NIST Technical Note 1719

U.S. Department of Commerce
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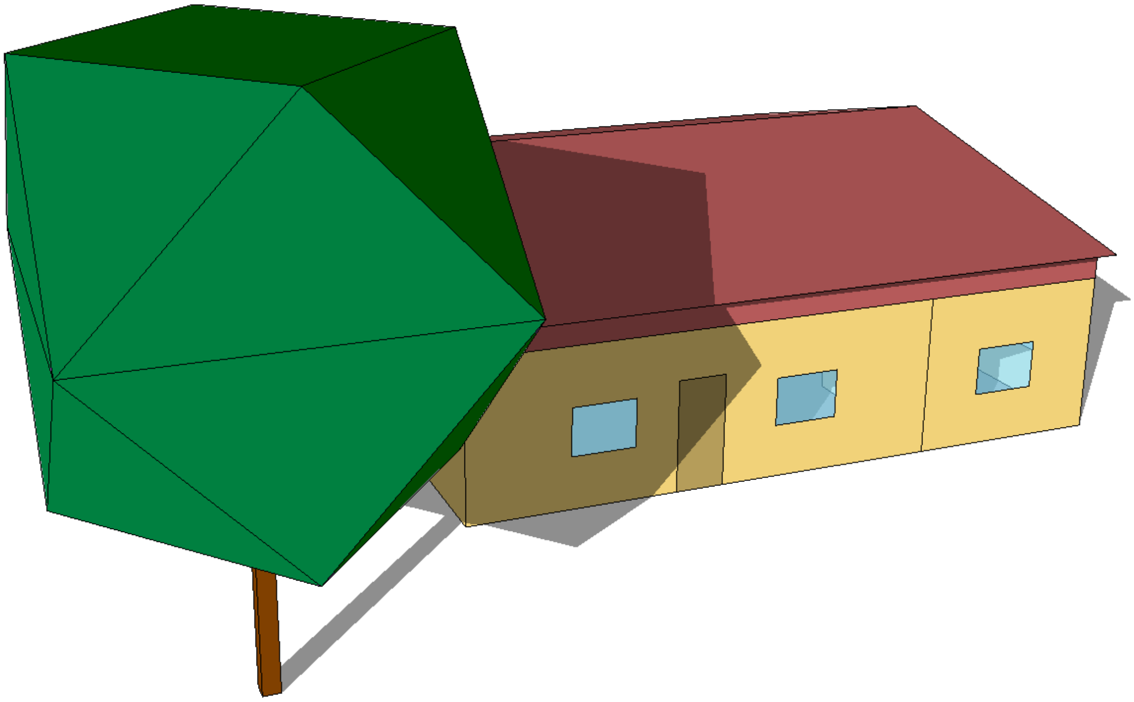
Applied Economics Office
Engineering Laboratory
Gaithersburg, Maryland 20899

Determining the Optimal Spatial Location of Shade Trees for Energy Savings: A Case Study Approach

Joshua D. Kneifel, David T. Butry, and Geoffrey H. Donovan



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Rebecca M. Blank, Acting Secretary

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Patrick D. Gallagher, Director

Abstract

Previous studies have shown that mature shade trees can reduce total energy use in residential homes in a life-cycle cost effective manner, particularly when located on the west side of a building. However, no study has precisely determined the optimal location for a shade tree, nor has the dynamic impact of the year-by-year growth of shade trees been studied. This research develops a basic method to determine the optimal locations of shade trees and compares results from six case-studies to evaluate whether the impact of shade trees varies across the United States. Building energy consumption is simulated for a prototypical residential structure over a 20-year time period after the planting of a two-year old shade tree sapling. Simulations are performed for six cities representative of five different climate zones. Overall energy reductions and life-cycle cost savings are found to vary over time and to a lesser, but similar extent between cities. Planting a shade tree is generally not cost-effective for a homeowner in the first 10 years, but is cost-effective over a 20-year time period. Given that electric utilities desire to reduce long-term peak electricity demand, the life-cycle cost results support the benefits of utility-supported shade tree programs.

Keywords

Building economics; economic analysis; life-cycle costing; tree shading; energy efficiency; residential building

Preface

This study was conducted by the Applied Economics Office in the Engineering Laboratory (EL) at the National Institute of Standards and Technology (NIST) in collaboration with the USDA Forest Service Pacific Northwest Research Station. The study is designed to determine the optimal shade tree location around a residential home and to estimate the benefits and cost impacts from shade tree growth on a residential house in six cities across the United States. The intended audience is the National Institute of Standards and Technology, electric utilities with shade tree planting programs, and any other government or private research group that is concerned with evaluating the effectiveness of using shade trees to decrease both peak and overall electricity demand.

