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Simple and low-cost method of planning for tree growth and lifetime effects on solar photovoltaic systems performance

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Abstract

The use of distributed solar photovoltaic (PV) systems is growing more common as solar energy conversion efficiencies increase while costs decrease. Thus, PV system installations are increasing in non-optimal locations such as those potentially shaded with trees. Tree-related shading can cause a significant power loss and an increasing collection of laws have been enacted and are under development to protect the right of PV owners to solar access. This paper provides a new method to predict the shading losses for a given tree species, orientation to a PV array, and geographic location using existing free tools in order to assist in the prevention of conflicts by creating an environment where PV systems and trees can coexist while maximizing PV performance. This methodology is applied to a case study in the Midwest US. Tree growth characteristics including height, crown width, and growth rate were investigated. Minimum planting distances were quantified based on tree species and orientation of planting with respect to the PV system and conclusions were drawn from the results. This novel open low-cost method to predict and prevent tree shading from negatively impacting the performance of roof-mounted PV systems assists in planning of technical design.

Keywords: Photovoltaic; Trees; Shading; Solar energy; Urban planning; Distributed generation

1. Introduction

Solar photovoltaic (PV) technology, which convert sunlight directly into electricity, offers a technically sustainable solution to the projected enormous future energy demands both in the US and throughout the rest of the world (Pearce, 2002; Asano and Saga, 2008; Fthenakis et al., 2009; Dincer, 2000). Already PV technology has obtained grid parity, which is where the cost of solar electricity is equal to or less than conventional sources, in a number of geographic markets as the cost of PV modules have plummeted (Schwabe and Jansson, 2010; Breyer et al., 2010; Branker et al., 2011). These cost declines have spurred significant growth. Since 1990, global solar PV module production has increased more than 500-fold from 46 megawatts (MW) to 23.5 GW in 2010 ($82 billion), and grew last year to reach 28 GW (Jäger-Waldau, 2011). If the current price declines continue, the billion dollar market will expand to a potential market in the hundreds of billions of dollars. For example, consider recent work by Keiser that showed that at US$3 per watt for complete PV systems – and some commercial projects are at this level now – addressable electricity consumption rises to 440 billion kWh, equivalent to over 300 GW of capacity in the US alone (Keiser, 2011). To catalyze this type of growth governments throughout the world are also providing

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incentives (REN, 2009; Branker and Pearce, 2010; Matsukawa et al., 2011) and novel funding mechanisms are being developed (Branker et al., 2011; Fuller et al., 2009). Given both the reductions in solar electric costs and the significant financial incentives available for solar technologies and the possibility of property-assessed clean energy ("PACE") financing programs around the country, it is likely that the number of operating solar energy systems will increase dramatically. This will result in PV systems being deployed in non-optimal locations such as those with partial tree shading. For example, a recent U.S. National Renewable Energy Laboratory study assumed that either 30–40% (cooler climates) or 10% (warmer climates) of the available roof space would be eliminated from PV deployment because of tree shading (Paidipati et al., 2008). This can be partially avoided using regional scale planning assisted with LiDAR technology (Nguyen and Pearce, 2012; Nguyen et al., 2012; Carneiro et al., 2009; Habib et al., 2008; Alexander et al., 2009; Rottensteiner and Briese, 2002), however, it is probable that either PV systems owners and their neighbors will have conflicts due to tree shading (Anders et al., 2007, 2010; Barringer, 2008; Patitucci Torvik, 2009). In some jurisdictions, under a 1978 state law protecting homeowners' investment in rooftop solar panels in California, shading of PV systems could already result in fines. Given the relative paucity of solar shading laws in the US, it is likely that other states will consider adding similar provisions to their statutes as the number of solar energy systems increase around the country (Anders et al., 2007, 2010). Normally, with such legislation, trees planted before the PV installation are exempt (Anders et al., 2007, 2010). In addition, the value of PV-generated electricity must be weighed against the benefits of trees around homes, which include economic benefits from urban forestry (McPherson et al., 1997), reduced respiratory disease associated with increased tree cover (Lovasi et al., 2008), reduce ozone concentrations (Taha, 1996), and increasing tree canopy cover is one of the most effective methods to both reduce urban heat islands and conserve energy for heating and cooling loads in buildings (McPherson et al., 2005; McPherson and Simpson, 2003; Rosenfeld et al., 1998; Rosenzweig et al., 2006). Thus, in order to optimize PV performance while minimizing conflict it is important for PV system owners, their neighbors, installers and planners to plan carefully for tree growth around PV systems.

