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A comparative study of the thermal and radiative impacts of photovoltaic canopies on pavement surface temperatures

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Abstract

Rapid urbanization of the planet is occurring at an unprecedented pace, primarily in arid and semi-arid hot climates [Golden, J.S., 2004. The built environment induced urban heat island effect in rapidly urbanizing arid regions – a sustainable urban engineering complexity. Environ. Sci. J. Integr. Environ. Res. 1 (4), 321–349]. This growth has manifested itself as a cause of various impacts including elevated urban temperatures in comparison to rural sites known as the Urban Heat Island (UHI) effect [Oke, T.R., 1982. The energetic basis of the urban heat island. Q. J. R. Meteor. Soc. 108, 1–24]. Related are the increased demands for electric power as a result of population growth and increased need for mechanical cooling due to the UHI. In the United States, the Environmental Protection Agency has developed a three-prong approach of (1) cool pavements, (2) urban forestry and (3) cool roofs to mitigate the UHI. Researchers undertook an examination of micro scale benefits of the utilization of photovoltaic panels to reduce the thermal impacts to surface temperatures of pavements in comparison to urban forestry. The results of the research indicate that photovoltaic panels provide a greater thermal reduction benefit during the diurnal cycle in comparison to urban forestry while also providing the additional benefits of supporting peak energy demand, conserving water resources and utilizing a renewable energy source.
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Keywords: Photovoltaic canopies; Urban heat island; Green engineering; Thermal and radiative characteristics; Renewable technologies; Sustainable development

1. Introduction

The nexus of rapid urbanization and urban climate is detailed as resulting in the Urban Heat Island (UHI) effect resulting in environmental, economic and social considerations and impacts which frame UHI as an exemplar for studying Sustainable Development (Golden, 2004). This paper presents sustainable engineering systems to support designing practical approaches to mitigating UHI impacts associated with surface pavements, using the Phoenix, Arizona region of the United States which has been extensively researched in regards to UHI.

Electricity demands to provide mechanical cooling as a result of UHI have steadily increased resulting in a penalty from a sustainability perspective including increased costs, reliance on limited water supplies as well as increased

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emissions from fossil fuel plants that provide electricity (Golden et al., 2006).

One alternative is to explore the microscale climatic benefits, if any, from utilizing photovoltaic panels to mitigate UHI in parking facilities. A research project was undertaken during the summer months of 2004 to evaluate two mitigation strategies for the impacts of surface parking pavements in the Phoenix region. The first mitigation strategy examined was the conventional utilization of urban forestry by which canopy coverage provides shading of paved surfaces. The second mitigation strategy evaluated was the utilization of photovoltaics as a possible sustainable engineering mitigation option. The research was undertaken to:

1. Evaluate the effectiveness of traditional urban forestry to reduce surface temperatures of pavements in parking lots and quantify 2 m ambient temperatures which correlate to human comfort. Includes examining the role of sky view factor.
2. Evaluate the effectiveness of photovoltaic canopies during the diurnal cycle to reduce parking lot pavement surface temperatures, with measurements at the pavement surface, PV canopy surface, and ambient temperature at 2 m height.
3. Compare the effectiveness of urban forestry mitigation, in comparison to PV parking lot canopy coverage, for reducing pavement surface temperatures.
4. Develop a listing of criteria and inputs which can be used to support a practical model in pavement selections that can used by engineers, policy makers, planners and architects.

2. Conventional urban forestry

The first portion of this research project was to investigate the effectiveness of urban forestry to reduce pavement temperatures at the surface in an arid region. Increasing the amount of urban vegetation decreases local ambient air temperatures through shading and evapotranspiration. The US Department of Agriculture Forest Service (1999, 2000) estimates that maximum mid-day air temperature reductions are in the range of 0.07 °F (−0.04 °C) to 0.36 °F (−0.2 °C) for every one percent (+1%) increase in the canopy cover.

Shading can play an important role in the lower canopy boundary of parking lots (2 m and lower) by preventing solar radiation from coming in contact with, and being absorbed by, engineered materials. Incident solar radiation reaches a tree's canopy, with some percent utilized by the leaves for photosynthesis and with the remainder either reflected back into the atmosphere or transmitted to the engineered surface below. The latter quantity determines the tree's transmittance, which is typically 10–30% in the summertime. A mature 40-ft tree with a crown of 30 ft can decrease air temperature by transpiring as much as 40 gallons of water per day (Akbari et al., 2001).

Urban forestry canopy coverage over paved surfaces has been evaluated as a mitigation strategy for the Urban Heat Island by examining temporal, hydrocarbon and stormwater impacts while potentially increasing pavement longevity (Akbari et al., 1993; Asaeda et al., 1996; Scott et al., 1999; Xiao et al., 1998; McPherson et al., 1999). Some municipalities within the United States have adopted parking lot canopy coverage. As an example, Sacramento, California requires 50% canopy coverage of the total parking lot area within 15 years of a project's development (Sacramento City Ordinance 17.64.030).

Although research has been carried out to investigate the singular benefits of urban forestry, there lacks quantitative analyses of the benefits of urban forestry in comparison to other canopy coverage mitigation strategies such as photovoltaic canopies. To conduct this analysis, an examination of the urban forestry mitigation strategy was conducted with desert forestry in the extreme temperatures of Phoenix at the Arizona State University Research Park located approximately 6 miles to the south of the main campus in Tempe. A typical urban parking lot was chosen at the US Army Flexible Display Center. The pavements consisted of dense-grade, hot-mix asphalt. The sampling location was not influenced from urban geometry shading beyond that of nearby trees and the research area was made free from any anthropogenic heating sources by use of barricade tape.

