



SIMULATION OF TREE SHADE IMPACTS ON RESIDENTIAL ENERGY USE FOR SPACE CONDITIONING IN SACRAMENTO

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Abstract—Tree shade reduces summer air conditioning demand and increases winter heating load by intercepting solar energy that would otherwise heat the shaded structure. We evaluate the magnitude of these effects here for 254 residential properties participating in a utility sponsored tree planting program in Sacramento, California. Tree and building characteristics and typical weather data are used to model hourly shading and energy used for space conditioning for each building for a period of one year. There were an average of 3.1 program trees per property which reduced annual and peak (8 h average from 1 to 9 p.m. Pacific Daylight Time) cooling energy use 153 kWh (7.1%) and 0.08 kW (2.3%) per tree, respectively. Annual heating load increased 0.85 GJ (0.80 MBtu, 1.9%) per tree. Changes in cooling load were smaller, but percentage changes larger, for newer buildings. Averaged over all homes, annual cooling savings of \$15.25 per tree were reduced by a heating penalty of \$5.25 per tree, for net savings of \$10.00 per tree from shade. We estimate an annual cooling penalty of \$2.80 per tree and heating savings of \$6.80 per tree from reduced wind speed, for a net savings of \$4.00 per tree, and total annual savings of \$14.00 per tree (\$43.00 per property). Results are found to be consistent with previous simulations and the limited measurements available. Published by Elsevier Science Ltd.

Key word index: Air conditioning, tree planting, tree shade, urban forest.

1. INTRODUCTION

Interactions between urban trees and the environment are numerous. Trees can reduce runoff by intercepting precipitation, absorb pollutants and emit hydrocarbons, and modify solar radiation, air temperature, wind speed and relative humidity. Of particular interest to electric utilities is the reduction in energy use for building space conditioning possible through modification of the solar radiation regime by urban trees and landscaping. Computer simulation studies using limited numbers of building and tree configurations for cities across the U.S. indicate that shade from a single well-placed, mature tree (about 8 m crown diameter) can reduce annual air conditioning use 2 to 8% (40–300 kWh) and peak cooling demand 2 to 10% (0.15–0.5 kW) (Huang *et al.* 1987, 1990; Heisler, 1991; Akbari and Taha, 1992; McPherson and Sacramento, 1992; Sand and Huelman, 1993; McPherson, 1994; Simpson *et al.*, 1994).

Sacramento Shade, a collaborative tree planting program between the Sacramento Municipal Utility District (SMUD) and the Sacramento Tree Foundation, has as its goal the planting of 500,000 shade trees by the year 2000. Over 200,000 of these trees had been planted in residential landscapes by the end of 1995 in order to increase shade on buildings and reduce air

conditioning demand. In this paper, shade impacts on residential space conditioning of this program are evaluated from computer simulations using data from a large sample of program participants. Magnitude of wind speed reduction effects on space conditioning are estimated based on literature values. Impacts of large scale tree planting on air temperature, which are thought to produce changes of the same order of magnitude as direct shade are discussed briefly, and treated elsewhere in this issue.

2. METHODS

Computer simulations were done for a random sample of 254 residential properties selected by SMUD from the 20,123 participants in the Sacramento Shade program for years 1991–1993. The sample was found to be in good agreement with the larger customer data base in terms of geographic distribution (zip code), number of trees per property, tree orientation, and tree size (Sacramento Municipal Utility District, 1994). Amount of wall and roof shade was determined due to the immediately surrounding trees, both existing and those planted as a result of the program, and due to adjacent buildings. Effects of program trees at maturity (assumed to occur in 20 to 30 yr) on cooling and heating were found as the difference between energy use with existing shade, and existing plus program shade. Tree locations and building footprints were obtained from Tree Care Agreements (TCA's) completed by Sacramento Tree Foundation

community foresters at the time of tree delivery to participants, augmented with information regarding glazing, existing trees, and adjacent buildings obtained on site visits by SMUD personnel.