This paper provides a novel methodology to assist this planning. The Midwest US is utilized as a case study, with trees commonly found there simulated for variable tree locations with respect to a PV system located on the roof of a standard one story house. The tree growth literature is reviewed and a low-cost reproducible method is introduced to determine the minimum distance for planting to avoid any shading over the PV system as a function of time. This research is developed to: (i) provide systems installers and owners with a clear guide for planting trees or shrubs near a PV system, and (ii) describe a clear methodology for the relationship between trees and PV systems to assist planners of both PV + tree legislation and planning to avoid future problems associated with coexistence of solar panels and trees.

2. Background

2.1. Tree shading and PV legislation

The laws which protect the right to access sunlight can be related to the nearby buildings, constructions or vegetation. In this paper, the main concern is the coexistence of trees and solar PV modules so the laws that directly address shading problems by the neighboring vegetation will be reviewed. The laws to protect people's rights to access sunlight are not something new, in fact they are continuing of the ancient rules of the Romans, whose architecture was designed to take advantage of sun light and heat (Anders et al., 2007). Modern day solar access laws vary by state and have many unique features, but can be grouped into four general categories (Anders et al., 2007, 2010):

(i) Prohibition of conditions, covenants, and restrictions (Solar Rights), generally limits a homeowners association or local government from undue restrictions on installation of solar energy.
(ii) Solar easements allow a landowner to enter into an agreement with an adjacent landowner to ensure that sunlight reaches their property.
(iii) Local zoning authority to adopt solar access regulations are permitted in several states that preserve solar access, including consideration for shading from other structures or vegetation.
(iv) Solar shading laws are laws that ensure that the solar energy device performance will not be compromised by shade from vegetation on adjoining properties.

More than 30 states have adopted legislation that provides one or more of the above solar protections (Anders et al., 2010).

Until the recent enactment of an amendment to the SSCA, property owners could face criminal prosecution if their trees grew to shade a neighbor's solar panels, with no consideration given to whether the trees were planted before the panels were installed (Anders et al., 2010). The amendment, enacted to remedy the situation that befell Treanor and Bissett, may have the effect it was designed to have–striking a balance between the rights of owners of trees and solar technologies. However, the amendment also forges new law in California, creating private nuisance liability for blocking a neighbor's sunlight. In other words, neighbors can now sue each other directly in civil court if PV systems are shaded by a neighbors tree (Patitucci Torvik, 2009).

The case of homeowners Treanor and Bissett, who were criminally prosecuted under the Solar Shade Control Act because their preexisting trees cast shadows over their neighbor's solar PV modules (Patitucci Torvik, 2009), can be given as an example to emphasize the importance of locating the trees as well as the significant contribution of this paper to avoid future conflicts.

2.2. Tree-related shading losses

Shading can occur on all types of PV installations and is generally due to nearby trees, telephone poles, horizon shading from faraway structures or self shading from adjacent rows (Deline, 2010b). The shade impact on PV performance depends on the module type, severity of shade and string configuration (Deline, 2009, 2010a, 2010b). To overcome partial shading problems, bypass diodes are placed to protect the sub-strings of 15–20 cells and shade on any of these cells turn on the bypass diode, removing those cells electrically from string (Deline, 2010b). However, any shade falling on a PV array causes power loss and the more shade the greater the loss. PV power loss from tree shading specifically, depends on several factors such as: tree height, crown diameter, crown height and the location of the tree with respect to the PV system.