Disclaimer

Disclaimer

The policy of the National Institute of Standards and Technology is to use metric units in all of its published materials. Because this report is intended for the U.S. construction industry that uses U.S. customary units, it is more practical and less confusing to include U.S. customary units as well as metric units. Measurement values in this report are therefore stated in metric units first, followed by the corresponding values in U.S. customary units within parentheses.

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List of Acronyms

Acronym	**Definition**
AEO	Applied Economics Office
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
COP	Coefficient of Performance
DOE	Department of Energy
EL	Engineering Laboratory
NIST	National Institute of Standards and Technology
SEER	Seasonal Energy Efficiency Ratio
SMUD	Sacramento Municipal Utility District
USDA	U.S. Department of Agriculture

1 Introduction

1.1 Background

Planting a shade tree has been suggested as one way to reduce residential energy use and life-cycle costs (Akbari et al., 1997; Simpson, 1998; Donovan and Butry, 2009). However, it is not clear how the energy savings generated by shade trees varies by precise tree location, over time as the tree grows, or across climate zones in the United States.

1.2 Purpose and Approach

The purpose of this paper is fourfold. First, develop a method of finding the optimal location of shade trees around a residential building. Second, determine the resulting energy use reductions for a prototypical house over the first 20 years after planting a tree in an optimal location. Third, compare the effects of a shade tree across six cities in the United States. Fourth and finally, determine the sensitivity of the energy savings to the location of the tree.

The whole building energy simulation software EnergyPlus V6.0 was used to simulate the energy use of a prototypical residential home with a "prototype" shade tree located between 2.1 m (7 ft) and 10.7 m (35 ft) from the house in all directions at increments of 2.1 m (7 ft). The "prototype" shade tree growth rate was chosen to be that of a London Plane tree located in Sacramento, California.[1] Simulations were run for each tree location over a 20-year growing period across six cities representing five distinct climate zones in the United States. The results are analyzed both year-by-year and over the entire study period.

1.3 Previous Study

Donovan, Butry, and Kneifel (2010) showed through both empirical and simulation analysis that a shade tree can reduce summertime electricity use. It was found that a 30-year old London Plane shade tree on the west side of the house reduces summertime electricity use by more than any other evaluated energy-conservation measures, which included improved HVAC efficiency, building envelope thermal performance improvements, and window shades. It was recommended from the previous study that future research on this topic should simulate the impacts of a shade tree growing over time, determine the optimal location around a house for shade trees, analyze the costs and benefits of shade trees using the life-cycle costing approach, and compare results for multiple cities in the United States.

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[1] The London Plane tree was the most commonly observed shade tree by Donovan and Butry (2009).

2 Simulation Design

Energy simulations are performed to evaluate the impact of a London Plane tree on the energy use of a one-story house. A London Plane tree was chosen because it is the same tree used in the literature, and therefore allows direct comparison of this study to previous shade tree studies. Results are generalizable to other tree species, so long as they exhibit similar growth rates.

The house and trees were constructed in Google SketchUp and imported into the whole building energy simulation software EnergyPlus V6.0 using the OpenStudio plug-in by NREL. The annual energy simulations used a prototypical residential home with a "prototype" shade tree located between 2.1 m (7 ft) and 10.7 m (35 ft) from the house in all directions at increments of 2.1 m (7 ft). The prototypical residential home is based on a representative home found in Sacramento, California. The parameters for the house are defined in Table 2-1.

Table 2-1 Simulation Parameters

Characteristic	Details
Floors	1
Rooms	5
Dimensions of First Floor	12.8 m Width x 12.8 m Length x 3.0 m Height
Sloped Roof	12.8 m Width x 12.8 m Length x 2.1 m Height
Central AC	15 Year Old SEER 10; COP = 2.538
Floor Area	164 m^2
% Single Pane Glazing	8.6 %
Wall Insulation	R-10
Roof Insulation	R-19
Thermostat Set Point	Constant 21°C
Air Infiltration Rate	Effective Air Leakage Area = 93.571 cm^2

As can be seen in Figure 2-1, the house includes 3 windows on each side of the house that are located approximately equal distances apart. The location of the windows will be of great importance in interpreting the results.

