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Cost and Benefit Tradeoffs in Using a Shade Tree for Residential Building Energy Saving

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Abstract

Global warming and urban heat islands result in increased cooling energy consumption in buildings. Previous literature shows that planting trees to shade a building can reduce its cooling load. This work proposes a model to determine the cost effectiveness and profitability of planting a shade tree by considering both its potential to reduce cooling energy and its purchase and maintenance cost. A comparison between six selected tree species is used for illustration. Using growth rates, crown sizes, and shading coefficients, cooling energy savings from the tree shades are computed using an industrial-standard building energy simulation program, offset by costs of purchase, planting, and maintenance of these trees. The result shows that most worthwhile tree to plant should have high shading coefficient and moderate crown size to maximize shading while keeping the maintenance costs manageable.

Keywords: cost-benefit analysis; shade tree; energy conservation; space cooling

1. Introduction

Rapid growth of cities is associated with a steady increase in ambient urban temperatures due mainly to the urban heat island phenomenon. Electrical cooling load demand of cities increases by about 3-4% per degree Celsius increase in temperature (McPherson *et al*., 1988). Approximately 3-8% of the electric demand for cooling is used to compensate for this urban heat island effect (Huang *et al.*, 1987). Thailand's annual electricity consumption in residential areas in 2008 was 28,000 GWh, and about 40% of that amount was expended for residential cooling (Kobayashi *et al*., 2010).

Trees have many benefits for urban environment such as carbon sequestration, air pollutant removal, and reduced energy consumption (Ames, 1987; McPherson, 1994; Thayer Jr and Maeda, 1985). Planting trees saves energy by reducing solar heat gains and peak power requirements of air conditioners and cooling fans. Huang *et al*. (1987) and Meier (1991) showed that trees can reduce 25-50% of a building energy cost when planted correctly. McPherson *et al*. (1985), Akbari *et al*. (2001) and Donovan and Butry (2009) found that trees to the west of the building produced the largest savings. There are studies that utilize simulation models to study the energy impact of tree planting projects in California (Simpson and McPherson, 1996; Simpson and McPherson, 1998). Heisler (1986) noted that the tree form maybe a more important factor than crown density in building energy saving. However, planting and maintaining the trees come with their own costs. McPherson and Biedenbender (1991) developed a method to evaluate cost effectiveness of planting a shade tree instead of constructing a shelter as a bus stop. An accounting approach to cost-benefit analysis of urban greenspace was developed by considering reduced air-conditioning cost against pruning, watering, and removal costs (McPherson 1992).

To select the proper species of tree to use as a shade, attentions must be equally focused on the benefits and costs involved in growing it. This work extends the previous literature by combining benefit calculations through building energy analysis and cost modeling of tree planting and maintenance expenses to determine profitability. The study location is Bangkok, a tropical area where air-conditioning is required almost year-round, though the study can be done for any other locations through the framework described herein. This work limits the scope of benefits and costs to financial ones only. With these considerations, the profitability of planting shade trees can be determined and compared for different species.

2. Materials and Methods

In this section, the assumptions on building, tree and shade characteristic, financial benefit, and cost models are discussed. The building parameters and thermal characteristics, along with its operation are detailed, followed by assumptions on trees, tree shade, and its relationship to their growth rate.

2.1. Building model

The building chosen for this study is a 100 m^2 (approximately 10 m x 10 m) two-floor house with one split-type direct-expansion air conditioning unit to keep the model simple yet realistic. The walls are made of 10-cm thick concrete. Floor-to-ceiling height is 3 m. On each wall there is a window that has the 30% surface area of the wall. The roof is made of light-colored ceramic tiles. Since this is a residential building, the air conditioning unit (with assumed coefficient of performance = 3) is required to keep the temperature inside the house at 25°C between 8 pm – 6 am on all nights.

2.2 Tree geometry and shade model

In this work, six evergreen tree species are examined: Rain tree (*Albizia saman*), Mango (*Mangifera indica*), Jackfruit (*Artocarpus heterophyllus*), Mahogany (*Swietenia macrophylla*), White cheesewood (*Alstonia scholaris*), and Indian cork tree (*Millingtonia hortensis*). For simplicity, they will be referred to in the figures as RT, MG, JF, MH, WC, and ICT, respectively. These species are commonly used for landscaping purposes in Thailand. Tree parameters that are important to building heat gain reduction are 1) shading coefficient—the fraction of solar radiation blocked by the crown, 2) crown diameter—the size of the crown, 3) crown height—the tree's height and 4) bole height—the distance from the bottom of the crown to the ground. In this work, the shading coefficient is assumed constant over the tree's lifetime, while the crown diameter and bole height are assumed linearly dependent on crown height (Hummel, 2000; Zhang *et al*., 2004).