The total research area measured 100 m × 100 m with a centered 15 m × 15 m area monitored with the use of thermocouples as well as handheld IR thermography. Temperatures were obtained within the hot-mix asphalt parking surface just below grade on four sides of a cement low-level planter box containing a South American mesquite, aka. Argentine mesquite or *Prosopis alba*.

Temperatures were also obtained on the trunk of the tree at 2 m and a Campbell meteorological station was established adjacent to the research site measuring solar irradiance, wind, rain, and temperatures every 10 min.

The tree measures approximately 7.62 m (25 ft) in height, has three diverging trunks with an equivalent diameter of 1.52 m (5 ft), and a canopy area of 6.10 m (20 ft) in diameter. The growth of this species depends on water availability and maintenance practices, but can reach a height of 12.19 m (40 ft) and spread 15.24 m (50 ft) respectively. An average life span has not been established for Phoenix as the tree was introduced into the area less than 30 years ago. Variability includes poor planting location, wind throw, poor nursery stock, and soil born pathogens. *In situ* (the wilds of South American), the tree lives for hundreds of years. The cost of the tree in Phoenix for a typical 0.07 m (24 in.) box is under $200 and variable depending on whether it is a cutting or seed grown.

2.1. Diurnal findings

Sensors were arranged within a four-quadrant array (Fig. 1) approximately 2 m from the trunk of the tree in

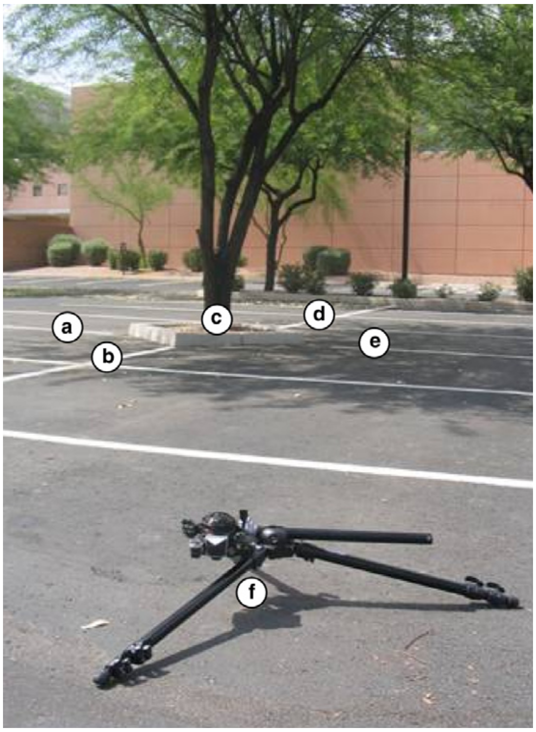

Fig. 1. Image shows the controlled parking utilized for the urban forestry research including camera equipment setup (foreground) and approximate thermocouple locations (background): (a) west edge of canopy cover, (b) south edge, (c) base of tree, (d) north edge, (e) east edge and (f) fully exposed pavement surface.

each navigational direction (north, south, east and west). Small cores were made in the HMA pavement and the sensors were placed approximately 2.54 cm (1 in.) below ground surface and covered with a cold asphalt patch which was allowed to cure. The wires were covered above the pavement for easy access in downloading the acquired data to a laptop computer. Each thermocouple sensor was placed in pavements shaded at least partially during the diurnal cycle by the canopy coverage of the tree. A control thermocouple was placed in the same HMA paving material at 2.54 cm below surface and approximately 30 m to the south of the researched pavement covered by the tree canopy in an area fully exposed to solar radiance with a calculated sky view factor (Ψ_{sky}) of approximately 0.90. Additionally, the exposed sensor was free from any urban geometry or urban forestry influences.

2.2. Sky-view factor

Sky-view factor (Ψ_{sky}) is a dimensionless parameterization of the quantity of visible sky at a location which is represented between 0 and 1. Ψ_{sky} will approach unity in a perfectly flat and open terrain, unlike the urban region with various geometries of the built environment that reduce Ψ_{sky} (Chapman et al., 2001; Oke, 1982). A rating of 1 indicates that the sky view is free of all obstacles, and outgoing radiation would radiate freely to the sky (Brown and Grimmond, 2001). The thermal hysteresis lag effect, that is, the thermal energy storage of engineered materials which leads to increased night-time temperatures, is impacted by Ψ_{sky} due to the limiting longwave radiation ($L\uparrow$) by a canopy-trapping effect.

2.3. Determining sky view factor and solar access

When conducting experimental research involving thermal behavior of pavements it is very important to have a good understanding of the environmental factors that will have the greatest impact. For this study it was assumed that the surface access to open sky (Ψ_{sky}) and its relation to direct sunlight were the most critical elements. Wind speed is usually an important factor relating to heat transfer through convection. However, in this study, both locations were in parking lots and would be subject to relatively consistent and similar low wind velocities; therefore it was not considered critical in this preliminary research.

To determine $\Psi_{\text{sky},}$ a Nikon F2® 35 mm camera with a 7.5 mm Fisheye Nikkor F5.6® 180° lens was used to take black and white images at each location. To be sure the camera would capture approximately the same view as what the surface ‘sees’, a Bogen Manfrotto® professional tripod with a large range of motion was used. The tripod provided a sturdy platform to hold the camera in a completely vertical and level position several inches from the HMA surface (Fig. 1).