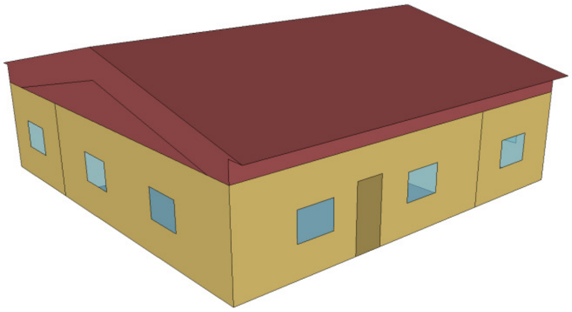

Figure 2-1 Prototypical home geometry

Figure 2-2 shows the prototypical tree height, crown height, and diameter at breast height by year.

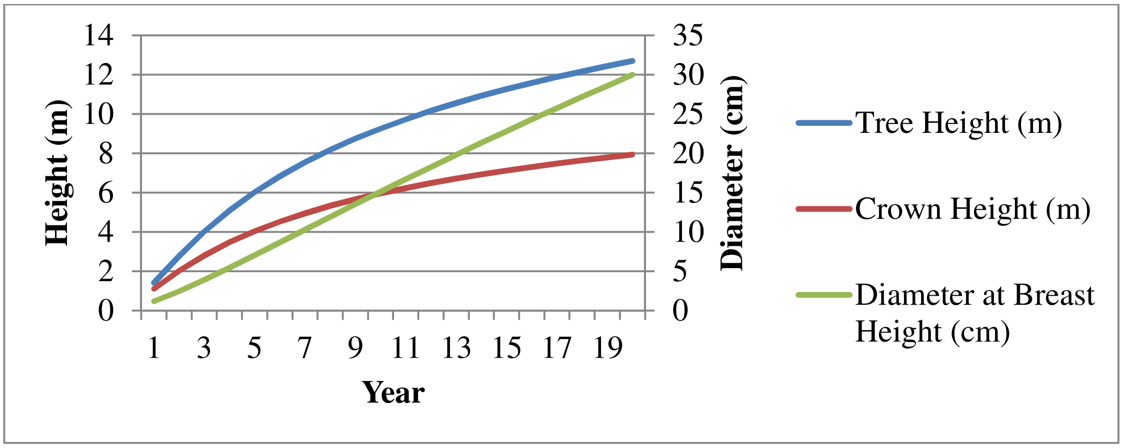

Figure 2-2 Prototypical tree height, crown height, and diameter at breast height by year

The simulations are for 20 year periods and assume the initial planting is of a two year old tree. They are run for each tree location around the house for the six cities listed in Figure 2-3, which shows the six cities and the climate zone in which they are located.

City	State
Miami	FL
Phoenix	AZ
Sacramento	CA
Washington	DC
St. Louis	MO
Boulder	CO

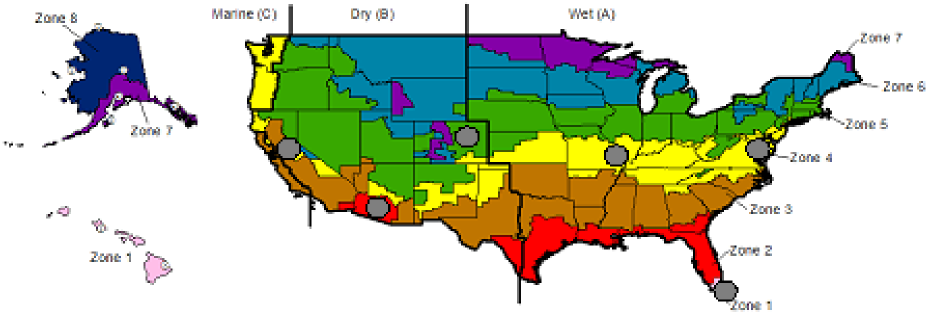

Figure 2-3 Selected Cities and Climate Zones

3 Data Analysis

The simulation results of the house with a shade tree are compared to a baseline simulation of an identical house without a shade tree. The measured difference between the two simulations is the change in energy use due to the shade tree, which determines the energy cost and life-cycle cost savings. The results are analyzed on four levels. First, a single city is analyzed over an entire study period to determine the optimal shade tree location relative to the house. Second, a single city is analyzed year-by-year to determine how the energy use and energy costs change as the tree grows. Third, the six cities are compared to one another to see how the optimal location and the related benefits and costs of a shade tree vary across different climate zones and regions of the United States. Finally, the sensitivity of the energy savings to the location of the tree is determined by comparing the energy use at the optimal location determined using the original 2.1 m (7 ft) to more precise 0.9 m (3 ft) increments.