A literature review was completed on urban trees (Frelich, 1992; Schoon, 1993; Peper et al., 2001; Weeks et al., 2005; Rhoads et al., 1981; Lamson, 1987; Urban Forest Ecosystem Institute, 2013), as the trees in backyards or on streets are those most likely to impact a residential PV system. Different tree species have different shading factors, for instance, broad and short trees cast relatively larger summer and shorter winter shadows than narrow tall trees (McPherson and Simpson, 2003). Area of the shade depends on several factors such as tree height, crown width, crown height and base height as shown in Fig. 1. All of these parameters are a function of time of growth. In general, the growth rate of a tree is rapid in early years and as the tree ages it grows more slowly. This generalization is well supported in the literature (Frelich, 1992; Schoon, 1993; Peper et al., 2001) and has been proven by the derived growth equations for different tree species shown in Eqs. (1)–(3) below (Frelich, 1992).

Diameter at breast height (D_{BH}) of trees is a required information to calculate the tree height (H_t), crown width (C_w), crown height (C_{ht}) and crown base height (C_{bht}).

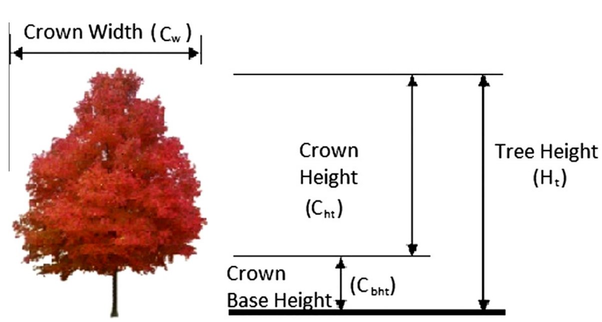

Fig. 1. Tree parameters.

Equations for diameter at breast height, tree height, and crown width are given below for Norway Maple, Sugar Maple, Green Ash and Red Maple.

$$D_{BH} = B_0(1 - e^{(B_1 xt)})^{(B_2)} \tag{1}$$

$$H_t = B_0 + (B_1)(D_{BH})^{(B_2)} \tag{2}$$

$$C_w = B_0 + (B_1)(D_{BH})^{(B_2)} \tag{3}$$

where B_0, B_1, B_2 are the coefficients with no unit and t is the age of the tree in years. Calculated values for tree height, diameter at breast height and crown with are in feet. Table 1 shows the equations of D_{BH}, tree height (H_t) and crown width (C_w) for some of the common trees as a function of year in feet as is standard in the forestry literature (Frelich, 1992; Schoon, 1993).

As an example, using Eqs. (2) and (3) and the values in Table 1, tree height and crown width are plotted with respect to tree age in years in Fig. 1. The curves become nonlinear as the tree grows. Solar PV modules are under warranty for 80% power output for 20–30 years (Zweibel et al., 2008), although it should be noted that recent work on the degradation of PV performance indicate the effective lifetime for PV should be considered much longer (Realini, 2003; Chianese et al., 2003). If the trees are planted simultaneously to the solar panel installation, it is practical to consider the height and crown width of a tree at the age of 30. From the curves in Fig. 2, it is clear that the relationship between tree growth with respect to year is roughly linear in the first 30 year period. Consequently, trees will be modeled by using their height and crown width at the age of 30. Therefore, for example, a modeled sugar maple tree will be 11.6 m (38 feet) in height and 7.6 m (25 feet) in crown width at the age of 30. For trees that have no available equation or coefficient to estimate their dimension at the age of 30, the average height and crown width are used at maturity.

3. Methodology

Simulations are made in Google Sketchup[1] 8 because of low cost of reproducing the methodology as there is free access to both the software and 3D models online. The Google Sketchup models were validated with Heliodon[2] 2.7-03, which is a proven method to determine the shadow pattern of trees (Heisler, 1986). In Google Sketchup the shadow calculations are based on the location thatis modeled and thus includes latitude and longitude, directional orientation, and an associated time zone, which is not adjusted for daylight saving time.

