countries is 10–15%. Of the window area, 14 m^2 were facing north and 4 m^2 facing south. Alternative assumptions: 36 m^2 and 9 m^2. [f]The *U*-values are given with the outside air-film subtracted [10]. A *k*-value of 1.5 W/m^2K can be attained using double panes, reflective coating, and gas filling. Commercially available windows have *k*-values down to 1.0 W/m^2K [22]. Advanced windows with *k*-values as low as about 0.5 W/m^2K are in the research stage [8]. However, for efficient windows the difference between the *k*-value and the *U*-value is large [23]. Furthermore, when the outside airfilm is subtracted, the *U*-values increase slightly for efficient windows, but more for inefficient windows. Alternative assumption: *U*-value of 1.0 W/m^2K, excluding the outside airfilm. [g]The shading coefficient is defined as the ratio of the heat gain through the window to the heat gain through a single-pane window with regular glass and no coating. According to Canha Da Piedade, a shading factor—defined as the ratio of the heat gain into the room to the heat radiation on the window area— of 0.15 can be reached using double glazing and horizontal overhang above the windows. With double glazing and opaque vertical shutters, the shading factor can be as low as 0.05–0.07 [7]. Alternative assumption: shading coefficient of 0.1. [h]The most efficient smaller AC unit on the U.S. market in 1988 was a Friedrich room air conditioner with a capacity of 3.0 kW and a coefficient of performance (COP) of 3.5. The seasonal COP (SCOP) of the larger AC unit Lennox Power Saver was 4.4 [24]. For a specific AC unit, the SCOP depends on the load and is typically 5–10% less than the COP. An R&D project in Japan aims at a COP of 7 for heat pumps used for cooling [25]. Alternative assumptions: SCOP of 4.4 and 7.0. [i]The interior cooling load included latent heat, because the humidity of the TDCC is high. [j]To supply people with residential amenities comparable to Western European standards in the 1970s, using energy-efficient technology, would require 56 W/capita for lighting and appliances and 29 W/capita for hot water [4]. A third of the heat used for hot water was assumed to stay in the building. The average appliances and lighting used today in a highly developed country like Denmark demand about twice as much energy as the equipment used in this scenario [26]. Alternative assumption: 13800 kWh/year. [k]Assuming that a human being generates an average 70 W of sensible heat and 30 W of latent heat, and that the inhabitants are in the building 50% of the time. [l]This value is fixed in PEAR to 78 °F (25.6 °C). It was not assumed to be an optimum temperature, but a reasonably comfortable one. To what level the humidity is reduced is not clearly stated in ref. 10. [m]When the ambient temperature is high, a higher ventilation rate increases the energy demand, but sufficient air circulation is necessary to get good indoor conditions. Alternative assumptions: 1.0 air changes per hour and 0.4 air changes per hour.

TABLE 3. The effects on the energy demanded for AC of some changes in the assumptions of the base case. Except for the single-family house only one assumption at a time was changed. The effect of one change depends on other assumptions. This means that the effects of different changes should not be added without care. The energy demand given in the Table is the average energy demand for residential AC in developing countries. The effect and demand with higher wall U-values are within parentheses, because they are very uncertain

	Relative effect on energy demand (%)	Energy demand (W/capital)
Base-case building	–	39
Single-family building	+22	48
Roof (base case 0.18 W/m^{2}K):		
U-value = 1.0 W/m^{2}K	+22	48
U-value = 0.12 W/m^{2}K	−1.5	39
absorptivity = 0.3 (base case 0.7)	−3.4	38
Walls (base case 0.23 W/m^{2}K):		
U-value = 2.2 W/m^{2}K	(+175)	(108)
U-value = 0.17 W/m^{2}K	−1.1	39
absorptivity = 0.3 (base case 0.7)	±0	39
Windows:		
area doubled	+6.7	42
area halved	−3.4	38
U-value = 1.0 W/m^{2}K (base case 1.9 W/m^{2}K)	−1.3	39
shading coefficient = 0.1 (base case 0.25)	−4.6	38
Cooling efficiency (base case 3.5):		
SCOP = 4.4	−20	32
SCOP = 7.0	−50	20
Doubled heat from appliances, lighting and hot water	+25	49
Air change rate (base case 0.6 ac/hour):		
1.0 ac/hour	+27	50
0.4 ac/hour	−13	34

mercially available today is used, and with the assumption that the climate of Miami is representative of the climate of 70% of the Third World population. The effect of that assumption is difficult to quantify, but with more accurate climate assumptions, the results would probably be higher.

The energy demand given in Table 3 with the assumed wall U-value of 2.2 W/m^{2}K is very uncertain. It was calculated through extrapolation of values which in themselves have significant uncertainty. The result with the high wall U-value should be considered only as an illustration of the fact that if the building envelopes are not improved before AC is installed, the energy demand is much higher than in the base case.

4. Discussion

To prevent environmental effects from becoming a constraint on development, and also to reduce the capital needed for construction of new power plants, etc., it is important to improve building technology and introduce efficient appliances before AC becomes widespread in developing countries. The per capita demand of electricity in the base case is more than half the current electricity consumption in developing reactions. If the population of these regions becomes five billion, the energy demanded to supply people with residential AC would be 0.2 TW_e, if the most energy-efficient technology was used. Otherwise it could be more than 1 TW_e.

In 1989 U.S. dollar terms, the World Bank estimated the capital needed to increase electricity production capacity to $1.9 trillion per TW_e (capacity, not average power). Since AC is largely responsible for the peaks on the load in warm countries [28], the capital demand for new power plants, etc., could be reduced by at least about $2 trillion, if the most energy-efficient technology were used.

The extra costs of energy-efficient technology are in many cases lower than the savings in power-plant construction and fuel. Energy-efficient appliances and lighting are often profitable, even when only their own energy costs are calculated [29]. They become even more profitable when the costs of AC are included, since they reduce not only the energy demand for the service obtained, but also the internal cooling load and thereby AC energy demand.

The interior cooling load is important for the AC energy demand, especially when the building envelope is efficient and the heat gain from outside the building is low. In the base case, interior cooling load was 44% of total cooling load (appliances 25%, inhabitants 19%). Exterior cooling load was due to air circulation (40% of total cooling load) and heat flow through the building envelope (16%) [11].

Improvements of the building envelope beyond the base case have little effect on energy demand. A more realistic way to reduce the energy demand significantly below the base-case value would be to develop more efficient air conditioners. If the Japanese heat pump project succeeds, the amount of energy needed for AC will drop roughly by 50%, compared to the base case.

The 1.0 kW/capita scenario by Goldemberg *et al.* is not significantly changed if AC is included. It is, however, important to note that an energy-efficient future will not come about automatically. It depends on introduction of new technology and new thinking, which demands information and possibly institutional changes and regulation such as performance standards. The changes must be brought about through active choices by individuals and decision-makers in governments, organization, and companies.

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