

UNDOING UNCOMFORTABLE SUMMER HEAT ISLANDS CAN SAVE GIGAWATTS OF PEAK POWER*

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Abstract

Man has created summer heat islands of daily average intensity of 3-5 °C, adding to discomfort and increasing in air conditioning loads. (For example the Los Angeles basin uses 5 GW of air conditioning, thus tying up \$10 billion of power plants and another \$5-10 billion in HVAC equipment). We have been studying how to mitigate this heat, with increasing the amount of urban vegetation as an example.

We first discuss the major factors that create the heat island, its magnitude and impact on residential cooling energy use, and mitigation techniques. We then simulate building cooling demand as a function of the heat island intensity. Simple heat island energy balance models are used to predict the changes in dry bulb temperatures that are then used as input to DOE-2 hourly simulations. The DOE-2 results enable us to rank measures for preventing the urban heat island.

Our preliminary results indicate that planting trees can save as much as 34, 18, and 44% of residential cooling demand on a hot summer day in Sacramento CA, Phoenix AZ, and Los Angeles CA, respectively. The cooling energy savings are 53, 33, and ~ 0%[†]. Direct shading of a house itself yields only 11, 6, and 12% savings in peak power in the same locations.

I. INTRODUCTION

The urban heat island is a well documented urban phenomenon [Landsberg 1981, Lowry 1967]. The larger the city, the more intense is the summer heat island [Oke 1973] and hence the magnitude of discomfort and air conditioning load. For instance for St. Louis, Missouri, the summer heat island intensity is 4 °C during nighttime and 1 °C at noon [Vukovich et al. 1979].

Researchers have started to look at the causes and implications of the heat island, and have correlated its magnitude to the activities within and physical

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† Study of the air conditioning control strategies for Los Angeles have yielded in a saving of 7% in peak power and 88% in the annual cooling energy by simply switching from the present indoor temperature control to "smart" dual outdoor/indoor temperature control.

characteristics of the city, such as its rate of anthropogenic heat release [Torrance and Shum 1975], concentration of pollutants [Bennett and Saab 1982, Bornstein 1968, Vukovich et al. 1979], and thermal storage capacity [Myrup 1969, Atwater 1972]. The urban energy balance has been related to the canyon geometry of city streets [Nunez and Oke 1976] and to urban physical characteristics [Ojima and Moriyama 1982]; its nocturnal intensity has been related to the sky view factor [Barring and Mattsson 1985].

In fact, all the above variables work together to create the urban heat island, which makes it desirable to closely investigate their interactions so as to isolate the important causes and, if at all possible, to avoid them. In the last two decades researchers have attempted to simulate the urban heat island with one, two and three dimensional models. For an overview of the heat island history and models, the reader is referred to [Landsberg 1981 and Bornstein 1984b].

On a qualitative level, traditional and scientific observations indicate there are simple tools to alleviate the microclimate problems associated with cities. Traditional urban architects in hot climates have used whitewashed exterior walls, central courtyards, fountains, plants, windtowers, air scoops, masonry and heavy materials to control the quality of the indoor and outdoor micro-climates. The effects of these simple techniques, however, have never been quantified, nor do they specifically address changing the microclimate of an entire urban area.

The objective of our work is to quantify the potential of strategies such as evapotranspiration and shading to mitigate the summer heat island and reduce cooling energy use. We have used the DOE-2.1C program to simulate the reduction in cooling energies due to the application of these strategies.

II. THE HEAT ISLAND PHENOMENON

The best way to understand the formation of urban heat island is to look at the basic surface energy balance equation:

$$A + R_S - R_L = A + R_n = LE + H + G$$

where,

- A is the anthropogenic heat release,
- R_S is the total absorbed shortwave radiation (direct and diffuse) at the surface,
- R_L is the net outgoing longwave radiation at the surface,
- R_n is the net shortwave and longwave radiation at the surface $\equiv R_S - R_L$,
- LE is the latent heat flux away from the surface,
- H is the sensible heat flux, and
- G is the downward ground heat flux.

On a cloudless summer day, the average insolation is about 500 W/m^2 (with a maximum of about 800 W/m^2), and is the dominant term in heating the city as well as the countryside. Urbanization acts to attenuate R_S by about 15-20% [Landsberg,1981], reducing the intensity of direct solar energy by absorption,

reflection and scattering, but the urban surface albedo ($\sim 15\%$) is lower than the rural values ($\sim 25\%$). Man-made heat, A , is usually an order of magnitude lower than the solar gain. During the winter in mid/high latitude cities, man-made heat constitutes an important term but in the summer its effect is overshadowed by other features of the city that intensify solar gain, such as lowered albedo and evapotranspiration due to the reduced amount of trees and vegetation.