There are four costs that must be calculated to determine the life-cycle cost of planting a shade tree: electricity costs, natural gas costs, first costs, and maintenance costs. The life-cycle cost analysis approach is defined in Rushing, Kneifel, and Lippiatt (2011) and is based on the *ASTM Standards on Building Economics*. All future costs must be discounted back to the present value by using a discount rate, which adjusts for the fact that apart from inflation, obtaining a dollar in the future is worth less than a dollar now. The real (unadjusted for inflation) discount rate is assumed to be 3 % as defined in *NISTIR 3273-26* for use with energy efficiency projects in 2011. The formulas and data sources used to calculate the life-cycle cost savings from planting a shade tree are described below.

Present value energy cost savings are the most complex costs to calculate because they must be adjusted for both the time value of money and fuel price escalation. Annual present value fuel cost savings from planting a tree ($C_{f,PV,t}$) is the difference between fuel costs with ($C_{f,alt,t}$), and without the tree ($C_{f,base}$), in today's dollars, and is calculated using the following equation:

$$C_{f,PV,t} = (C_{f,base} - C_{f,alt,t}) \times \frac{I_{f,t}}{(1+d)^t},$$

where d = discount rate,
t = number of years between the present time and the time costs are incurred,
I = fuel price index,
f = fuel type,
base = baseline case (no shade tree), and
alt = alternative case (shade tree).

Annual fuel costs are the product of simulated energy use and associated fuel cost rates. Electricity cost rates are based on the U.S. Energy Information Administration's (EIA) average residential electricity cost by state. The natural gas cost rates are based on EIA's average residential natural gas cost by state. The electricity and natural gas rates are shown in Table 3-1.

Table 3-1 Energy cost rates for the different locations

City	State	Electricity Rate ¢/kWh	Natural Gas Rate $\$/m^2$ (1000 ft^3)
Miami	FL	11.65	0.64 (18.14)
Phoenix	AZ	10.27	0.56 (15.86)
Sacramento	CA	13.81	0.33 (9.43)
Washington	DC	12.79	0.49 (13.92)
St. Louis	MO	8.00	0.45 (12.61)
Boulder	CO	10.13	0.29 (8.14)

Total present value energy cost savings over the study period ($C_{energy,PV,N}$) is the sum of the present value annual electricity cost savings and natural gas cost savings over the study period, as shown in the following formula:

$$C_{energy,PV,N} = \sum_{t=1}^{N} \left(C_{elect,PV,t} + C_{gas,PV,t} \right)$$

where t = number of years between the present time and the time costs are incurred, and
N = number of years in the study period.

The first cost (C_F) is the cost difference in initial costs with and without the tree. The cost of purchasing and planting the tree, which is assumed to be \$80/tree (C_F = -\$80).[2] First costs do not need to be discounted because they are in present value terms.

A recurring maintenance cost of \$10/year for watering and pruning is assumed for all years. The differential maintenance cost, C_M, is therefore -\$10/year. The present value of differential maintenance costs over the study period (N) is calculated using the following formula:

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[2] Based on the average cost of planting a tree in the Sacramento Municipal Utility District (SMUD) tree planting program.

$$C_{M,PV} = C_M \times \frac{(1+d)^N - 1}{d(1+d)^N},$$

where d = discount rate and
N = number of time periods (years) over which C_M recurs.

The life-cycle cost savings, or net savings (NS), of planting a tree is the sum of present value first cost, differential maintenance cost, and differential energy cost savings over the study period.

$$NS = C_F + C_{M,PV} + C_{energy,PV,N}$$

If the net savings of planting a tree is positive, then it is beneficial for the homeowner to plant the tree. The expectation is that the change in energy costs is positive while the first costs and maintenance costs are negative. If the energy cost savings are greater than the sum of the first cost and maintenance costs, planting the tree is cost-effective.

4 Results

A few generalizations can be made from the results for the six cities. Figure 4-1 shows the house (represented by the black box) and all the simulated tree locations (represented by the dots) for 5 years (left) and 10 years (right) after planting the tree. Darker green indicates larger energy savings. The darker the contours, the greater the difference in energy use.