Since the pilot area is chosen to be the Midwest US, the common trees for urban planting are found and studied, and their growth rate are approximated. The cumulative percentage of trees in the study area of the top twenty most

[1] http://sketchup.google.com/download/gsu.html.
[2] http://www.heliodon.net/heliodon/news/v2.7-03/news_2703.html.

Table 1
Tree growth equations and the required coefficients (Fthenakis et al., 2009).

Species	Equation (ft)	B_0	B_1	B_2	Species	Equation (ft)	B_0	B_1	B_2
Norway Maple	D_{BH}	43.37	−0.0240	1.805	Green Ash	H_t	−48.370	46.54	0.252
Sugar Maple	D_{BH}	30.49	−0.0308	1.836	Red Maple	H_t	0.4058	5.09	0.788
Green Ash	D_{BH}	40.94	−0.0248	1.660	Norway Maple	C_{wt}	−1.010	3.819	0.767
Red Maple	D_{BH}	32.75	−0.0254	1.415	Sugar Maple	C_{wt}	−0.543	4.691	0.688
Norway Maple	H_t	3.30	6.7800	0.598	Green Ash	C_{wt}	−7.000	7.72	0.589
Sugar Maple	H_t	4.0000	7.5000	0.600	Red Maple	C_{wt}	−0.899	3.8150	0.802

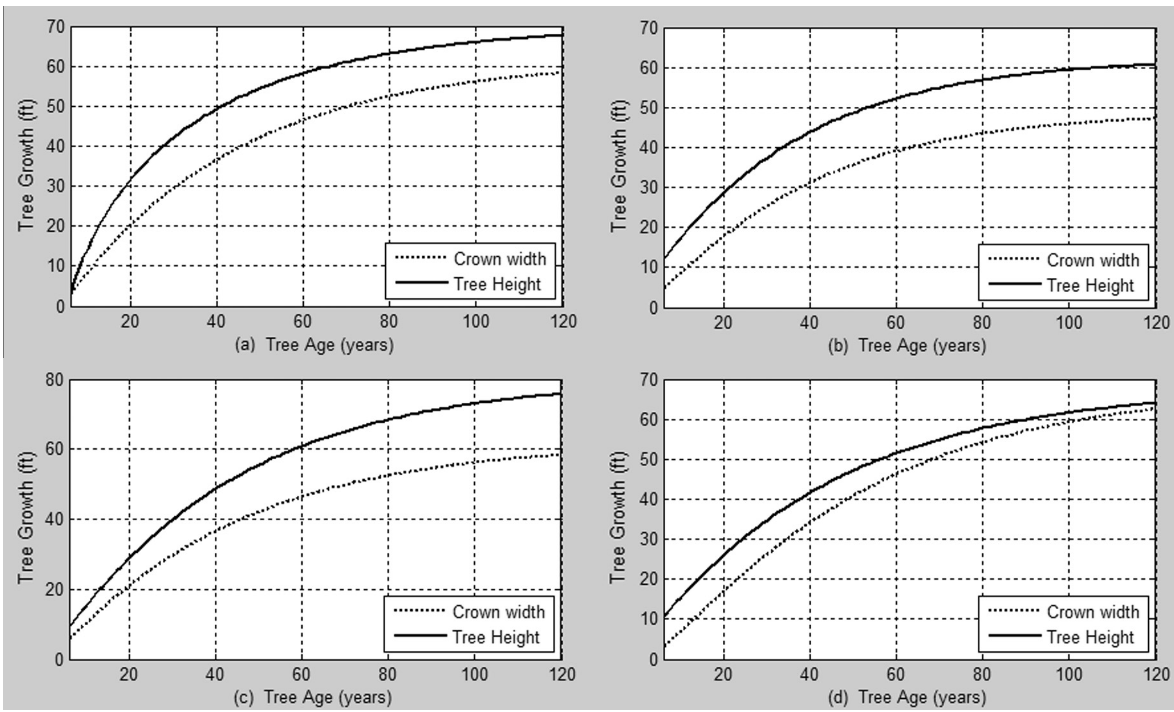

Fig. 2. The tree growth in height and crown width with respect to year for (a) Green Ash; (b) Sugar Maple; (c) Red Maple and (d) Norway Maple.