The images were developed and scanned into a computer enabling them to be processed digitally using MATLAB® 6.5. First, it was necessary to delineate the sky pixels from the non-sky pixels in each image. This was accomplished both through manual manipulation in Photoshop® and a threshold process similar to that used by Chapman et al. (2001). This gave a good contrast between sky and non-sky elements. Next, a well established method developed in Steyn (1980, 1986) which calculates Ψ_{sky} through a series of mathematical steps was applied to each fisheye image. The process begins by delineating the images into concentric annuli of equal width and then multiplies the resulting matrix with a weighted matrix that relates each pixel to its distance from the center (Steyn et al., 1986). The result is a Ψ_{sky} for the fisheye image. Many times the process can be sensitive to several factors usually relating to the delineation of sky and non-sky. To verify that the program used in the study produced accurate results each of the images was also processed using a program developed in Chapman et al. (2001) called SKYVIEW. The calculated Ψ_{sky} for each location were found to be within 5% of that determined using SKYVIEW. The sky view factors were determined to be as follows; 0.11 under the PV modified canopy, 0.53 at the base of the tree, 0.76 at the end of each point, and 0.90 at the fully exposed pavements. Examples of the fisheye images, their corresponding sky delineated images and the calculated Ψ_{sky} for each location are presented in Fig. 2.

It is essential to understand when a surface is shaded and not shaded, commonly referred to as its *solar access*.

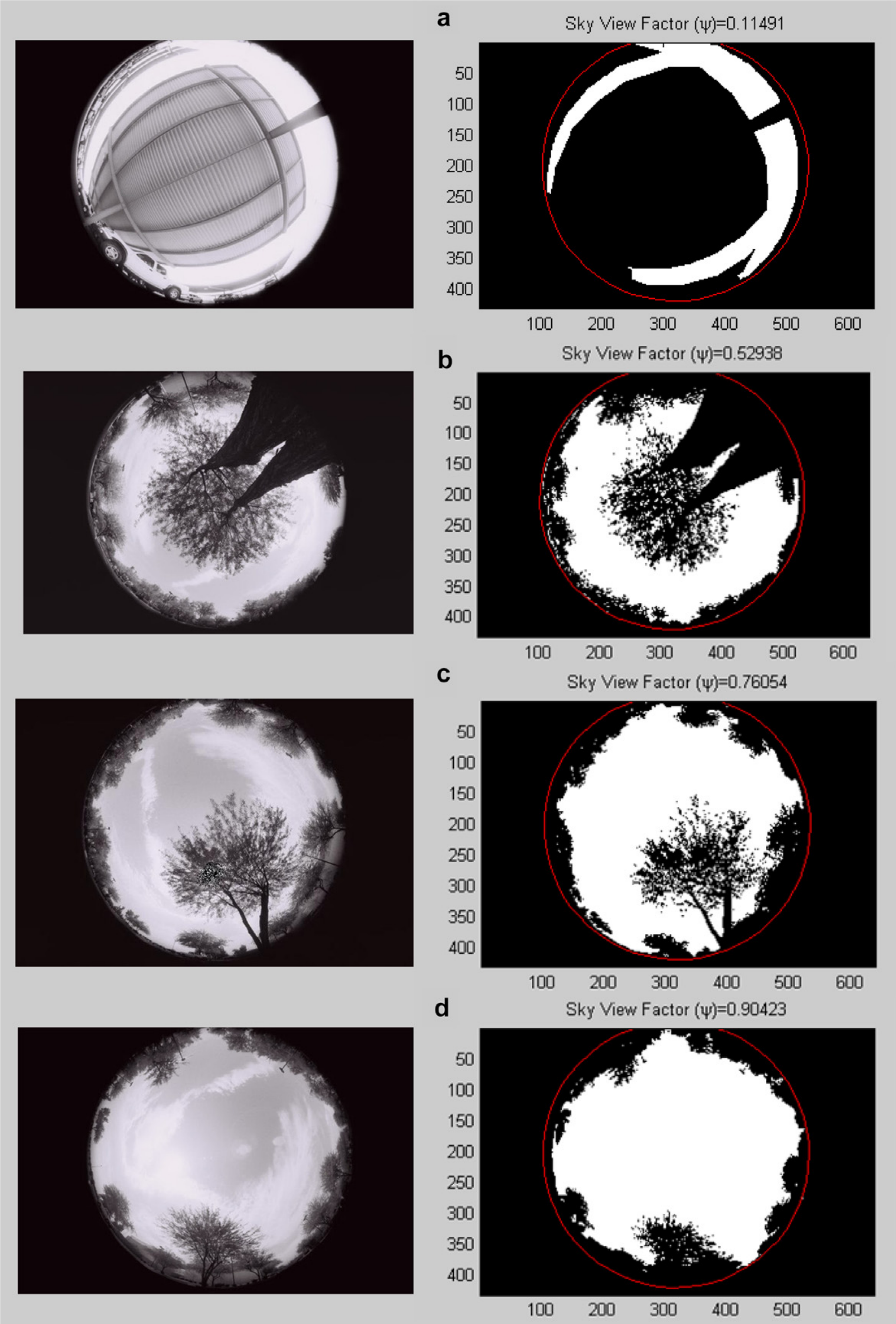

Fig. 2. The first column includes the original fisheye images taken at each thermocouple location. The right column includes the processed images using MATLAB® 6.5 showing the delineation between sky and non-sky as well as the calculated SVF for each image: (a) beneath PV modified parking canopy, (b) at tree base, (c) at eastern edge of canopy, (d) at fully exposed surface.