The longwave radiation budget depends on the balance between the incoming and outgoing radiation to the surface. The incoming longwave radiation is about 5% higher in the city as compared to rural area [Landberg, 1981]. The outgoing radiation primarily is a function of the surface temperature which in turn is being determined by the heat balance equation. Lower vegetation (urban areas) result in higher surface temperature and, hence, higher outgoing radiation. This in turn would result in lower absorbed net radiation R_n in less vegetated areas. By contrast, higher vegetation would result in higher net absorbed radiation.

The net absorbed radiation R_n is channeled into three major fluxes: LE , H , and G . It is the division of the net incoming flux into these fluxes that determines the intensity of the heat island. In areas where evapotranspiration is high (vegetated areas, forests and lakes) most of the incoming energy goes to evaporating water. Therefore less energy is left for sensible heat, resulting in lower daytime temperatures. In these conditions, usually more than 50% of R_n will go to latent heat fluxes and the other 50% is almost equally divided into sensible and ground fluxes. This is a typical condition of green rural areas [Kalanda and Oke, 1980].

In dry desert areas, sensible heat flux H is the dominant element of the energy balance and carries off more than 50% of the net incoming radiation R_n . The ground heat flux G usually accounts for 30%-40% of the heat gain and the latent heat flux LE is limited to the remaining 10%-20% or even much lower than that. This is a condition for desert areas where it is extremely hot during the day and cools off rather rapidly after sunset.

Urban areas carry their own characteristics in the energy balance equation. Use of heavy construction materials in city streets and buildings results in a higher thermal storage capacity. During the day, a substantial amount of energy is stored in the building materials and released slowly during the night. Stored heat can be both beneficial and detrimental to cooling energy requirements. The process of heat storage delays temperature rise, and thus the cooling energy and peak cooling demand during the day. The slow release of the stored heat during the night, however, will tend to accentuate the nighttime heat island. It is this slow release of stored energy which causes the *maximum* heat island to occur during the evening, when the rural areas with their small heat storage capacity have started to cool.

More important than thermal storage at least in dry climate is the lower concentration of vegetation and therefore, lower sources for evapotranspiration. During the day, more energy goes into the sensible and storage fluxes [Nunez and Oke, 1977], resulting in higher temperatures in the city as compared to the rural areas. In American cities, the daytime peaks are higher only by $\sim 2^\circ\text{C}$, but in some Latin American cities with little urban vegetation, 8-10 $^\circ\text{C}$ daytime heat islands have been recorded [Lombardo, 1985]. In desert cities, tree planting may

produce more evapotranspiration than the surrounding areas, actually lowering temperature in the city. This is referred to as the “oasis” effect [Oke 1978, Rosenberg 1974]. Smaller urban factors include the increased rate of artificial heat release and lowered albedos due to use of dark colors on roofs and walls.

To reduce the intensity of the heat island during the day, we have focused on strategies that reduce the sensible heat component and increase the latent heat flux. These strategies will decrease daytime sensible heat gain, and thus, minimize thermal discomfort and cooling energy use. Our analysis of the energy balance in the city suggests the following energy and peak power conservation measures may be effective:

- Increase shading with natural or man-made elements, with careful consideration of the orientation of buildings and urban blocks so as not to block the sun when needed in the winter [Knowles 1982].
- Increase evaporation, such as by sprinkling water on rooftops, using ponds and fountains in urban places, and by promoting trees and vegetative cover.
- Increase the thermal mass of building superstructures through using masonry (where appropriate to climate) instead of the lightweight curtain walls and glass-box architecture. This allows heat to be stored in the structures during the day, and to be flushed at night, when conditions permit. As discussed earlier, the use of the thermal mass can be either beneficial and detrimental. Further analysis is required to correctly assess the effect of the thermal mass on the electric cooling energy and power.
- Increase the urban albedo through the use of light color finishes and whitewashed buildings, keeping in mind problems of glare and other visual and thermal aspects. Light-color concrete pavements can be also substituted for asphalt.
- Reduce the artificial heat release within the city, such as by reducing the traffic load or by relocating heat sources such as factories.

In this preliminary work, we have decided to quantify only one of the above strategies - the effects of shading and evapotranspiration in reducing the daytime sensible heat flux, and therefore the cooling power and energy required in hot cities. We have studied these effects for both a hot-arid location (Phoenix) and two temperate locations (Los Angeles and Sacramento). A quantitative model has been developed to calculate the micro-climatic effects of tree evapotranspiration and to generate modified weather tapes. The cooling electricity use for a typical house in each location is then calculated for the modified weather, using the DOE-2.1C building energy simulation program. A simplified economic models along with the estimates of possible power and energy savings for each conservation scenario, is used to calculate the Cost of Conserved Energy (CCE) and the Cost of Avoided Peak Power (CAPP)*.