common trees is 80.14% (listed in Table 2), which is sufficient for this analysis. Tree height and crown width are determined for each tree at the age of 30. A 3D model of each tree is downloaded from Google Warehouse[3] and modified according to the actual tree dimensions. A 3D model of a one story house with the dimensions of $16 \times 9 \times 5$ m length–width–height is used as shown in Fig. 3.

For the case study in Michigan, solar PV modules are placed on the roof facing solar south 3.7 m (12 feet) high off the ground at a 30° tilt angle on a house at 47° latitude. Trees are placed on the south side of the house as well at geometrically defined locations as shown in Fig. 3. Since SSCA specifically states that trees must not shade more than 10% of the PV panel from 10 am to 2 pm, simulations are made during this time period. During the winter when the altitude of the sun is minimized, the area of the total shade increases. Therefore, the simulations are made in December 21st when the area of the shade was found to be nearly maximum. On Google Sketchup, the location for the entire simulation can be changed under the model info tab and any location can be chosen from the Google map. The location of the tree is changed by dragging it on the x and y axes and placing it on the lines defined as W, 30°-SW, 60°-SW, 90°, 60°-SE, 30°-SE and E. By adjusting the time of the year and the time of the day, the model is simulated from 10 am to 2 pm on December 21st. It must be noted that the simulation is using the local time (clock time), not solar time – and thus 12 noon does not mean the sun is directly overhead.

4. Results

The 20 most common tree species for the case study are simulated with each tree placed on the orientation lines shown in Fig. 3. The minimum distance is determined so that the tree placed on any of these lines does not cast any shade over the solar PV system and the results are summarized in Table 2. As local time was used the minimum distances for both E and W and the same degree E and

[3] http://sketchup.google.com/3dwarehouse/.

Table 2
Simulated trees and their minimum distances in meters.

Species	Height	Width	W	30 SW	60 SW	90 S	60 SE	30 SE	E
Silver Maple[b]	18.6	13.7	9.1	12.2	47.5	41.1	73.2	30.5	11.0
Sugar Maple[b]	11.3	7.6	9.8	8.2	26.2	21.3	41.1	15.2	7.6
Norway Maple[b]	10.1	7.9	9.8	7.6	21.3	17.7	34.7	19.8	8.2
Green Ash[b]	12.8	9.1	5.5	7.9	31.4	26.2	48.8	24.7	6.4
American Elm[a]	16.2	7.9	5.8	7.6	38.7	33.5	59.7	17.1	5.5
Red Maple[b]	12.2	9.1	8.2	9.1	27.4	24.4	43.6	21.9	7.9
White Ash[a]	15.2	10.7	5.8	10.7	39.6	32.3	57.9	28.0	7.3
Honeylocust[a]	14.3	10.1	4.9	9.8	36.0	31.1	52.7	17.1	7.6
Siberian Elm[a]	18.3	14.0	6.4	11.3	48.8	39.6	69.2	22.9	8.5
Hackberry[b]	15.2	15.2	9.1	13.1	40.2	30.8	55.2	21.3	7.6
Crabapple[a]	7.6	7.6	6.1	7.0	12.2	10.1	25.0	14.6	6.1
Pin Oak[a]	13.4	10.1	6.1	11.3	30.5	23.8	41.5	21.9	7.9
American Sycamore[a]	22.9	15.2	7.0	13.7	64.3	53.0	84.1	19.5	7.3
Little Leaf Linden[b]	11.0	7.6	4.6	7.0	20.4	19.2	36.6	17.7	5.8
Northern Red Oak[a]	11.9	7.9	5.8	9.4	25.9	20.7	34.4	20.4	7.3
Mulberry[a]	15.2	12.2	6.7	11.6	37.8	32.0	55.8	26.8	10.1
Eastern Cottonwood[a]	15.2	12.2	8.2	12.2	38.7	35.7	60.4	28.0	7.3
American Basswood[ab]	11.0	7.6	4.6	7.0	20.4	19.2	36.6	17.7	5.8
Eastern White Pine[b]	12.2	7.0	3.7	6.1	21.6	22.9	41.8	15.2	5.8
Northern Catalpa[a]	15.2	9.1	6.1	10.1	36.3	31.4	57.6	27.4	8.5