Trees were located according to SMUD tree-siting guidelines approximately 90% of the time. These guidelines stipulate that trees may not be planted in north locations; trees must be sited no farther than 35 ft from the house; trees cannot be sited where they interfere with power lines; trees of smaller mature size must be sited a minimum of 8 ft away from the house, while those with larger mature size must be 15 ft away from the house; trees must be sited at least 6 ft from sidewalks, patios, driveways, or any other concrete surfaces; and smaller trees must be spaced a minimum of 8 ft apart, while larger trees must be 15 ft apart.

2.1. Shade

Solar gain reduction due to shade was calculated from tree and building data with the Shadow Pattern Simulator (SPS) program (McPherson *et al.*, 1985). SPS calculates the percentage of each wall and roof surface shaded for each hour based on building and tree dimensions, orientation and distance of trees and adjacent structures from buildings, local time zone, latitude and longitude, and time of year. Shading was determined at monthly intervals for a year to be compatible with the building energy use simulation model (see below). Annual shading data for existing and existing + program tree shade required approximately 510 SPS simulation runs.

Shade from program trees was classified based on predicted growth rate and size 30 yr after planting, and characterized based on mature shape, bole and crown height, crown diameter and shade coefficient (Table 1). Tree data were obtained from limited field sampling and species-specific values taken from the literature (PG&E, 1994; Street Tree

Fact Sheets, 1993; Sunset Western Garden Book, 1988; Johnson, 1978; Dirr, 1977). Shade from existing trees was determined from their current configuration based on the assumption that, on average, mortality and removal during the next 30 yr would be approximately balanced by tree growth and replacement. Mature size of existing trees was assigned during site visits based on species as either small, medium or large (Table 1); in cases where surveyors were unsure of species, medium size was assigned. Adjacent building shade was approximated by arrays of opaque cylinders of 1.8 m diameter located so that edges were coincident with adjacent building perimeters (Table 1; SPS allows ellipsoid, paraboloid, and cylindrical shapes only).

2.2. Building space conditioning

Hour-by-hour cooling energy (kWh) and capacity (kW) and heating energy (GJ; 1.055 GJ = 1.0 MBtu) were calculated with Micropas 4.01 (Enercomp, 1992). Primary model inputs are (1) building construction characteristics, (2) hourly weather data for a typical year supplied with Micropas for Sacramento, and (3) hourly shading data for each month of the year from SPS. Simulations for no shade, existing shade, and existing plus program shade required approximately 765 Micropas simulation runs. Building footprints were described by rectangles which most closely approximated actual building layout with the same conditioned floor area. Attached garages, defined as those with one common wall with the residence, were treated by not subjecting the common wall to solar gains. Internal garages, those with at least two common walls with the conditioned space, were modeled as unconditioned spaces with no internal gains. Since weather data represent typical conditions, results are more reflective of long term impacts, rather than impacts of extreme events.

Table 1. Tree classes and characteristics for mature program and existing trees.

Tree class		Bole ^a height (m)	Crown height (m)	Tree height (m)	Crown width (m)	Shading coeff. ^b		Shape
Size	Growth rate					Summer	Winter	
(a) Program Trees								
Small	Moderate	2.1	5.5	7.6	7.6	0.175	0.7	Ellipsoid
Medium	Moderate (Upright)	2.1	8.5	10.6	6.1	0.175	0.7	Ellipsoid
Medium	Moderate (Spreading)	2.1	8.5	10.6	10.6	0.175	0.7	Ellipsoid
Large	Slow to Medium	3.0	10.7	13.7	12.2	0.175	0.7	Ellipsoid
Large	Rapid	3.0	13.7	16.7	13.7	0.175	0.7	Ellipsoid
(b) Existing Trees								
Small		2.1	5.5	7.6	7.6	0.175	0.7	Ellipsoid
Medium		2.1	8.5	10.6	10.6	0.175	0.7	Ellipsoid
Large		3.0	13.7	16.7	13.7	0.175	0.7	Ellipsoid
Shade from adjacent 1 story building		0	3.7	3.7	1.8	0	0	Cylinder
Shade from adjacent 2 story building		0	6.7	6.7	1.8	0	0	Cylinder

^a Average height from ground to bottom of crown.

^b Fraction of irradiance transmitted through tree crown.