* Cost of Conserved Energy (CCE) =
$$\frac{\text{Annualized Investment } (\$/\text{yr})}{\text{Saved Annual Energy } (kWh/\text{yr})}$$

Annualized Investment =
$$\text{Total Investment} \times \frac{1}{1 - (1 + d)^{-n}}$$

III. MODELING

A. Shade

Two shading scenarios are modeled, the addition of one tree or three trees near each house. We have placed the trees on the west and south sides of the house so as to maximize shading effects and to minimize the peak power consumption of the house. The tree shading model is restricted to the reduction of the solar radiation on the building envelope, while in actuality, trees will also affect the ambient temperatures, wind speeds and humidity ratios. Those changes are simulated in other models we have developed that will be explained later.

We have assumed that each mature tree has a top view projection area of 50 m^2 , and that the suburban housing density is one house per 500 m^2 of land. Therefore, an increase of one tree per house is equivalent to a 10% increase in the urban tree canopy.

We have modeled the location of the trees relative to the prototype house such that the canopy does not overlap the roof and extends from 3 to 10 meters above ground surface (see Figure 1). This location maximizes window shading without seriously reducing night sky radiation from the roof.

B. Wind Modification

Depending on its position upwind of a reference point, a barrier might increase or reduce the wind speed and turbulence. In our work, we have assumed that the trees are close enough to the building envelope so that their effect is to retard the wind flow. At the city scale, the effect of the increased roughness is to decrease the wind speed at the surface. In both cases we have used a wind speed reduction formula derived by McGinn in his study of the vegetation and canopy effects at Davis, California [McGinn 1982].

C. Evapotranspiration

Estimating the effect of evapotranspiration of trees on the ambient conditions requires the solution of the transport equation in three dimensions. The authors are not aware of a verified model to analyze moisture migration and its effect on ambient conditions. To get an early estimate of this effect, we have devised a simplified model which assumes adiabatic evaporation. Given the unperturbed ambient condition as available from weather tapes and the added amount of tree cover, we use agricultural data to estimate the evapotranspiration rate as a function of insolation and dry-bulb temperature. The heat of evaporation is assumed to be extracted from the ambient air. The air volume (per unit width) contributing to this process is estimated as the product of the wind speed and the urban mixing height which is calculated for each hour. The mixing height is a function of many ambient variables including wind speed, anthropogenic heat release, heat

$$\text{Cost of Avoided Peak Power (CAPP)} = \frac{\text{Total Investment (\$)}}{\text{Avoided Peak Power (kW)}} \text{ normalized for life of a nominal power plant (normally 20 years).}$$

island intensity, rural lapse rate upwind of city and surface roughness. We have assumed a complete mixing of ambient air in this volume. Details of this model are described in [Huang 1986a]. An example of the original and modified dry bulb temperature for some trees covers for Sacramento is shown in Figure 2.

D. Prototypical House

To estimate the energy savings due to increased tree canopy, we used DOE-2.1C to calculate the air conditioning usage for a prototypical house in three cities under varying canopy conditions. The prototypical house is a one story house with 143 m^2 of floor area and a window-to-floor ratio of 10%. A 0.6 m roof overhang is assumed on the south. Construction details are standard U.S. building practices and the operating conditions as well as the infiltration rates are based on statistical surveys of current typical houses [NAHB 1979]. The house has $R=3.34$ $W/(m^2K)$ roof insulation, $R=1.95$ wall insulation, and single-pane windows. The assumed equipment is an air conditioner of SEER 9.2 and capacity dependent on the climate. For peak air conditioning demands see Tables 1 and 2. Thermostat is set at $25.5^\circ C$ for cooling and it is assumed that the occupants or a “smart” control system turns off the air conditioner and open the windows whenever the temperature and enthalpy of the outside air is lower than that of the indoors, and cooling loads can be met by ambient air at 10 air changes per hour. To account for venetian blinds, curtains, etc, a shading coefficient of 0.63 is assumed for all windows. The shading on the south and west windows due to trees is calculated automatically by the DOE-2.1C program. This house has been used in many previous studies to simulate energy performance of houses in different climates. The details of this prototype house are fully explained in [Huang 1986b].