[a] Average height and Crown Width at maturity.
[b] Height and Crown Width are at the age of 30.

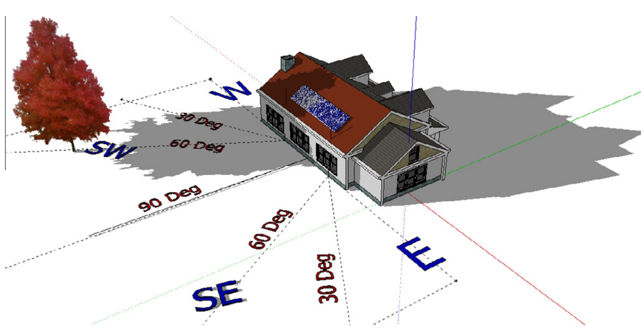

Fig. 3. Orientation of trees with respect to residential PV system installation.

W are different as can be seen in Table 2. Distances ranged from a minimum of 3.7 m (12 feet) for an Eastern White Pine located onto the West of the array to 84.1 m (276 feet) for an American Sycamore located 60° SE.

5. Discussion

Tree shading over PV systems can dramatically reduce the PV output. Unshaded cells produce higher power than shaded cells however, this power is wasted on shaded cells resulting in increasing amount of heat that eventually may damage the cells (Ramaprabha and Mathur, 2008; Masoum et al., 2010). To prevent damaging the cells, bypass didoes are used (Ramaprabha and Mathur, 2008). Bypass diodes electrically remove the strings from the circuit, which normally contain 15–20 cells (Deline, 2009, 2010a, 2010b). Removing these strings will protect the cells from being damaged, but also will reduce the output power of the module by more than the simple geometric reduction from the few shaded cells. For instance, a PV system consisting of 5 modules where each module has three strings will have total of 15 strings. If a single tree branch shades at least one cell of two different strings, this will result in elimination of these two strings. So, the PV system will work with 13 string instead of 15. As a result the power output will be 86.6% even though only 2 cells are shaded out of a total population of perhaps 100. Thus a 15% reduction in PV output can be the result of only 2% of the PV system being shaded. Therefore, it is important to note that due to the nature and the design characteristics of PV modules, even small quantities of shading may result in significant reduction on the PV system performance.

Both tree height and crown width have an impact on the tree shade resulting in different minimal planting distances from a PV system for different trees. Also, crown type (oval, conical, and cylindrical) affect the required minimum distance for tree planting. Trees can be planted closer to the house if the W or E line is chosen. Due to the use of local time to determine requirements, the second place that requires minimum distance is line SW-30, which always requires less distance than other SW and SE lines. However, it should be noted that for simply maximizing yearly yield with a south-facing roof the values on the E or W at the same degree of orientation for a given tree will provide the same results. Trees planted at 90° or due south are directly affected by the tree height since it is perpendicular to the center of the PV array. So, the trees with small height, but wider crown width can be planted on this line. No matter what the tree height or crown width is, when local time is used the line SE-60 always requires the greatest distance among other lines. Thence, SE-60 and SW-60 are not recommended for houses where space is limited.