Table 2. Building characteristics as a function of building vintage

Vintage	R-values, m ² k W ⁻¹ (ft ² °F h Btu ⁻¹)			Glazing panes	Glazing shading coeff. ^a	Heating system efficiency	Cooling system efficiency
	Wall	Roof	Attic Ducts				
Pre-78	0 (0)	1.94 (11)	0.37 (2.1)	Single	0.63	0.75	2.3
78-83	1.94 (11)	3.35 (19)	0.37 (2.1)	Single	0.63	0.75	2.3
Post-83	1.94 (11)	5.28 (30)	0.74 (4.2)	Double	0.55	0.78	2.9

^a Includes shading coefficient of window coverings (0.63), single (1.0) and double (0.88) glazing.

^b Defined as coefficient of performance, COP = (kW cooling output)/(kW electricity input).

Building vintage was used to specify insulation levels (thermal resistance, or R -value), number of glazing panes, and HVAC equipment efficiency (Table 2). Vintages were divided into three time periods based upon original implementation of California Title 24 residential energy efficiency standards in 1978, and their revision in 1983: pre-78, 1978–83 and post-83 (Sacramento Municipal Utility District, 1994; California Energy Commission, 1992). Gross floor area was divided equally between floors of two storey buildings. Buildings were simulated as slab-on-grade, wood frame construction, with 0.45 m (1.5 ft) overhangs. Blinds had shade coefficients of 0.63, and were assumed closed when the air conditioner was operating. Summer thermostat settings were 25°C (78°F); winter settings were 20°C (68°F) during the day and 16°C (60°F) at night. It was assumed that all buildings had gas furnaces, since heating system information was not readily available. Approximately 75% of SMUD's customer base uses gas heat (Sacramento Municipal Utility District, 1994).

3. RESULTS

We present results for annual cooling energy (kWh), peak demand (kW, averaged for 8 h from 1–9 p.m. Pacific Daylight Time for the peak cooling day of 7 August), and annual heating energy (GJ) for two scenarios: existing shade from trees and adjacent buildings, and existing plus program tree shade. Peak demand changes for energy conservation measures are computed over this 8 h period since SMUD's peak load is relatively constant for these hours. Effects of program trees on energy use were calculated as the difference between the two scenarios. Results are presented for the entire sample, and also grouped by building vintage and numbers of program trees, both on a per property and per tree basis. Grouped results were normalized for differences in conditioned floor area (CFA) by multiplying energy and capacity expressed on a per unit CFA basis by mean CFA for the entire sample.

3.1. Average shade and wind impacts for all properties

Average conditioned floor area for the entire sample was 159.6 m² (1718 ft²); 71% of sample buildings had one storey with average CFA of 146 m² (1573 ft²), and 29% had two storeys with CFA of 192 m² (2070 ft²). There were an average of 2.8 existing trees, 3.1 program trees and 1.4 adjacent buildings per property. Mean annual energy use for air conditioning was 2164 kWh before and 1693 kWh after addition of mature program trees, for a change of 471 kWh (22%), or 153 kWh (7.1%) per tree. Peak demand dropped from 3.18 to 2.95 kW with addition of program trees, for an average change of 0.23 kW (7.1%) per property and 0.08 kW (2.3%) per tree. Although trees were simulated as leafless from December to March, it was assumed that shade from stems and trunks blocked 30% of winter sun, so that annual heating energy use increased from 44.1 to 46.8 GJ (41.8 to 44.4 MBtu), or 2.7 GJ (2.6 MBtu; 5.9%) per property and 0.85 GJ (0.80 MBtu; 1.9%) per tree. For the sample of 254 homes, mean differences in cooling and heating en-

ergy use from addition of program trees were significantly different from zero using a paired t -test, with 95% confidence intervals no larger than $\pm 14\%$ of the mean. It is expected that variability for actual homes would be larger, where operating conditions and internal loads for each home are likely to be different.

We evaluate net effects of wind and shading on space conditioning by estimating changes in annual net heating and cooling costs for a typical gas heated home with central air conditioning. Energy prices, adjusted for marginal costs associated with total monthly consumption, were \$6.51 MBtu⁻¹ for gas and \$0.10 kWh⁻¹ for electricity. For shade, we found annual cooling savings of \$15.25 per tree and heating penalty of \$5.25 per tree, for a net savings from shade of \$10.00 per tree. Average impacts of wind speed reduction from trees on heating and cooling load for unshaded buildings in Sacramento were estimated to be 2.5% (1.0 GJ, 0.95 MBtu) decrease per tree for heating, and 1.3% (28 kWh) increase per tree for cooling (Huang *et al.*, 1990). This resulted in an annual cooling penalty of \$2.80 per tree, which was more than offset by heating savings of \$6.80 per tree, for a net savings of \$4.00 per tree from reduced wind speed. Total average annual savings were \$14.00 per tree, which is \$43.00 per property or 9% of heating plus cooling costs for homes with existing shade.