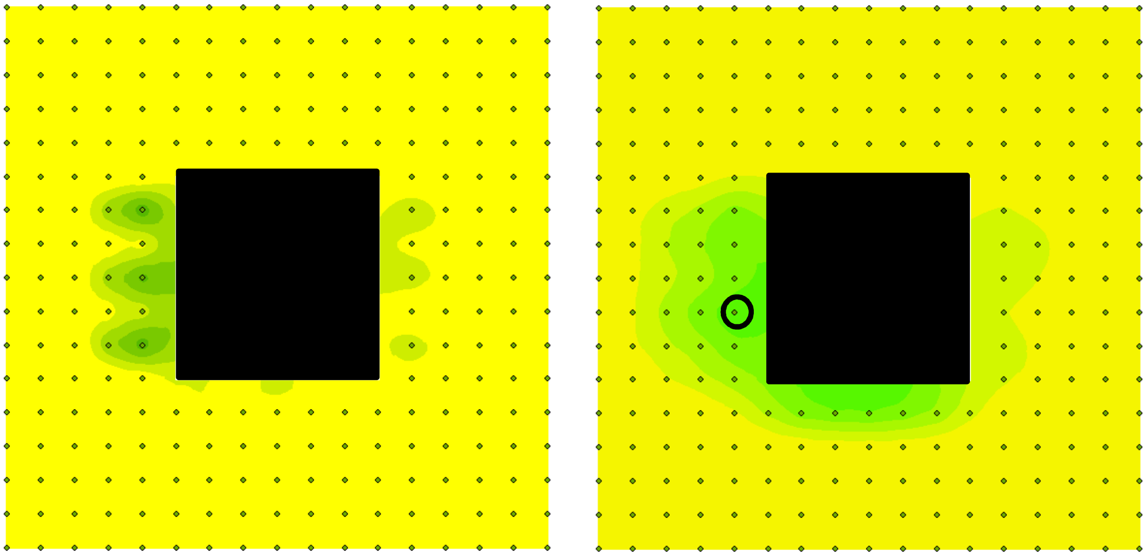

Figure 4-1 Energy use reductions, Sacramento, year 5 (left) and year 10 (right)

The optimal shade tree locations for study periods of 10 years or more are the same across all 6 cities, and located 2.1 m (7 ft) west and 4.3 m (14 ft) north of the southwest corner of the house. Unless specified otherwise, the results in this section are for the optimal location as shown by the black circle in Figure 4-1.

The optimal location shifts over time from the northern part of the west wall (1-year study period) to the center of the west wall (5-year study period) to slightly south of the center of the west wall (10-year to 20-year study periods). As can be seen in Figure 4-1, the specific location is much more defined and localized in the earlier years, as demonstrated by the dark contours. The location of the windows is the key driver of this result because windows allow sunlight to enter the house. Tree locations that block more sunlight result in lower energy use. Since the tree is much smaller in earlier years, the difference of 2.1 m (7 ft) in its location can make a significant difference. The three darkest spots for Year 5 in Figure 4-1 correlate with the location of the windows in Figure 2-1. However, in later years window placement and orientation become less important. So much so that by year 20 there are locations on the south side of the house that exhibit the same reductions as those on the west side of the house. This shows that the precise tree location is not vital to obtaining near optimal energy reductions in the long-run.

Benefits to the homeowner increase over time. The energy use reductions shown in Figure 4-2 increase from no reduction after one year to a 1.4 % to 2.7 % reduction 20 years after the tree is planted, depending on the city. Figure 4-2 shows that these reductions gradually increase over time as the tree grows and shades a larger portion of the house.