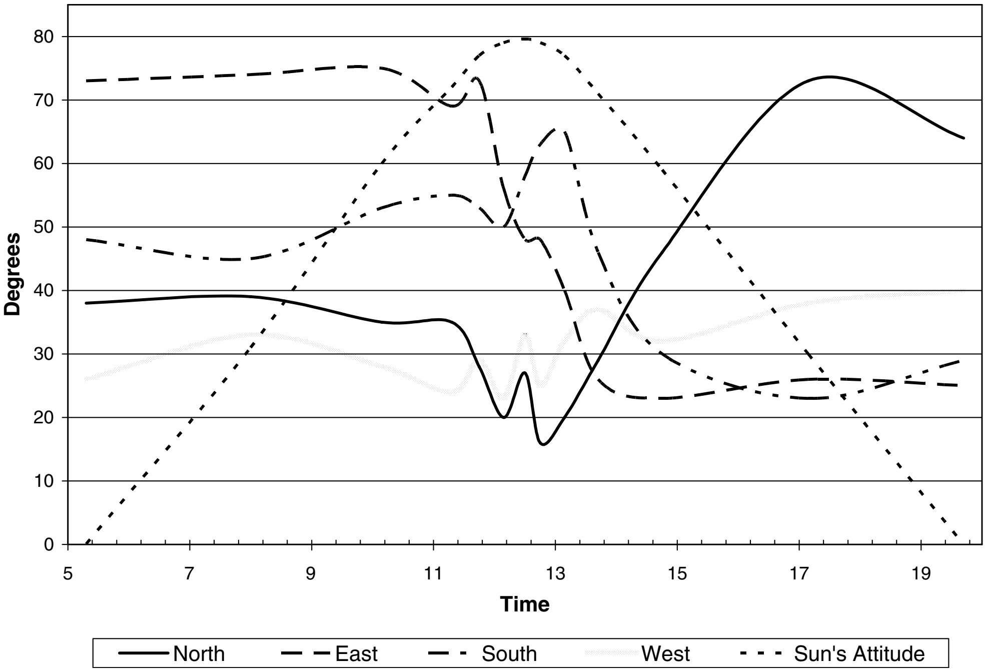

Fig. 3. Azimuth and zenith angles of the urban forest canopy for the investigated site in Tempe, Arizona, USA, on June 14, 2004. The North, East, South, West correspond to the azimuth positions of 0°, 90°, 180° and 360°.

The data utilized for Fig. 3 was obtained on 14 June 2004 to be consistent with similar data used in this research. The figure shows geometric azimuths and zenith angle measurements in degrees. It was important for this experiment to measure the zenith angle for various azimuths for each pavement location relative to the overhanging tree canopy, with open sky occasionally showing itself at various times of the day, since the overhanging tree canopy blocks solar radiation and variably impacts the pavement surface temperature evolution during the daytime diurnal period. Alternatively, future research could examine leaf area index (LAI) to solar penetration in respect to surface temperature evolutions for the urban forest.

Zero degrees zenith means exactly on the local horizon and 90° is "straight up." Azimuth is the angle along the horizon, with zero degrees corresponding to North, and increasing in a clockwise fashion. Thus, 90° is east, 180° is south, and 270° is west. Using these two angles, one can describe the apparent position of an object (such as the Sun at a given time). The angles were calculated by laying perpendicular and approximately 1 m from the base of the tree using a Brunton Transit. Field readings were done for true north, east, west and south of the tree trunk.

The angles at which the pavement below the tree canopy is shaded are indicated in Fig. 3. Pavement surfaces are not covered by the canopy until 73° (y-axis) at 05:30 h (x-axis). The lower the sun's zenith angle the greater is the coverage of the pavement during the diurnal cycle. In urban parking lots, trees are continually trimmed up and the lengths of the branches are shortened to allow larger vehicles to park on the pavements of the parking lots. As represented in Fig. 4, the eastern pavements are exposed to direct solar irradiance until the flux is reduced by tree canopy coverage at 10:15 h.

After obtaining the sky view factors, experimentation then quantified how the role of sky view and desert canopy coverage influences surface temperatures (Fig. 4). Based on data acquired every 20 min from thermocouples, it was determined that the non-shaded HMA ($0.90\Psi_{\text{sky}}$) pavement consistently maintained the highest surface temperature during the complete diurnal cycle. This pavement was to the south of the experimental tree. The pavement was fully exposed to solar irradiance.

As expected, pavements under the tree canopy on the eastern side of the tree had a comparable heating rate and surface temperatures as the fully exposed pavements to the south during the first cycle of heating (0800–1200 h). This can be explained by the angle at which the pavement is shaded by the tree canopy as was presented in Fig. 3. In comparing G.T. and Fig. 4, the heating and cooling of the pavements are consistent with the canopy coverage.

Handheld thermal infrared imagery captured using the FLIR Systems™ ThermaCAM™ S60 was obtained during 17 June 2004 of the pavement covered by the tree canopy. Images for 0940 h, 1612 h, 1800 h and 2118 h showed the influence of canopy coverage on surface pavements. The temperature data obtained from the infrared thermographs is within certain levels of accuracy for different types of pavements. A previous study compared the temperature results between thermocouples and infrared images using the FLIR Systems™ ThermaCAM™ S60. Table 1 contains the results of the study for the various materials that were analyzed. The study concluded that for asphalt and