When trees are planted near a PV system, it is also important to consider the height of the PV modules, tree height, crown width and growth rate of the tree. As the results make clear, for a one story house, most trees require at least 9 m (~30 feet) distance from the edge or the center of the PV systems corresponding location on the ground. For two or more story houses, this distance will be reduced. To show how the height of the PV panels reduce the minimum required distance for tree planting, another set of simulations was performed for a Sugar Maple tree. In this case, a two story house is selected and the panel height is chosen to be 7.3 m (24 feet) instead of 3.7 m (12 feet). These results are summarized in Table 3. The greatest reduction on distance (Δd) is observed on W-line where the required distance is reduced by two thirds from 9.8 m (32 feet) to 3.4 m (11 feet). The smallest reduction on distance is observed on E line where Δd is only 2.4 m (8 feet) as seen in Table 3.

This study focused on existing one or two story homes in the northern hemisphere and trees planted to the south. PV systems, however, can also be installed on ground mounted racking with variable heights. The methodology described here can be generalized to the situation where there are existing trees that obstruct direct sunlight to a ground mounted array. The minimum height of the array can be established by simulating the existing trees at their end of life heights using the method described above. Then the PV array should be placed as far north from the trees as possible and then the height of the array should be adjusted upward in Sketchup following the method described here until the shading maximum threshold is overcome. This will provide the minimum height of the array for a specific situation and will be highly variable depending on the situation (e.g. tree type, orientation to the array and distance from front edge of array to the tree).

The height of the tree determines the height of the shade and the maximum point that the shade will reach. Crown width on the other hand, determines how wide the shade will be and also the area of the shade. Fast growing trees can cause problems since they reach a height that can easily cast shade over the PV panels within 10 years if they are located within the 9 m radius. If the trees are not planted at the right location with respect to the PV system, they may start casting a shade over the solar collectors. This will require tree owner to either remove or trim the tree. If the tree owner decides to trim the tree it can be a substantial maintenance expense associated with the PV system. The cost of tree trimming starts around US$50/h in the US. The total cost of tree trimming may cost as low as US$75 and this price can go up to US$1000 or more depending on the species and the condition of the tree.

Table 3
Results of simulation with a Sugar Maple for one and two story house for minimum planting distances in meters.

House	W	SW 30	SW 60	90	SE 60	SE 30	E
One story	9.8	8.2	26.2	21.3	41.1	15.2	7.6
Two story	3.4	5.2	14.0	10.7	25.6	12.5	5.2
Δd	6.4	3.0	12.2	10.7	15.5	2.7	2.4

Pine trees are categorized as medium to large size trees and they can reach up to 30.5 m (100 feet) or even higher (Weeks et al., 2005). They are evergreen trees so they have leaves (needles) in every season, which aggravates shading problems in the winter since the altitude of the sun is low and trees with leaves will cast larger shadows. Furthermore, pine trees such as Red Pine, Norway Pine and Eastern White Pine can grow fast so they will be high enough to cast shade over the PV system within 30 years if they are not planted far away from the array. Therefore, most pine trees are not recommended on the south side of a PV system, although they have been shown to improve thermal performance of a building by acting as a wind break if planted on the north side (Thirugnanasambandam et al., 2010).

Maple trees such as Sugar Maple, Red Maple and Silver Maple trees are very common in the Midwest US, however these trees can grow quickly up to 24.4–27.4 m (80 or 90 feet) Weeks et al., 2005. They are deciduous trees so they do not have leaves in winter. However, since they are tall, fast growing trees with a wide crown shape they are likely to be detrimental to PV output if planted near to the system because of in small yard areas.

If the distance between the tree planting and the PV systems are restricted, smaller trees can be utilized. In general, small size and slow growing trees are recommended since they grow only up to 9.1 m (30 feet) or 12.2 m (40 feet) high. Flowering dogwood is one of these tree species, which could be used in space restricted areas. American hornbeam is another small tree with average height of 9.1 m (30 feet) and it can be a good choice for planting in backyards where PV systems are installed. Jack pines are fast growing trees, but are a third choice for these more challenging applications as their average height is 9.1 m (30 feet) or 12.2 m (40 feet). Small to medium size trees are also potential candidates if they are slow growing. Even though these trees can reach up to 15.2 m (50 feet) or higher, they will not grow high enough to cast a shade over the PV panel within 30 years for its warranted lifetime. Eastern red cedar, black spruce, northern white-cedar and striped maple are slow growing trees with average height of 15.2 m (50 feet).