IV. RESULTS AND DISCUSSIONS

Two sets of analyses were performed for one tree or three trees per house. The addition of three trees per house will probably cancel out the urban heat island, restore the original rural climate, and perhaps even introduce an “oasis” effect. A preliminary parametric analysis performed for Los Angeles confirmed that trees shading the west window produced the largest peak power savings.*

The simulation results for both the one-tree and three-trees cases in the three locations are presented in Table 1. It may be surprising that Table 1 shows only 65 cooling hours per year for the base case house with no additional trees in Los Angeles (all of which, incidentally, occur on only 10 days). This low number is due to our assumption of diligent occupants or a “smart control” that opens windows

* The impact of tree location on the peak power of a typical house in Los Angeles with “smart” air-conditioning control is as follows:

Tree location	none	west	south	east
Peak kW	4.46	4.03	4.41	4.32

The peak power reduction due to trees on the south is relatively small because it is assumed that a south overhang already exists.

to allow natural venting whenever the outside conditions are suitable. If we had assumed air conditioning control without natural ventilation, the number of cooling hours would have been increased more than tenfold (see Appendix; a more detailed description of air conditioning control strategies and their effects on energy and power consumption is the subject of a forthcoming paper).

The following observations are made from Table 1 :

- Percentage power savings potential is highest for Los Angeles with 44%, followed by Sacramento with 34%, and Phoenix with only 18%. In terms of absolute power saved, the potential is highest in Sacramento with 2.44 kW, second in Los Angeles with 1.96 kW, and finally Phoenix with 1.57 kW.
- Percentage energy savings potential is highest for Sacramento with 53% followed by Phoenix with 33%. Potential energy savings in Los Angeles is negligible. As we discussed earlier, most of cooling energy use in Los Angeles can be overcome by ventilation cooling.
- In all cases the effect of having two trees to the south and one to the west (=30% cover) is about twice as effective as a single tree on the west (10% cover), thus clearly showing the importance of orientation in trees placement.
- In Los Angeles, 30% cover reduces the number of cooling hours by 84% , bringing them down to only 10 hours, or one day during the whole cooling season. In Sacramento, the curtailment is of the order of 56%, down to 390 hours from an original of 904 cooling hours. In Phoenix, the reduction is 17%, down to 3028 hours.
- The net effect of wind reduction on the cooling load (both peak and energy) is negligible 1%.

The Present Value (PV) of the power and energy saved by planting trees for two scenarios are shown in Table 2. These two scenarios are based on the age of trees and their prices; we expect these two cases provide upper and lower limits for cost of conserved energy and power. For the first case we assume planting seedlings at a price of \$5 per tree [McPherson 1984, p. 173]; it takes 10 years for the seedling to mature [McPherson 1984, p. 159]. For the second case, we assume planting 5-ft trees at a price of \$60 per tree including labor costs [McPherson 1984, page 173]; we estimate that it would take 7 years for the 5-ft tree to grow to full size. We add this cost to the water cost in order to obtain the total cost of each tree.

The water consumption of a beech tree is estimated to be ~ 1 kg/h [Berustzky, 1982]. This would translate to an annual consumption of ~ 2000 gal/year. Current prices of water varies between 7-10 cent per hundred gallons*. Therefore, total water consumption of a tree is about \$2/yr. In addition to the above, we have made the following assumptions:

*The current price of water from the San Francisco East Bay Municipal Utility District is 63.5 cents per one hundred cubic feet.

- The energy and power conservation potential of trees during the growing period is neglected.
- As trees mature, their roots grow deep in the ground and for most parts of the country they will become self-sufficient in absorbing water from ground; they do not need further watering.
- Even though the average life span of a tree is high (100 years) we have assumed here a time horizon of 20 years, same as an average power plant.
- Interest rate is assumed to be 7% real.

The results from this table are encouraging. The cost of conserved energy (CCE) and avoided peak power (CAPP) is between 0.3 to 4.3 ¢/kWh and 19 to 217 \$/kW for all three locations studied. The present value of conserved energy is much higher in Phoenix and Sacramento than Los Angeles. The high but indeterminate values of conserved cooling energy in Los Angeles is due to use of “smart” control algorithm where the initial annual air conditioning energy use is only 359 kWh. It is interesting to note that the average price of electricity is about 8 ¢/kWh, and major utilities in California offer a rebate of \$100-\$300 for each kW of peak power avoided. Therefore, even with the upper limit cost of trees the CCE and CAPP seem extremely appealing.

To obtain the actual power savings in each of these locations, three essential data are required. This data include the number of households that may undergo tree planting project, the saturation and average size of actual air conditioning units used in houses, and the coincident factors for use of air conditioning units for each location. Presently, we do not have enough data to make a detailed calculation. Alternatively, we assume that one million air-conditioned houses in Los Angeles, and 250,000 each in Sacramento and Phoenix will plant trees. Table 1 can then be transformed into Table 3. The results obtained for power and energy savings in each location is encouraging; in Los Angeles ~ 2 GW (equivalent to 2 standard GW power plants) could be unloaded. Peak power savings in Sacramento and Phoenix are about 0.6 GW and 0.4 GW, respectively. These encouraging results warrants further investigation of this subject.