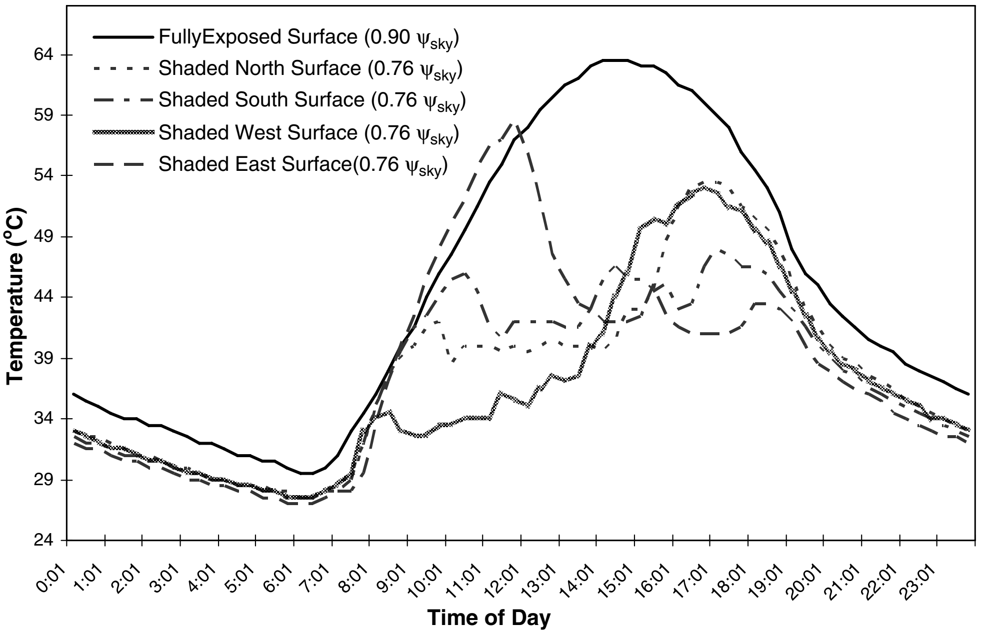

Fig. 4. Diurnal pavement surface temperatures via urban forest canopy coverage Tempe, Arizona, 14 June 2004.

Table 1
Comparison of simultaneous surface temperature readings (°C) utilizing standard thermocouple sensors and infrared images captured using the FLIR Systems™ ThermaCAM™ S60

Time	Air temp	Dense graded hot-mix asphalt			Portland cement concrete (PCC)			Thin whitetopping PCC			Crumb rubber PCC			Gap graded asphalt rubber HMA		
		Sensor	IR therm	ΔT	Sensor	IR therm	ΔT	Sensor	IR therm	ΔT	Sensor	IR therm	ΔT	Sensor	IR therm	ΔT
12:00	36.56	60.5	58.2	2.3	50	50.2	−0.2	50.5	50.3	0.2	51	52	−1	55	56.4	−1.4
13:20	37.44	63	62.4	0.6	52.5	51	1.5	51.5	51.2	0.3	53.5	55.6	−2.1	59	60.2	−1.2
15:20	38.78	64	62.8	1.2	53.5	54.4	−0.9	54.5	55.8	−1.3	54.5	55.9	−1.4	61	63.2	−2.2
17:00	38.89	55.5	56.4	−0.9	49	48.2	0.8	51	52.3	−1.3	50	51	−1	58.5	58.8	−0.3
19:00	37.44	44.5	46.2	−1.7	42.5	43.4	−0.9	43	45.6	−2.6	43.5	44.2	−0.7	48.5	49	−0.5
21:00	33.17	38.5	44	−5.5	37.5	37.3	0.2	37	38	−1	38	38.6	−0.6	40	39.7	0.3
23:00	30.33	35	38.2	−3.2	34.5	35.4	−0.9	33.5	32.3	1.2	35	34.4	0.6	36	36.4	−0.4
1:00	28.72	33	35.4	−2.4	32.5	33.3	−0.8	31.5	32	−0.5	33	32.6	0.4	34	33.5	0.5
3:00	28.33	31	33.3	−2.3	31	32.5	−1.5	30	31.2	−1.2	31.5	32.4	−0.9	32	31.7	0.3
5:00	25.94	29.5	31.2	−1.7	30	30.3	−0.3	28.5	28.8	−0.3	30	31.2	−1.2	30.5	31.9	−1.4
7:20	27.5	34	34.4	−0.4	31	32.6	−1.6	31	33	−2	31	32.8	−1.8	31.5	32.5	−1
8:40	30.44	41	43	−2	35.5	37.1	−1.6	35.5	36.4	−0.9	35	36.8	−1.8	37	36.7	0.3
		Mean ΔT		−1.45	Mean ΔT		−0.48	Mean ΔT		−0.85	Mean ΔT		−1.05	Mean ΔT		−0.64
														Total mean ΔT		−0.89

All times local Mountain Standard Time.

concrete surfaces the temperatures obtained from the IR camera are within ±0.89 °C.

An additional task was to evaluate how urban forestry canopy coverage affects human comfort. This was examined by evaluating ambient air temperatures at 2 m height levels. Thermocouples were placed on the north side of the tree with the wires attached but the thermocouple not in contact with any surface. A similar setup was constructed in the full exposed pavement with the thermocouple attached to a 3 m tree stake, again with the thermocouple not in contact with any surface but shaded by a cardboard coverage. This reduced the direct influence of solar irradiance on the thermocouple while allowing for the microscale influence of the pavement surfaces in the immediate vicinity to be analyzed.

The results indicated that the tree canopy effect provides for a reduction in ambient air temperature during highest solar irradiance, in comparison to the un-shaded parking area, by 3.5 °C (Fig. 5).