When considering the potential for conflict (Anders et al., 2007, 2010) between PV systems owners adjacent to neighbors with trees or considering planting trees, there are several approaches that may help to dissolve tension. First, is simply to supply accurate information on the impact of trees on the solar energy system to all parties. The methods used in this paper can be replicated by homeowners looking at a specific house, PV system (or other solar energy system), tree species/ages and tree locations. Thus the need to replant, change the location of the array (e.g. mount closer to the top of the roof if it is only going to cover part of a south-facing roof top), trim the tree, or use some other corrective measure can be quantified. The authors speculate that providing gifts of acceptable trees to neighbors may improve goodwill so that the use of lawyers can be avoided. For example, fruit or nut trees such as an apple tree would provide both aesthetic value, lawn shade, and added value (food). The necessary trimming of the tree to ensure the added value of food production is maximized would also ensure that the tree did not grow to a height that impeded solar energy production.

The analysis presented here can be extended to different tree varieties in different geographic regions both within the US and the rest of the world. This analysis can assist policy makers design bylaws that enable solar energy technologies such as PV to coincide in the same neighborhood as trees. This analysis can also be coupled to regional scale planning assisted with LiDAR technology (Nguyen and Pearce, 2012; Nguyen et al., 2012; Carneiro et al., 2009; Habib et al., 2008; Alexander et al., 2009; Rottensteiner and Briese, 2002), to create a more granular analysis of individual buildings. This methodology can also be integrated into software to obtain specific electrical loss estimates. Future work could also modify this method to investigate other types of solar energy systems such as solar thermal (Thirugnanasambandam et al., 2010) or solar photovoltaic thermal (PVT) hybrid systems (Chow, 2010; Parida et al., 2011). It should be noted that this simple methodology neither provides a full optimization routine nor does it give fine-grained information on the effects of the growth of tree branches and leaves on PV performance, which are both left for future work. The latter complexity of the shade impact of individual branches or leaves on PV performance is substantial because it depends on the module type, severity of shade and string configuration (Deline, 2009, 2010a, 2010b). For example, most PV systems have multiple strings connected in parallel and thus the layout of the system itself will cause a wide variability in the magnitude of the tree related shading losses even for identical shaded areas in identical climate conditions as discussed above. These complexities are also all expanded with both the type of inverter, but also the magnitude of the solar flux at a given time and even the spectral distribution of the incoming light with varying PV materials (Andrews and Pearce, 2013). This level of complexity is beyond the typical homeowner, however, could be integrated into a commercial PV system design and optimization tool such as PVSyst. Finally, future work can focus on the creation of automated easy-to-use, open-source software to help homeowners determine potential losses for solar energy systems from tree shading as a function of time for their own homes.

6. Conclusions

This paper introduced a novel open low-cost method to predict and prevent tree shading from negatively impacting the performance of roof-mounted PV systems. The clear methodology for the relationship between trees and PV systems to assist decision makers in both legislation and planning to avoid future problems associated with coexistence of solar energy technologies and trees. A case study was presented investigating the most common trees in the Midwest US. Tree growth characteristics, such as height, crown width, and growth rate were investigated as these are the primary factors that determine the total area of the shade from a tree. Trees were modeled by using their average dimensions at the age of 30 assuming that trees were planted right after a PV system installation so they are not exempt from existing and likely future laws covering tree shading of PV. The minimum planting distances were quantified based on tree species and orientation of planting with respect to the PV system. The tree species based on crown width was also found to play a role in planning of planting location. For buildings with limited space to plant trees on the surrounding grounds this paper provides a clear guide to installers and owners of PV systems to avoid shading related losses.

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