3.2. Shade impacts as a function of building vintage.

There were 73 pre-78, 35 1978–83 and 146 post-83 vintage homes in the sample; of these, 64, 24 and 92 were one storey, respectively, and the remainder two storey. Average CFA ranged from 152 m² (1639 ft²) for post-83 to 135 m² (1451 ft²) for pre-1978 one storey homes; two storey homes ranged from 195 m² (2095 ft²) for post-83 to 173 m² (1867 ft²) for pre-1978 homes. Since numbers of two storey buildings were small, especially for older vintages, and energy use results were similar when two storey buildings were included with the one storey buildings in the analysis. Subsequent results combine one and two storey buildings.

Older buildings had more existing trees and fewer program trees, on average. Existing tree numbers increased from 2.5 to 3.0 to 3.4 trees per property for post-83, 78–83 and pre-78 buildings, respectively. Conversely, program tree numbers decreased with building age from 3.5 to 3.0 to 2.3 trees per property.

Normalized cooling load, peak demand and heating load increased with building age from 1689 to 3507 kWh, 2.4 to 5.0 kW, and 29.2 to 72.3 GJ (27.7 to 68.5 MBtu) per property, respectively, for buildings with existing shade. Normalized reductions in cooling load and peak demand per property were larger for older buildings, increasing from 447 kWh (26%) to 572 kWh (16%), and 0.21 kW (9%) to 0.29 kW (6%), respectively (Fig. 1). Normalized increases in heating load from shade was also larger for older buildings, changing from 2.5 GJ (2.4 MBtu; 9%) to 2.9 GJ (2.8 MBtu; 4%), respectively (Fig. 1).

Vintage effects on changes in space conditioning were accentuated for data expressed on a per tree basis (Fig. 2), since newer properties had more program trees compared to older properties. Absolute values of space conditioning energy use and changes were smallest, but percentage changes greatest, for newer buildings. These observations are related to the fact that solar gain is a relatively greater proportion of overall envelope heat gain for more energy efficient construction, for which total heating and cooling loads were the smallest.

3.3. Shade impacts as a function of number of trees

The number of properties with 1, 2 or 3 program trees were similar (61, 62 and 54 properties, respectively); 23 properties had 4 or 5 program trees. Of the remaining 31 properties, 16 had 6 trees, 7 had 7 trees, 1 had 8 trees, 4 had 9 trees, and 1 each had 10, 11 and 15 trees, respectively. In the analysis that follows, properties with 8 or 9 trees were combined, and the

three properties with 10, 11 and 15 trees were not considered in order to minimize variability due to small sample size. Elimination of these three properties had negligible effects on average results for all properties, changing calculated energy use by less than 2%.

Mean conditioned floor area (CFA) for properties with 6 or fewer trees was similar, ranging from 150 to 166 m² (1616 to 1792 ft²); increasing to 234 m² (2524 ft²) for properties with 7 trees, and 185 m² (1990 ft²) for 8 to 9 trees. Adjacent building numbers decreased from about 1.6 for residences with 1 or 2 program trees to 1.0 for those with 7 or more program trees. Average number of program trees tended to increase as number of existing trees decreased. Properties with 1 program tree had 3.6 existing trees, those with 2 to 5 program trees ~2.7 existing trees, declining to 1.7 existing trees for 6 program trees, and 1.3 for existing trees for 7 program trees. The 5 properties with either 8 or 9 program trees had an average of 2.0 existing trees. The increase in CFA and number of existing trees for larger numbers of program trees may be a result of variability due to the relatively small number of properties with 7 or more trees. It may also reflect correlation between tree numbers and CFA with lot size (data on lot size were not available).