V. SUMMARY AND RECOMMENDATIONS

The major factors that create the heat island, its magnitude and impact on residential cooling energy use, and mitigation techniques are discussed. We have correlated the effect of planting trees on residential cooling energy and power, with specific case studies for three U.S. cities. The effects of two selected strategies (evapotranspiration and shading) and their potential in reducing the heat-island induced cooling load have been simulated.

Simulations were performed using DOE-2 building energy analysis program, in conjunction with some simple models to predict the effect of planting trees on the atmospheric dry-bulb temperature and humidity ratio. These simulations were done for three locations: Sacramento CA, Los Angeles CA, and Phoenix AZ. The location of trees is optimized with respect to the house so as to maximize the effects of shading and evaporative cooling.

Our work suggests potential energy and power savings can be realized by use the simple strategy of planting trees.* In the cities studied, the effect of planting three trees around the house can save 18%-44% of the peak power, and up to 53% of the total annual cooling electricity use. The present value of the saved peak power and the saved electricity are 29-217 \$/kW and 0.3-4.3 ¢/kWh for three seedling or three trees. Planting three trees for the approximately one million houses in the Los Angeles area can save up to 2 GW peak power. For the other two cities, 250,000 trees can save ~ 1 GW.

At this stage, we believe the following topics deserve further investigation:

1. Study the effect of changing the thermal mass of building materials.
2. Study the effect of changing the city albedo by substituting concrete pavements for asphalts, and by painting roofs and city surfaces in light colors.
3. Refine the evapotranspiration model used in this work and analyze its effect on temperature depression.
4. Refine the evapotranspiration model to consider differences between local and global effects. Although shading is modeled on a local level, evapotranspiration has been modeled assuming that the city is uniformly vegetated at the given cover percentage. We need to know the effect of spatial variations in vegetation canopy on the overall global as well as the local distribution of temperature and humidity ratio.
5. Gather observational data to validate various aspects of the heat island model. This data should include quantification of urban and neighborhood variations in surface conditions, including amounts of vegetative cover, albedo, etc., along with recorded variations in microclimate conditions.

REFERENCES

- Barring L. and Mattsson J.O, 1985, "Canyon Geometry, Street Temperature and Urban Heat Island in Malmo, Sweden", in *Journal of Climatology*, **5**, pp.433-444.
- Bernatzky, Aloys, 1982, "The Contribution of Trees and Greenspaces to a Town Climate," in *Energy and Buildings*, **5**, pp.1-10.
- Bornstein R., 1984b, "Urban Climate Models: Nature , Limitations and Applications," Reprints from WMO Technical Conference on Urban Climatology and its Application with Special Reference to Tropical Areas, Mexico City.
- Huang J., Taha H. and Akbari H. and Rosenfeld H, 1986a, "The Potential of Vegetation in Reducing Summer Cooling Loads in Residential Buildings," LBL Report No. 21291.
- Huang J., Ritschard R. et al., 1986b, "Affordable Housing through Energy Conservation," LBL Report 16343.

* A byproduct of our simulations are data showing that additional savings are possible by improving our habits or air conditioner control; i.e: opening windows ("smart" control) instead of turning on or leaving on the air conditioner ("dumb" control) when the outdoor conditions are suitable and pleasant.

- Knowles R., 1982, *Sun, Rhythm, Form*, MIT Press, Cambridge Mass.
- Landsberg, H.E., 1970, "Man Made Climatic Changes," in *Science*, Washington, **170**, pp.1265-1274.
- Landsberg, H.E., 1981, *The Urban Climate*, Academic Press, N.Y.
- Lombardo Magda, 1985, *Ilha de Calor nas Metropoles*, Editora Hucitec, Sao Paulo, Brazil.
- Lowry, W.P., 1967, "The Climate of Cities," in *Cities, Readings from Scientific American*, San Francisco, 1973.
- McGinn C., 1982, *Micro Climate and Energy Use in Suburban Tree Canopies*, Ph.D. Thesis, University of California at Davis.
- National Association of Home Builders Research Foundation, Inc., 1981, "Sustained Builder Survey Responses Result in Data Bank of Over One Million Houses," NAHB Research Foundation, Inc., Rockville MD.
- Nunez M. and Oke T.R., 1976, "The Energy Balance of an Urban Canyon," in *Journal of Applied Meteorology*, **16**, pp.11-19.
- Ojima O. and Moriyama M., 1982, "Earth Surface Heat Balance Changes Caused by Urbanization," in *Energy and Buildings*, **4**, pp.99-114
- Oke, T.R., 1973, "City Size and the Urban Heat Island," in *Atmospheric Environment*, **7**, pp.769-779.
- Torrance K.E. and Shum J.S.W., 1975, "Time-Varying Energy Consumption as a Factor in Urban Climate," in *Atmospheric Environment*, **10**, pp.329-337.