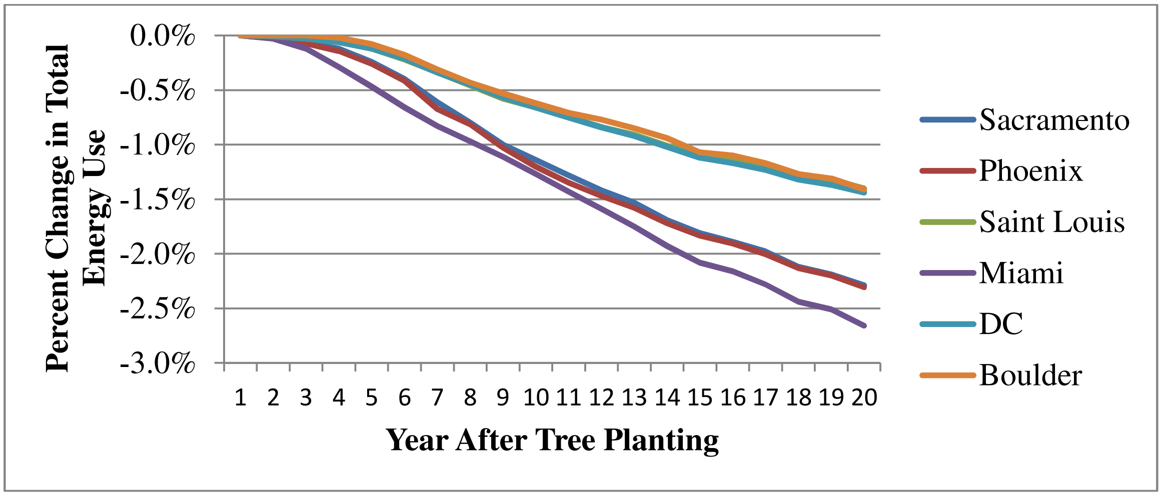

Figure 4-2 Energy use reductions by year by city

Cities in warmer climates (Miami, Phoenix, and Sacramento) realize greater energy use reductions than cities in colder climates (Boulder, Saint Louis, and Washington). While shade trees block solar radiation, which lowers the cooling loads during the summer to maintain the cooling set-point temperature, they also increase the heating loads during the winter to maintain the heating set-point temperature.

The peak electricity demand, as shown in Figure 4-3, drops 2.7 % to 3.4 % (171 W to 258 W) in 20 years depending on the city. As with energy use, peak electricity demand gradually decreases over time as the tree grows and shades a larger portion of the house. However, the variation across cities is not solely driven by cooling degree days and heating degree days. The greatest reductions occur for Sacramento followed by Miami and Boulder. The smallest reductions occur for Saint Louis and Washington. Surprisingly, Phoenix does not realize as significant a peak demand reduction as Boulder. How the reductions change over time vary across cities as well. In the first five years, Miami realizes the greatest peak demand reductions while Boulder realizes the lowest reductions. However, by year 20 both realize the same percentage reduction in peak demand.

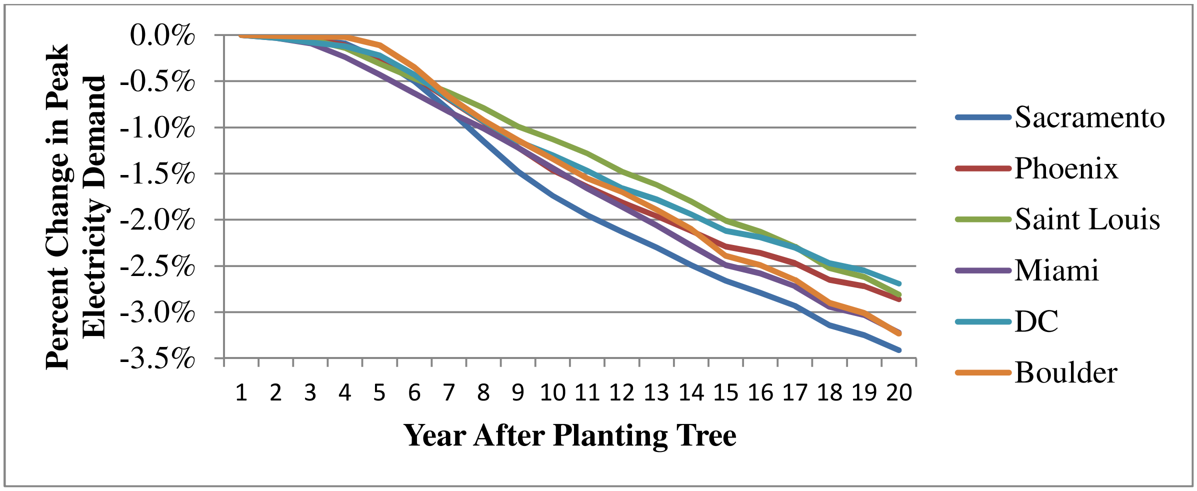

Figure 4-3 Peak electricity demand reductions by year by city

The overall net savings are negative for a 10-year study period (-$106 to -$25), but positive for a 20-year study period ($48 to $411). Figure 4-4 shows that Sacramento realizes the greatest net savings followed by Miami, Phoenix, and Washington. Saint Louis realizes the lowest net savings followed by Boulder.