Normalized changes in annual cooling energy (kWh), capacity (kW) and annual heating energy (GJ) per property increased in magnitude as program tree numbers increased from one to six trees per property (Fig. 3). Largest increases were 890 kWh (39%) and 0.42 kW (14%) and maximum decreases were 5.3 GJ (5.0 MBtu; 14%) for 6 program trees. Smaller changes for seven or more trees should be interpreted cautiously, since, with one exception, seven or more trees were found for the post-83 vintage only, and these newer homes produced smaller savings per tree than older vintages (Fig. 2). In addition, larger changes observed for properties with about six trees (Fig. 3) may be associated with the inverse relationship noted

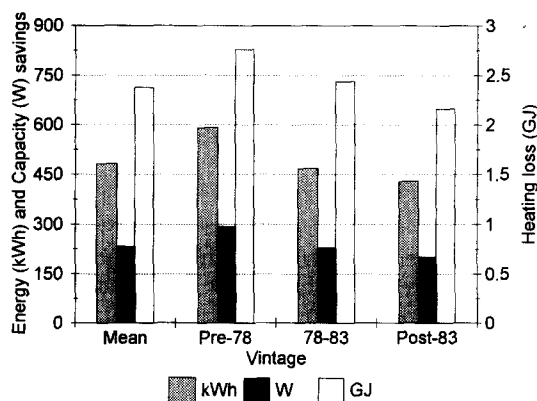


Fig. 1. Energy use impacts per property for program trees, normalized for differences in conditioned floor area, grouped by vintage.

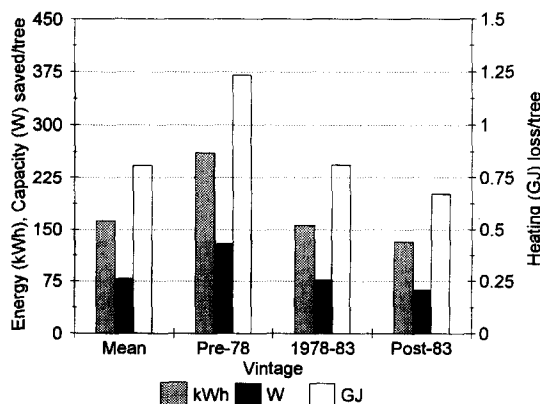


Fig. 2. Energy use impacts per program tree, normalized for differences in conditioned floor area, grouped by vintage.

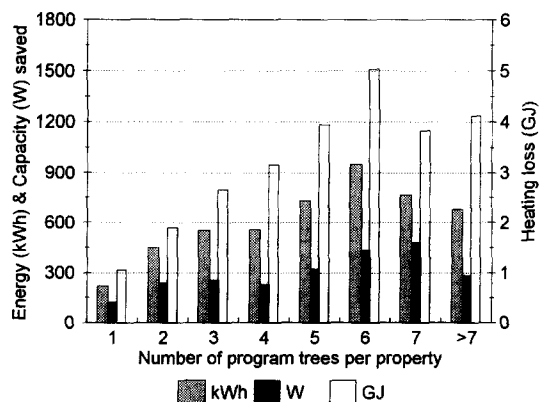


Fig. 3. Energy use impacts per property, normalized for differences in conditioned floor area, for program trees grouped by number of program trees.

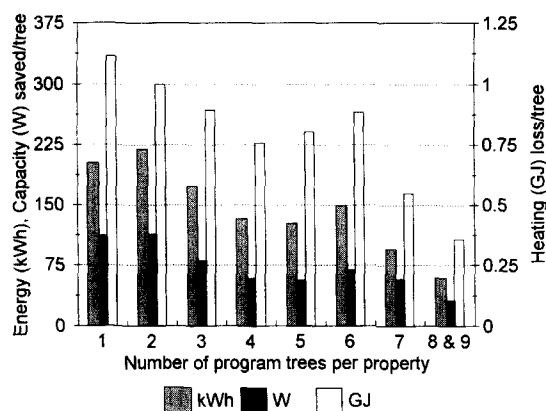


Fig. 4. Energy use impacts per program tree, normalized for differences in conditioned floor area, grouped by numbers of program trees

previously between existing and program trees; fewer existing trees tend to make program trees relatively more efficient in providing shade. Finally, there were fewer properties and hence possibly less representative samples for properties with 7 or more program trees.