APPENDIX. THE ENERGY SAVING POTENTIALS OF "SMART" WINDOW VENTILATION

For most places in the U.S., ventilation cooling is practical during much of the cooling season. The energy savings can be observed in Table A.1 where two algorithms, mechanical cooling "dumb" and a combination of ventilation and mechanical cooling "smart" are compared. Use of the "smart" algorithm has resulted in savings of 375 watts of peak power. The reason for this saving is that the building is pre-cooled as its mass exposed to the cool ventilation air. Therefore, although the loads are similar in both "smart" and "dumb" modes, the former requires less cooling power. In our simulations, we have assumed the "smart" option to avoid overpredicting the energy savings for vegetation, although we realize that windows in most homes would not be operated in this optimal fashion.

This preliminary result on the savings of "smart" window ventilation is of great importance to utilities in Los Angeles area. It shows that by changing the control of the air conditioning unit from only the indoor temperature ("dumb" control) to the dual control by both indoor and outdoor temperature ("smart" control) the peak power and annual cooling energy use will be reduced by 7% and 88%, respectively.

Table A.1 Comparison of air conditioning without ventilation (“dumb”) to combined air conditioning and ventilation with “smart” controls in Los Angeles.

Control strategy	Peak kW	Hours Cooling (annual)	kWh/year
“dumb”	4.83	752	886
“smart”	4.46	65	108

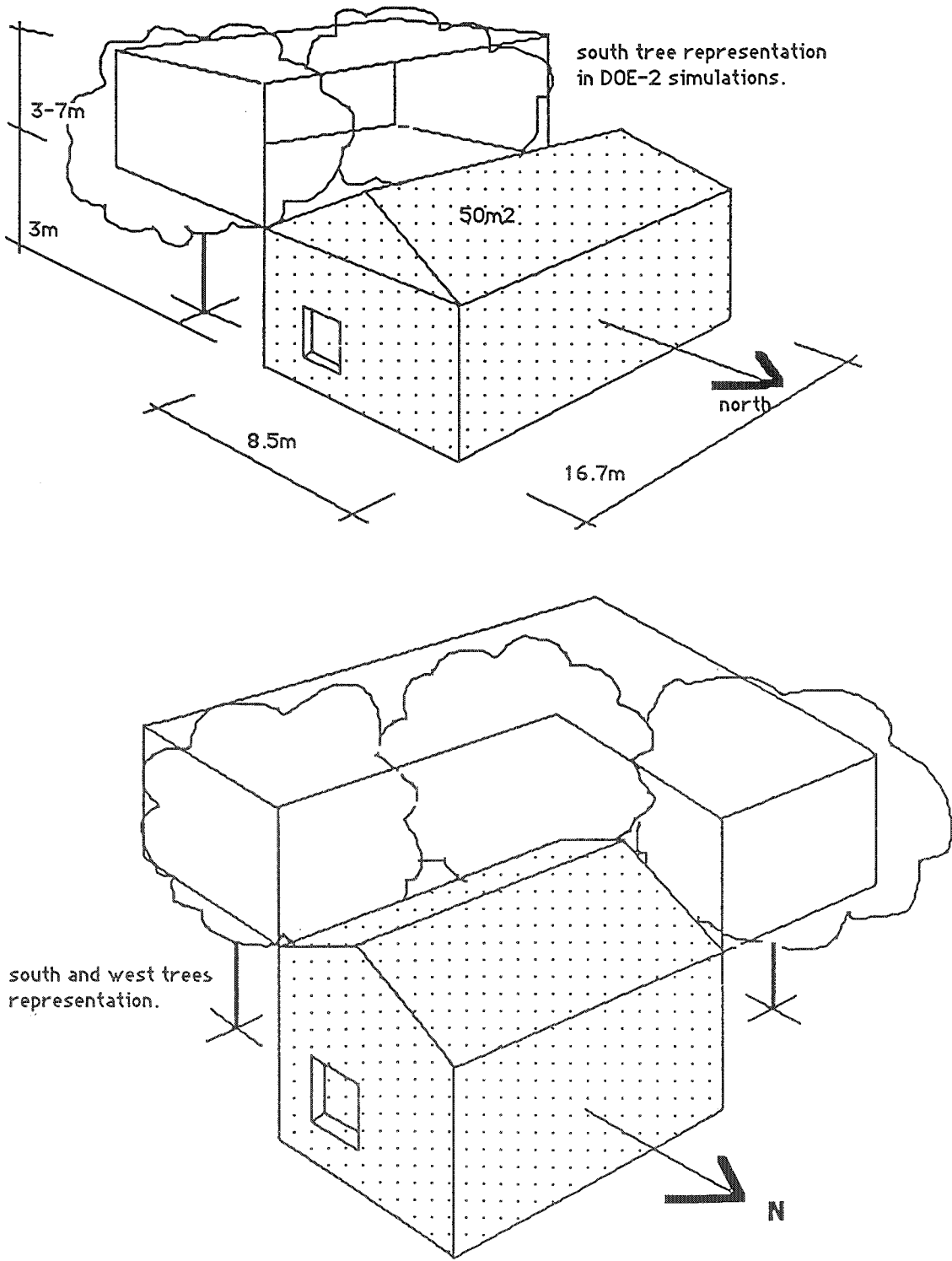


Figure 1. Schematic sketch of the simulated tree canopy. It is simulated by means of planar surfaces that approximate the tree effect.