The shading coefficients, crown diameters, crown heights, and bole heights are based on field sampling data of 20 matured trees representing each of the six species. Growth rates are based on values taken from literature (Abbott *et al*., 2006; Bunyavejchewin, 1999; Gerhold *et al*., 1993; Peralta, 1985). In this work, tree growth rates are categorized by their annual crown height increase and divided into three rates: slow (0.5 m/yr), moderate (1 m/yr) and rapid (1.5 m/yr). All trees are assumed to have a constant growth rate until they reach their mature sizes, after which they stop growing entirely.

2.3. Financial benefit of planting a tree

The financial benefit of planting a tree in this article is attributed solely to reduction in solar heat gains from tree shade, which lowers the space cooling energy. The income from selling the trees at the end of their useful lives are not included as different species produce varying timber qualities which may or may not be suitable for sale. The cooling load is simulated using eQUEST, which was originally developed by the United States Department of Energy. It utilizes sun-building geometry and shade geometry to compute hourly shading on the building for each specified day. It can compute hour-by-hour estimation of building energy use based on the building's thermal characteristics, occupant behavior, and specified weather data.

The tree is planted west of the building 5 m away from the wall. For each year the tree crown height, crown diameter, and bole height are calculated based on the tree assumed constant growth rate. The parameters are subsequently modeled in eQUEST as a fixed shade west of the building and the simulation is run to determine the cooling load. The load are then translated to cost using electricity tariff formula utilized by the Metropolitan Electricity Authority (MEA) of Thailand for residential building (Metropolitan Electricity Authority of Thailand, 2013).

2.4. Cost of tree planting and maintenance

McPherson and Biedenbender (1991) attributes the costs besides plant purchase to watering, pruning, and removal. We obtained plant purchase, pruning, and removal estimates from vendor interviews at one of Thailand's largest tree markets (Chatuchak Market). According to the interview, the cost of replanting (one-time payment of 200 baht) is identical for all species. The costs of pruning and removal, following the cost model in (McPherson and Biedenbender, 1991), are constant per leaf area. The annual costs of pruning and removing a mature rain tree are 2000 baht and 5000 baht, respectively. Divide this by the total leaf area (281 m^2), these costs are calculated to be 7.11 baht and 17.7 baht per square meter of leaf area for pruning and removal.

Table 1. Species growth rates from literature Bunyavejchewin, 1999; Gerhold et al., 1993; Peralta, 1985)

Tree Species	Growth Rate
Rain tree	Moderate
Mango	Rapid
Jackfruit	Rapid
Mahogany	Slow
White Cheesewood	Moderate
Indian Cork Tree	Moderate

Table 2. Purchase costs of species of interest. Each species has a 10 cm stalk diameter.

Tree types / species	Tree Cost (Baht)
Rain tree	1,100
Mango	1,600
Jackfruit	1,400
Mahogany	600
White Cheesewood	600
Indian Cork Tree	1,300

The watering rate also follows the model by (McPherson and Biedenbender, 1991), while the water tariff is obtained from a governmental document (Metropolitan Waterworks Authority of Thailand, 2013). However, the purchase cost varies depending on the initial stalk diameter and its rarity, as shown in Table 2.

2.5. Evaluating profitability

As discussed earlier, the benefits and costs of a shade tree vary as it grows. Here, a 40-year net present value (NPV) will be used to determine the profitability of tree planting to reduce cooling energy. The NPV is the sum of all present and future cash flows discounted by a proper discount rate at the time of the transactions. In this work, it is assumed that the costs and savings incurred from tree planting occur at the following intervals:

1. Cost for plant purchase and replanting: once at the beginning.
2. Cooling energy saving: annually.
3. Watering: annually for the first 15 year, none afterwards.
4. Pruning: once every five years, except in year 40.
5. Removal: once at the end of 40-year lifetime.

These costs and savings are discounted at 10% annual rate. The NPVs of planning the species are compared and the optimum tree species can be determined.

3. Results and Discussion

The results of field sampling data of selected matured tree species, cooling energy requirements, and profitability of tree planting are presented and discussed. The shading coefficient and tree geometries are used to determine the linear relationship among crown height, crown diameter, and bole height for each species. Those parameters are used to model shading in the eQUEST to determine the cooling energy saving, while the planting and maintenance costs are calculated using a cost model. Finally the net present value of planting each species can be evaluated.