However, after sunset, the ambient air temperatures influenced by the tree coverage were on average 1 °C higher than ambient temperatures measured in the fully exposed

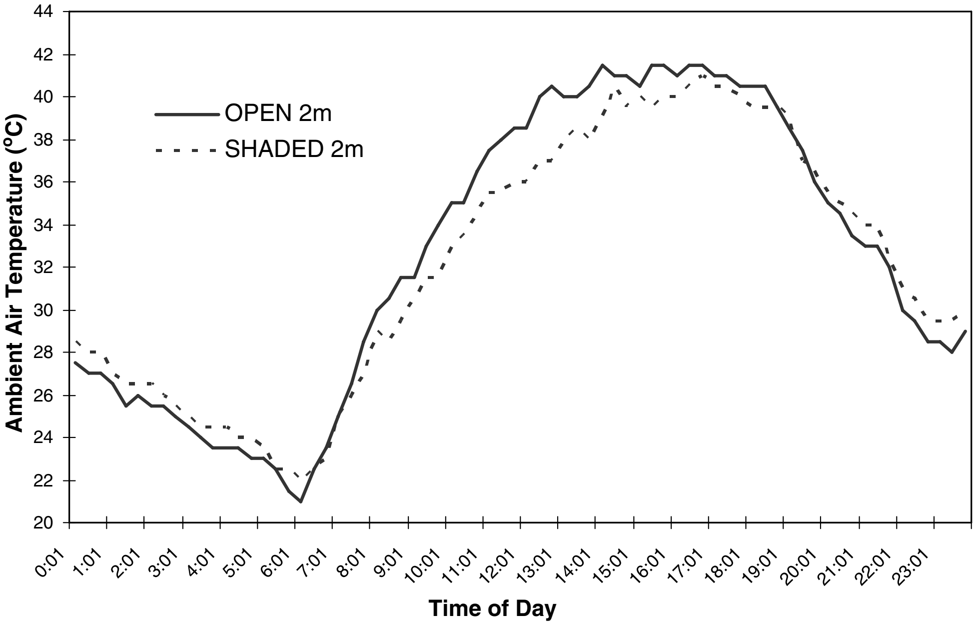

Fig. 5. Ambient air temperature evaluation at 2 m height above both the exposed pavement and the location under the urban forestry canopy.

parking lot area. This held constant until surface heating in the early morning hours (∼0830 h). The canopy effect of trapping longwave radiation can help explain the lower cooling rate than a similarly sampled area with $0.90\Psi_{\text{sky}}$.

3. Photovoltaic mitigation strategy

The next stage of the research was to conduct a comparison study to contrast and compare findings from urban forestry mitigation (Section 2) with that of photovoltaic panels.

The goal is to examine if the utilization of photovoltaic (PV) panels is an effective canopy coverage in parking lots, reducing the solar heat flux to the ground and thus decreasing surface pavement temperatures, both during daytime and nighttime hours. The field trials quantify the efficiency of the PV canopy coverage to reduce surface pavement temperatures relative to urban forestry canopy coverage for parking lot pavements.

A research project was carried out at the City of Phoenix Pecos Road Park and Ride Facility. The facility is utilized by residents of the southeastern portion of the City to park their personal vehicles and utilize public transportation to areas of central city and throughout the region. As seen in Fig. 6 the facility, which opened in 2003, accommodates 562 personal vehicles with covered canopy parking. The Salt River Project (SRP), a regional public utility, joined with the City of Phoenix Transit Department in a $1 million project to install solar power panels on covered parking structures on top of two existing sheet metal parking covers. It is a fixed-tilt flat system containing 768 modules of 165 W each on two parking canopies. The array area for the combined parking system is 11,000 ft^2 which provides coverage for ∼80 American sized vehicles. The main PV power system has a design rating of 127 kW dc, or 100 kW ac, which produces an annual output of ∼178,000 kW h (SRP, 2003).

Fig. 6. Aerial view of the subject research site for PV canopy coverage shows (a) PV modified parking canopies and (b) conventional parking canopies, Phoenix, Arizona.

3.1. Microclimate variability

During June 2004, research was conducted utilizing handheld infrared thermography, *in situ* thermocouples, and the establishment of a stationed meteorological station. An example infrared image is presented in Fig. 7. One set of thermocouples was embedded within the HMA pavement surface fully exposed with $0.90\Psi_{\text{sky}}$. Additionally a second thermocouple was attached to a vertical stake at 2 m height above ground surface (ags). A second set of thermocouples was placed at a ‘‘conventional’’ parking canopy area which

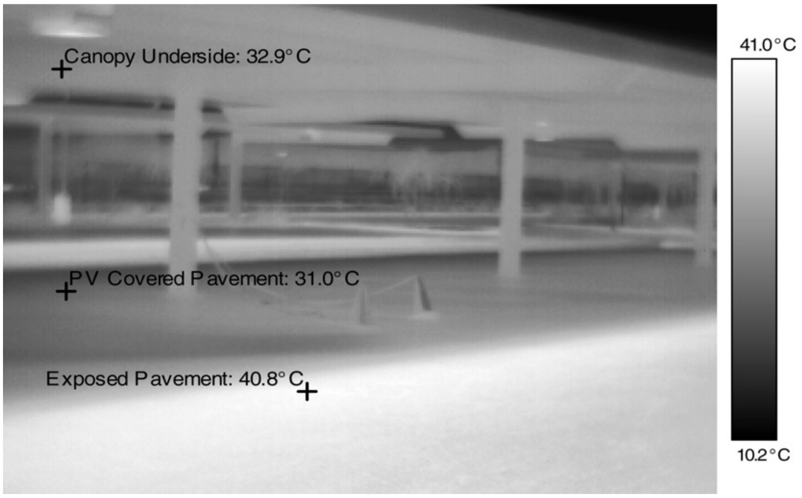

Fig. 7. 17 June 2004 20:26 h handheld infrared thermograph showing the surface temperature variability of the PV covered canopy cover ($0.76\Psi_{\text{sky}}$) versus the fully exposed pavement ($0.90\Psi_{\text{sky}}$).

is a corrugated metal canopy. This included placement within the HMA pavement, at 2 m above the surface, a third directly underneath the canopy top and a fourth just above the canopy top. A third set of thermocouples was placed at a modified photovoltaic parking canopy cover, which is a conventional canopy with PV panels placed 4 cm above the conventional panel.