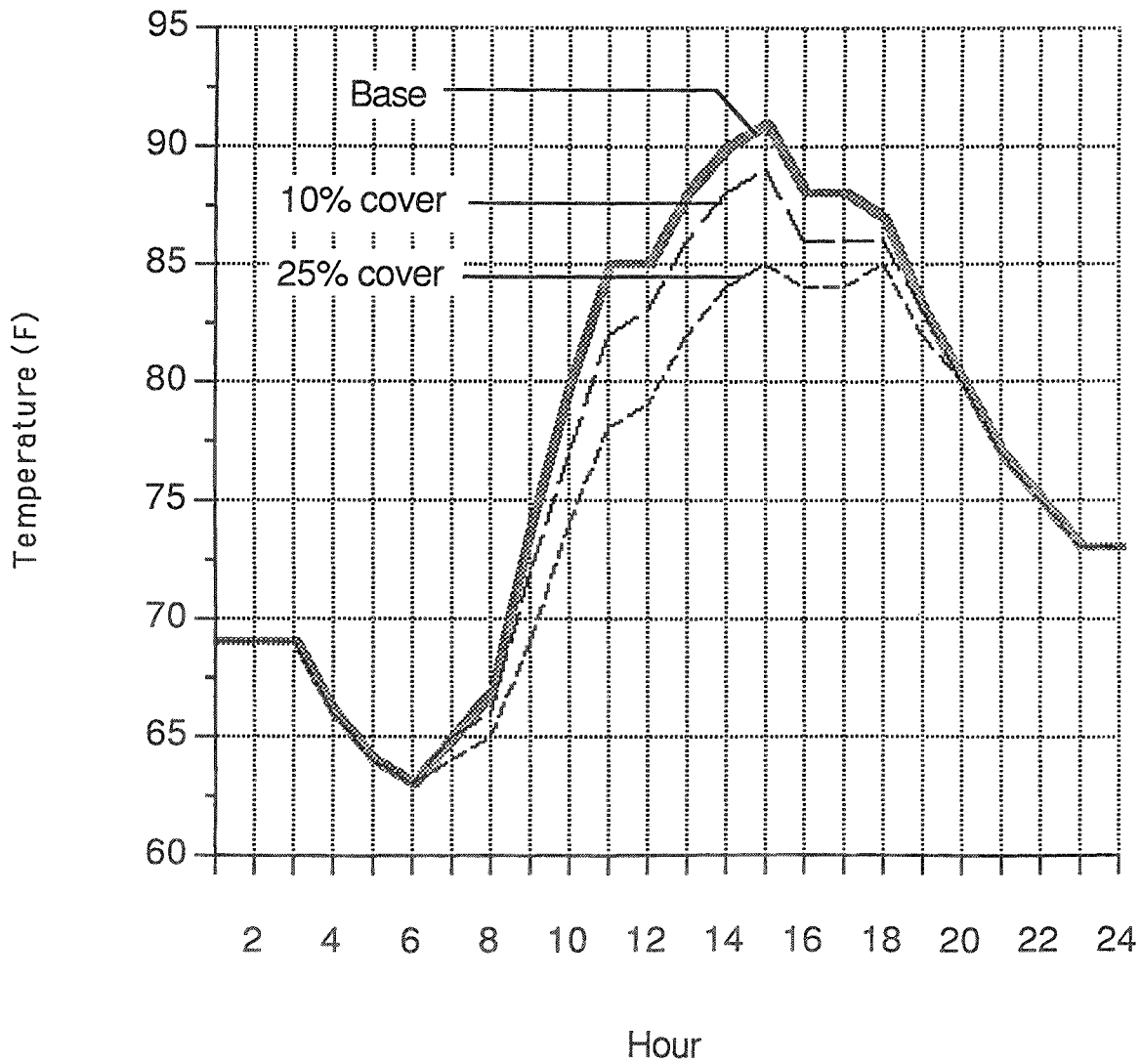


Figure 2. Outdoor dry-bulb temperatures for Sacramento, as simulated for July 27, 1980. The “base” curve shows the original temperature at the present level of vegetation. The subsequent curves show the new temperatures resulting from the evaporative cooling effect of trees, as produced by the evapotranspiration model.