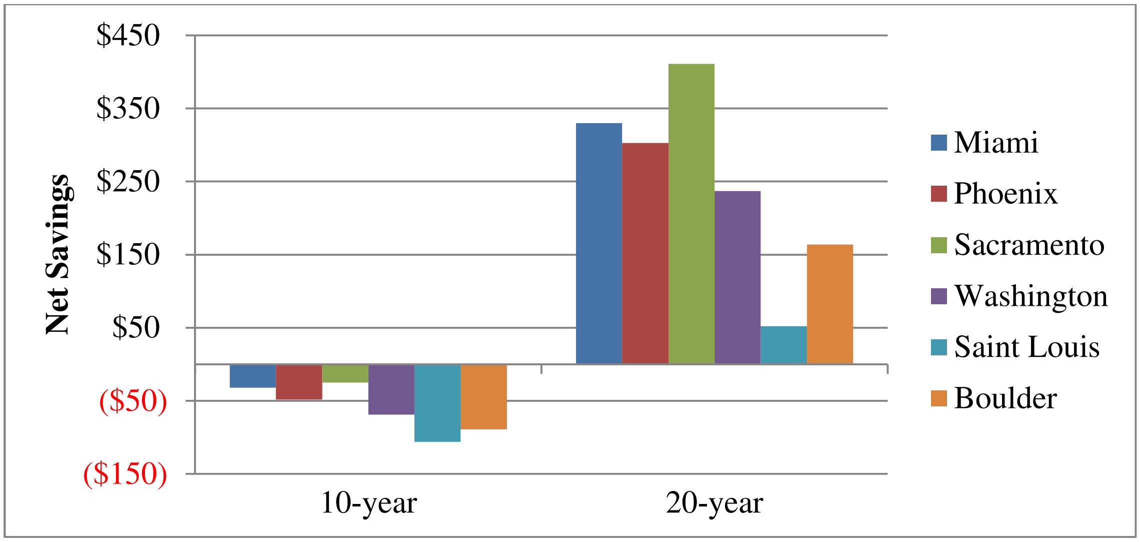

Figure 4-4 Net Savings by Study Period Length

According to the 2007 American Housing Survey (ACS), only half of homeowners have been living in their home for at least 10 years, and only a quarter have been in their home for 20 years. Based on this data, the second owner of the house is more likely to obtain more of the benefits than the initial owner at the time of the tree planting.[3] The gradual

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[3] Emrath (2009)

change in costs is represented in Figure 4-5, which shows the change in electricity costs over time by city.

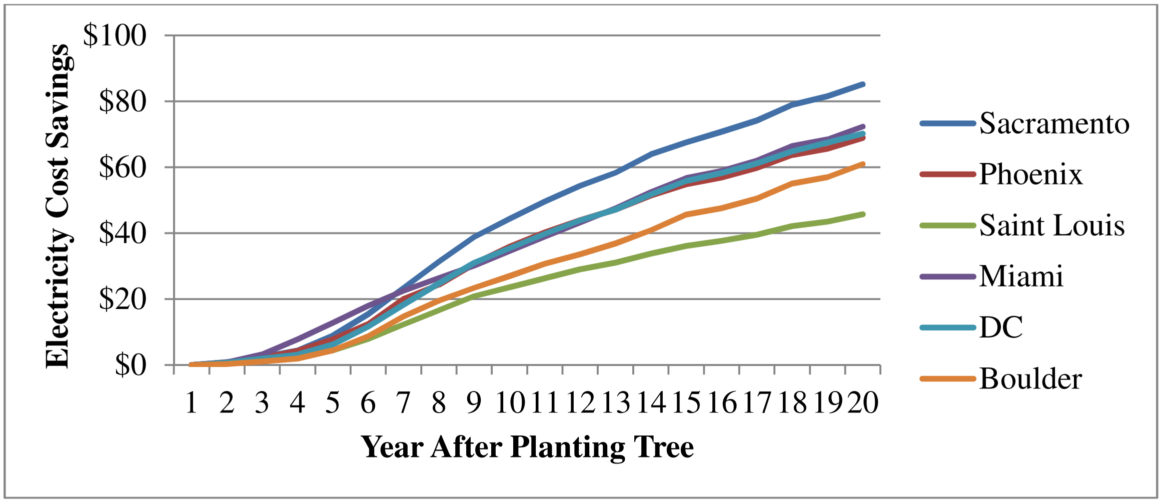

Figure 4-5 Change in electricity costs by year by city

Thus, utilities realize more benefits, over a longer time horizon, than the initial (planting) homeowner because of the impact of shade trees on peak electricity demand and current electric utility concerns regarding long-run trends of increasing peak electricity demand.. Subsidizing the homeowner by having a program to plant these trees may be beneficial for both parties since the homeowner may not feel it is beneficial to plant a tree if they have to internalize the costs of the tree.