3.1. Tree field sampling data

From the gathered data for matured trees, Jackfruit tree has the highest crown density, while Indian cork tree has the lowest. Rain tree has the largest crown diameter and therefore the largest shade area. The parameters utilized in modeling fixed shades in the cooling load simulation are listed in Table 3.

3.2. Evaluating profitability

To calculate the annual cooling energy saving, first the building cooling load is calculated based on the observed species parameters, growth rate, and thermal characteristics of the building. It is then translated to the electrical consumption of the air conditioning system. The required annual cooling energies for a building shaded by a matured shade tree are illustrated in Fig. 1.

The cooling energy consumption for the building shaded by a rain tree is the smallest because of the tree's large, dense crown. On the other hand, Indian Cork Tree and White Cheesewood provide the smallest energy reduction due to their relatively thin and small crowns. Using growth rates to calculate for crown diameters, heights, and bole heights for the trees, year 1 through 40 cooling energy requirements can be simulated. The annual energy requirements are then converted to costs using electricity tariff rates from the MEA. The energy costs are then compared with that of the unshaded building to determine the savings, illustrated in Fig. 2.

Table 3. Field sampling data for shading coefficients, crown heights, crown diameters, and bole heights of mature trees.

Tree Species	Shading Coefficient	Crown Height (m)	Crown Diameter (m)	Bole Height (m)
Rain tree	75 %	15.1	15.9	5.1
Mango	88 %	13.5	11.7	1.5
Jackfruit	90 %	13.7	10.5	2.3
Mahogany	80 %	16.7	8.1	2.5
White Cheesewood	70 %	13.6	6.5	2.7
Indian Cork Tree	69 %	15.5	6.3	4.3

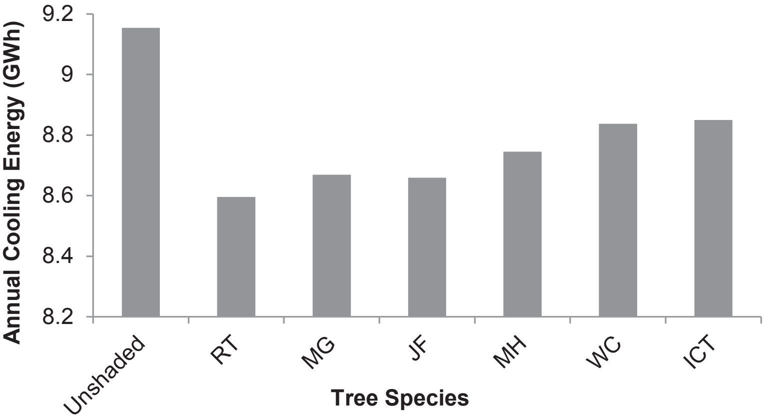

Figure 1. Annual cooling energy for unshaded and shaded building by a matured tree

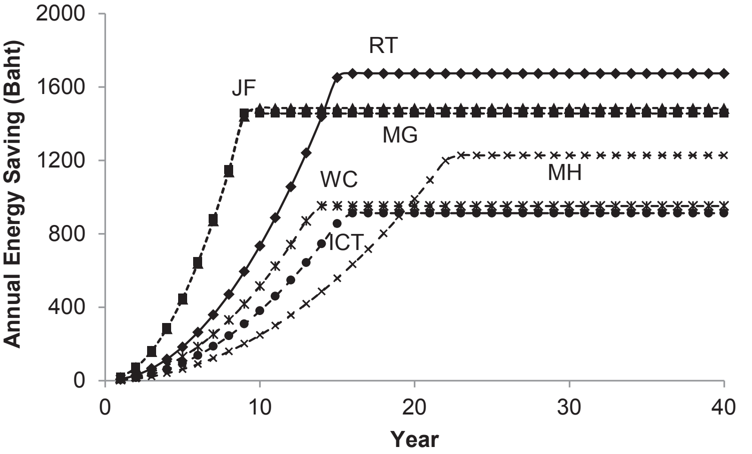

Figure 2. Simulated 40-year annual cooling energy savings for the building shaded by selected species.