Table 1. Peak power and energy savings per house resulting from planting trees. All entries except the base-case column are savings compared to that column. Note that wind modification contributes little, and evapotranspiration overshadows direct shading. Note that the macro-effect of 10% coverage (1 tree/house) is to avoid about 1 kW/tree; for 3 trees/house we can avoid 2/3 kW/tree.

Location	Number of additional trees								
	None	1 tree = 10% cover				3 trees = 30% cover			
	Base case energy use (not savings)	Energy savings				Energy savings			
	shade only (Δ)	shade +wind (Δ)	shade+wind +evapotrans. (Δ)	(% Δ)	shade only (Δ)	shade +wind (Δ)	shade+wind +evapotrans. (Δ)	(% Δ)	
Sacramento									
kW	7.10	0.66	0.72	1.24	17.5	0.76	0.81	2.44	34.4
Cooling hrs	904	36	29	165	18.3	64	95	514	56.9
kWh/yr	1420	122	114	343	24.2	225	218	757	53.3
Phoenix									
kW	8.87	0.47	0.53	0.80	9.0	0.53	0.57	1.57	17.7
Cooling hrs	3647	18	16	157	4.3	86	79	619	17.0
kWh/yr	6911	208	208	873	12.6	417	418	2289	33.1
Los Angeles									
kW	4.46	0.43	0.45	0.90	20.2	0.53	0.55	1.96	43.9
Cooling hrs	65	12	8	43	66.2	18	17	55	84.6
kWh/yr	359	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0

Table 2. Present value of saved peak power and cooling energy in 1986 dollar for savings of Table 1. Each entry shows two value corresponding to planting seedlings or 5-ft trees at \$5 and \$60, respectively. Water consumption for a growing tree is estimated to average to \sim \$2/yr for 10 years for the seedling and 7 years for the 5-ft tree. A time horizon (n) of 20 years for trees and a discount rate (d) of 7% real is assumed for these calculations.

Location	None Base case power use (kW)	Number of additional trees					
		1 tree = 10% coverage Present Value			3 trees = 30% coverage Present Value		
		shade only	shade +wind	shade+wind +evapotrans	shade only	shade +wind	shade+wind +evapotrans
Sacramento	7.10						
CAPP [†] (\$/kW)		36-172	33-158	19-92	93-449	88-421	29-140
CCE [‡] (¢/kWh)		1.9-8.8	2.0-9.4	0.7-3.1	3.1-14.3	3.2-14.8	0.9-4.3
Phoenix	8.87						
CAPP (\$/kW)		50-242	45-214	30-142	134-643	124-598	45-217
CCE (¢/kWh)		1.1-5.2	1.1-5.2	0.3-1.2	1.7-7.7	1.7-7.7	0.3-1.4
Los Angeles	4.46						
CAPP (\$/kW)		55-264	53-253	26-126	134-643	129-620	36-174
CCE (¢/kWh)		N/A	N/A	N/A	N/A	N/A	N/A

[†]Cost of Avoided Peak Power (CAPP) = $\frac{\text{Total Investment } (\$)}{\text{Saved Power } (kW)}$ normalized for life of a nominal power plant (normally 20 years).

[‡]Cost of Conserved Energy (CCE) = $\frac{\text{Annualized Investment } (\$/\text{yr})}{\text{Saved Annual Energy } (kWh/\text{yr})}$.

Annualized Investment = $\text{Total Investment} \times \frac{d}{1 - (1 + d)^{-n}}$.

Table 3. Peak power and energy savings resulting from planting trees near 1,000,000 houses in Los Angeles and 250,000 houses in Sacramento and Phoenix. All entries except the base-case column are savings compared to that column.

Location	No. of trees per house	Base-case (not Savings)	1 tree = 10% cov. Savings				3 trees = 30% cov. Savings			
			shade	shade+wind	shade+wind+evap.	$\Delta =$ (%)	shade	shade+wind	shade+wind+evap.	$\Delta =$ (%)
SACRAMENTO										
MW		1775	$\Delta =$	$\Delta =$	$\Delta =$	$\Delta =$ (%)	$\Delta =$	$\Delta =$	$\Delta =$	$\Delta =$ (%)
GWh/yr		355	165	180	310	17.5	190	202	610	34.4
			30.5	28.5	85.8	24.2	56.3	54.5	189.3	53.3
PHOENIX										
MW		2,218	118	133	200	9.0	133	143	393	17.7
GWh/yr		1,728	52	52	218	12.6	104	104	572	33.1
LOS ANGELES										
MW		4460	430	450	900	20.2	530	550	1960	43.9
GWh/yr		359	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0