Similar to the conventional canopy, thermocouples were placed within the HMA pavement, at 2 m above ground surface, directly underneath the canopy top and placed in the layer between the conventional canopy top and the bottom of the photovoltaic panels. No thermocouple was placed at the top of the PV panels as the readings would represent the incident solar absorption of the thermocouple and not the PV panel. The diurnal evaluations of the PV panel temperature are most appropriately evaluated at the base of PV panels. The field research for the three locations was carried out through the month of June 2004. As an active parking facility, only a month of research could be negotiated since the area had to be closed off to users of the facility during the field trials. The results are presented in Table 2 which indicate that the un-shaded pavement reaches the highest maximum surface temperatures, while the pavement surfaces covered by the conventional and PV modified canopies had lower, but similar, maximum surface temperatures.

These findings are represented in the two expressions below. Eq. (1) shows that the exposed maximum surface temperature minus the minimum surface temperature equals a diurnal variance of 37 °C. Eq. (2) shows that the pavement surface covered by the photovoltaic canopy observes a diurnal temperature variance of approximately 11 °C which is a 70% reduction from that of the uncovered pavement:

$$\text{Đ}\Delta T_{\text{Exposed}} = {}^{\text{surface}}T_{\text{Max}}(65.5\ ^{\circ}\text{C}) - {}^{\text{surface}}T_{\text{Min}}(28.5\ ^{\circ}\text{C}) = 37.0^{\circ}\text{C} \quad (1)$$

$$\text{Đ}\Delta T_{\text{PV modified canopy}} = {}^{\text{surface}}T_{\text{Max}}(38.5\ ^{\circ}\text{C}) - {}^{\text{surface}}T_{\text{Min}}(28.0\ ^{\circ}\text{C}) = 10.5\ ^{\circ}\text{C} \quad (2)$$

where $\text{Đ}\Delta T$ = diurnal surface temperature delta (maximum minus minimum).

The temperature fluctuations of HMA pavements can have drastic implications on their durability and functional lifetime. High temperatures such as those experienced by the exposed pavements in Eq. (1) can significantly increase the oxidation and volatilization of these materials. These processes lead to losses in plasticity, resulting in hard and brittle pavements, susceptible to cracking under stress. In fact, the rates of oxidation and volatilization in asphalt pavements nearly double for every 10 °C rise in temperature (Somayaii, 2001). It is then plausible to assume that based on the temperature difference of 27 °C observed here, the non-shaded pavement regions will oxidize and volatilize at nearly eight times the rate of those paved areas covered by the PV modified canopy. Furthermore, the severe temperature fluctuations of 37 °C observed in the pavements exposed to direct radiation result in severe thermal expansion and contraction which can lead to decreased elasticity and pavement resiliency over time (Tonias, 1996). This loss of elasticity coupled with the cyclic thermal stresses often

Table 2
Mean pavement surface temperatures for various types of coverage

Pavement coverage	Mean maximum temperature	Mean minimum temperature	Mean average temperature
Fully exposed pavement (Ψ_{sky} 0.90)	146.2 °F/63.5 °C	83.3 °F/28.5 °C	110.5 °F/43.6 °C
Under conventional canopy (Ψ_{sky} 0.11)	99.9 °F/37.7 °C	81.1 °F/27.3 °C	90.3 °F/32.4 °C
Under PV modified canopy (Ψ_{sky} 0.11)	98.7 °F/37.0 °C	81.9 °F/27.7 °C	89.7 °F/32.1 °C

Phoenix, Arizona, 17 June 2004.

result in joint and shrinkage cracking, drastically affecting their maintenance costs and life span (Tonias, 1996). From this observation it is evident that when a property owner conducts a cost–benefit analysis of using PV modified canopies it is essential to consider the life cycle cost savings associated with the extended lifetime of pavements shaded from the damaging radiation of the sun.

3.2. PV cooling rates

The examination of photovoltaics as a means to reduce surface temperatures has been researched on a limited basis. Genchi et al. (2003) modeled mesoscale use of PV panels in a large area of Tokyo on rooftops. They concluded the large-scale impact would be negligible but that energy consumption for cooling may be reduced by up to 10% by the shading effect. The present research, however, is focused on comparing the pavement surface temperatures underneath the PV/canopy top versus the surface temperatures underneath exposed pavements, and the nocturnal energy storage and release. The issue being at the mesoscale, can PV present a greater or lesser influence to the UHI by having a greater or lesser surface temperature during the diurnal cycle? This would require a quantification of the thermal storage capacity of the PV units as installed, together with that of the pavement being shaded below the PV canopy coverage. By reducing heat storage (Q_s) of any surface there is the potential to mitigate the UHI at the micro and mesoscale.

3.3. Variability influences

Wind speed during the 24-h period of 17 June 2004 obtained from the adjacent meteorological station averaged 0.86 m/s with a high wind speed of 2.65 m/s sustained for less than 15 min around 1415 h. Solar irradiance initiated at 0515 h with the last recorded reading taken at 2000 h. Maximum ambient air temperature was 40.98 °C (105.76 °F). This particular facility is utilized by commuters who arrive prior to 0700 h and leave their vehicle in place after post work (1700–1900 h). No quantification of the anthropogenic heat flux was measured as a result of the vehicle engines. However, the flux is primarily generated during cool early morning hours for durations of less than one hour, which would be negligible to the diurnal hysteresis lag effect. The after-work heat flux from vehicles is also minimized as vehicles are started and removed quickly from the parking area. A higher volume parking lot, such as those found in retail establishments, would present higher fluxes primarily during peak shopping hours when greater vehicle movements will occur. The areas that were sampled were tapped off restricting any vehicles parking in the sampling locations, thus minimizing anthropogenic fluxes and shading from parked cars.