For properties with 1 or 2 program trees, normalized annual decrease in cooling load and capacity, and increase in heating load, were 200 kWh (10%), 0.11 kW (3%) and 1.0 GJ (0.95 MBtu; 2%) per program tree, respectively (Fig. 4). These values were 20 to 30% less for 3 to 6 program trees, declining even further for more than 6 trees. The fact that these changes remain relatively high for up to six program trees may have been influenced by the decline in existing tree numbers as program tree numbers increased as noted earlier. Fewer existing trees implies less shading of a building initially, making shade from added program trees more effective.

4. DISCUSSION

Substantial cooling energy and capacity savings were found due to direct shading of walls and roofs of single-family residences. Relatively small diminution in savings per tree was found for up to ~ 6 trees per site. While increased heating costs from shade were approximately 33% of cooling savings, the former were more than offset by lower heating costs from reduced wind. The relatively small remaining increased cooling (\$2.80) resulting from reduced wind speed is likely an overestimate, since it assumes unshaded buildings. Shaded buildings are expected to have a relatively smaller increase in cooling load from decreased wind speed since solar heat gain is smaller for shaded buildings. In addition, we ignore savings from reduced infiltration gain, which occurs in both summer and winter, especially for older homes.

Results here are in general agreement with other studies for Sacramento which have been done for

more limited tree and building configurations (Thayer and Maeda, 1985; Huang *et al.*, 1987, 1990; Akbari *et al.*, 1993). Annual AC savings per tree in those four studies ranged from 3.2 to 8.0% for newer buildings, and 7.5 to 7.7% for older buildings, with savings from our current study being 7.7% for newer buildings and 5.2% for older buildings. Peak AC savings per tree range from 4.8 to 9.9% for newer buildings, and 2.5 to 5.6% for older buildings; savings from our current study are 2.5% for newer buildings and 1.9% for older buildings. Somewhat larger kW savings found in other studies (e.g. 5 to 10% per tree) reflects the 1 h averaging period used there compared to 8 h averages used here. Annual heating penalty from shade for these studies, about 1 and 2% per tree for old and new construction, respectively, were very similar to current results.

Energy and cost estimates found here for trees are indicative of what an individual homeowner might experience if their heating and central air conditioning systems are usually left on with thermostat set points of 20°C (68°F; 15°C or 60°F at night) and 25°C (78°F), respectively. Savings (penalty) per residence from a utility perspective will be smaller due to system diversity. Diversity accounts for differences in heating or cooling equipment between residences, and for the fact that not all air conditioners or furnaces in the utility service territory are turned on, and those that are on are not all in operation simultaneously. In a related study, for example, cooling energy and demand estimates for the average home in the system were 70 and 58%, respectively, of those found here (Sacramento Municipal Utility District, 1995). While the absolute amount of savings decrease when diversity is included, our analysis indicates that the percentage savings remain about the same.

We estimate a 7% increase in residential tree canopy cover in Sacramento residential areas in 30 yr from the proposed planting of 500,000 trees, after accounting for tree mortality and attrition. Annual energy and capacity savings from reduced neighborhood air temperature due to this increase in tree canopy are expected to be comparable in magnitude to those from direct shading (e.g. Huang *et al.*, 1987; Sailor *et al.*, 1992), possibly doubling the savings from direct shade estimated here.

No attempt was made to address impacts of changes in occupant behavior on space conditioning that might result from amelioration of the local environment by added tree canopy. These effects are difficult to evaluate, and could either reduce or enhance shade tree impacts. For example, thermostats may be set lower to increase comfort in response to overall reduction in net cooling costs; however they may be set higher if thermal comfort can be maintained at higher air temperatures as a result of cooler building surfaces.

Data reported here have been used to compute benefit cost ratios for Sacramento's tree planting program, and results indicate that the program is a cost

effective strategy from a utility perspective (Hildebrandt, 1996). Although a number of other benefits (e.g. carbon storage, runoff avoidance, air quality improvement), as well as costs (maintenance, mortality), have been associated with the urban forest (e.g. McPherson, 1993, 1995; McPherson and Simpson, 1995), energy savings appear to be one of the largest tangible benefits.

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