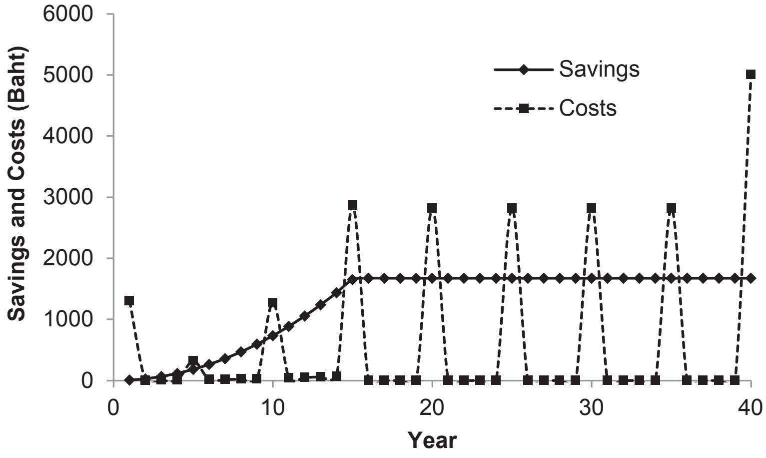

Figure 3. Energy savings and total costs of planting a rain tree over 40 years

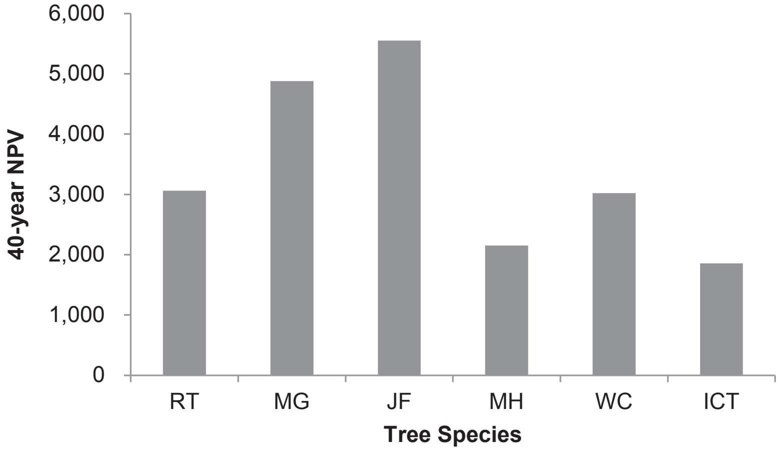

Figure 4. 40-year net present values of planting a tree of selected species

Jackfruit and mango, the faster growers, provides the highest energy savings for the first 10 years but rain tree overtakes them in year 13 since it has a larger matured crown diameter. Mahogany is the slowest grower and thus has the slowest rate of annual energy saving increase. The energy savings are constant after the trees reach their matured crown diameters. The costs of replanting, watering, and removal are modeled based on crown heights, crown diameters, bole height, and shading coefficient as detailed in 2.4. The comparison of simulated savings and modeled costs of a matured rain tree over 40 years are illustrated in Fig. 3.

As Annual energy savings normally outweigh annual costs of planting a tree-except for the first year (plant purchase and replanting), every fifth year (pruning), and year 40 (removal). It is important to note that watering costs (less than 80 baht annually) are almost insignificant compared to these costs. Finally, the net present values of the selected species are compared.

The simulated 40-year net present values (Fig. 4) show that jackfruit is the optimal choice of all six selected species for a shade tree. Despite its moderate crown size, jackfruit yields the highest 40-year net present value. The reasons for this are (1) it has the highest shading coefficient, so it is very effective at providing shade, (2) its moderate crown size provides sufficient shades without costing excessive water, pruning, and removal expenses, and (3) it is the least expensive among the listed species. Notice that a rain tree, with the largest and relatively dense crown, gives a third best smaller net present value despite the highest energy savings because of costly pruning, watering, and removal due to its large crown. Mahogany and Indian cork tree provide the smallest returns because of the slow growth rate (mahogany) and the low shading coefficient (Indian cork tree).

4. Conclusions

This work proposes a method to evaluate benefit and cost of planting a shade tree to reduce cooling energy for a residential building. The method employs a combination of a building energy simulation model and a tree planting and maintenance cost model to project financial benefit and expenses over a tree's lifetime. Our results show that an optimal choice for a shade tree should have a dense but moderate-sized crown so that it can provide a large cooling energy saving without costing excessive pruning, watering, and removal expenses. Furthermore, a shade tree should be relatively inexpensive to obtain.

The scope of the proposed method is not limited to the selected species, Bangkok, or residential buildings; it is simply a framework for which various shade trees can be compared for their energy saving benefits and cost effectiveness. Field data for other species and weather records for other locations can be obtained or collected and used to simulate energy savings in different conditions, while air conditioning schedule can be modified for other types of buildings.

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