Simulations were run testing the sensitivity of energy use reductions to tree location. Figure 4-6 shows that the greater precision in tree location from 0.9 m (3 ft) to 2.1 m (7 ft) does not significantly change the results in terms of the impact variation. However, the greater precision leads to a different optimal location, 2.1 m (7 ft) south and 4.9 m (16 ft) east of the southwest corner of the house as shown in Figure 4-6. The difference in the change in energy use between the two locations is negligible enough, 2.38 % vs. 2.29 %, that the optimal location could be generalized to any location with energy use reduction greater than 2 %, which includes all locations on the southwest and center portions of both the west and south sides of the house that are 2.1 m (7 ft) from the exterior of the house.

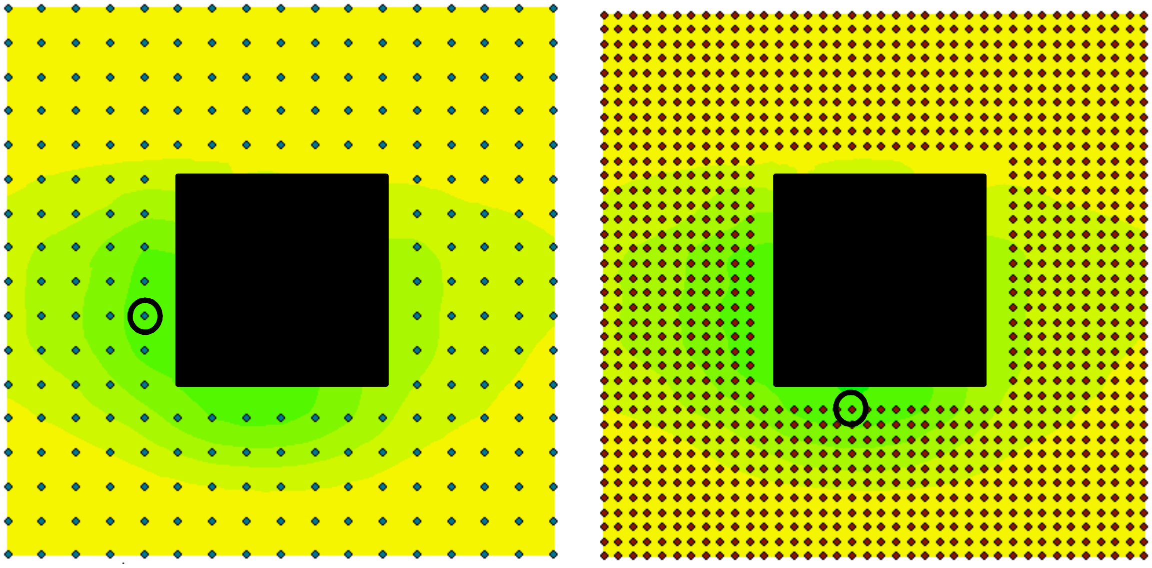

Figure 4-6 Energy use reductions, Sacramento, year 20, 2.1 m (7 ft) (left) and 0.9 m (3 ft) (right) increments

5 Discussion and Future Research

The results from this study further support the findings by previous studies that shade trees can be an effective energy efficiency measure to decrease both energy use and peak electricity demand. This study expands the literature in four ways: developing a method to determine the optimal location for shade tree planting around a house, determining the optimal spatial location of shade trees and the resulting energy use reductions while controlling for tree growth over a 20 year study period, comparing these shade tree effects across six cities throughout the United States, and determining the sensitivity of the energy reductions to the location of the tree.

Future research on this topic should target several areas. First, most landscaping designs include more than a single tree. A study could determine the optimal locations and analyze the life-cycle costs of simultaneously planting multiple shade trees for multiple cities across the United States. Second, the “prototype” house is overly simplistic in its design, and may not be representative of the building envelope of the typical house in different areas of the United States. By using more detailed, code-compliant residential building simulation designs, the results can provide more refined estimates of the benefits of shade trees.

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