4. Urban forestry versus PV canopy mitigation

An analysis was conducted to understand the mitigation benefits of reducing surface pavement temperatures in paved parking lot surfaces comparing the conventional urban forestry canopy strategy versus photovoltaic canopy coverage. An initial evaluation period was for the diurnal cycle of 14 June 2004. The Arizona State University Research Park (Urban Forestry canopy coverage) and the City of Phoenix Park and Ride lot (photovoltaic canopy coverage) are approximately 7.2 miles in distance by road networks.

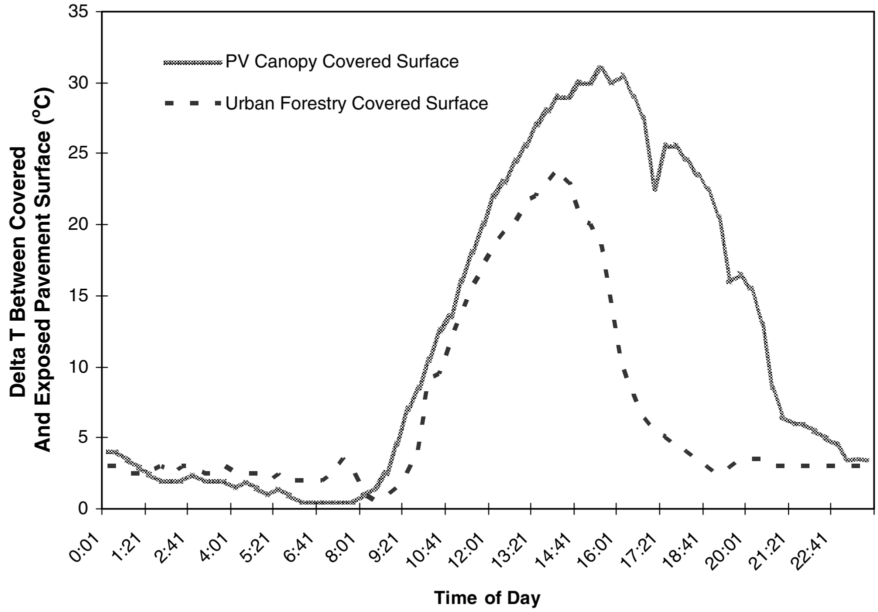

Fig. 8. Graph of the surface pavement mitigation benefits comparing the temperature reductions of pavement under the PV canopy coverage and pavement under the Urban Forestry Coverage, 14 June 2004.

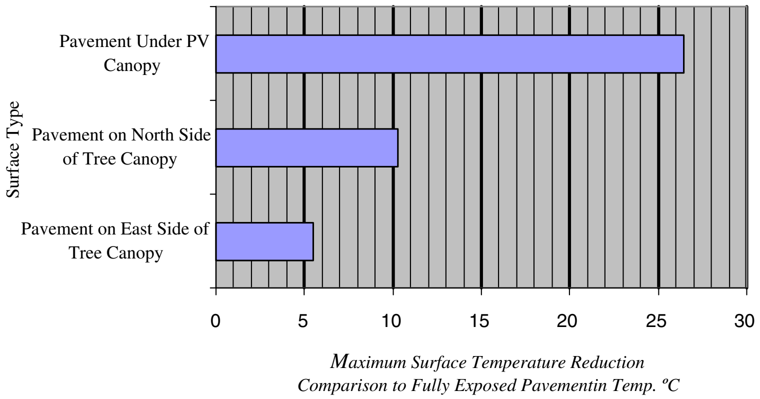

Fig. 9. Comparison of mitigation strategies for surface pavements by canopies indicating the surface temperature reduction compared to fully exposed pavements. Mean reduction for 10–20 June 2004.

Of interest was comparing the ÐΔT^{surface} achieved by both mitigation strategies. As presented in Fig. 8, the HMA surface shaded by a PV canopy achieves a 55.8 °F (13.2 °C) surface temperature reduction in comparison to the adjacent fully exposed HMA while the HMA surface mitigated (covered) by the urban forestry achieves a maximum reduction of 43.2 °F (6.2 °C) in comparison to the adjacent fully exposed HMA.

The maximum temperature reduction for the urban forestry canopy would have been lower if surface temperatures for the eastern shaded pavements were used, as this area had a greater rate of heating (Fig. 9). In part, this variation of surface temperature reductions between the two mitigation strategies can be explained due to the large sky view factor (0.76Ψ_{sky}) of the urban forestry mitigation strategy. Figs. 8 and 9 present the temperature reduction benefits of the two mitigation strategies. As depicted, the research indicates that the utilization of photovoltaic canopies provides a greater reduction of surface temperatures during the diurnal cycle in comparison to pavements covered by urban forestry. PV canopies provide a more optimal benefit during the time of peak solar irradiance at the surface layer, however future research needs to be undertaken to fully quantify the diurnal microscale impacts to human comfort.

5. Mitigation policy considerations

After examining the conventional mitigation strategy of urban forestry and introducing the use of photovoltaic canopies, this section presents sustainable engineering considerations towards mitigating surface pavement contributions to the Urban Heat Island.

5.1. *Urban forestry and pavements*

One implementation consideration regarding the use of urban forestry as a mitigation strategy has to do with the urban climate itself. Baker et al. (2004) examined the changing dynamics of cold stress versus heat stress days from 1945 to 2003. The broad and narrow leaf woody trees and shrubs used are generally grouped under the category of urban forestry in the Phoenix region.

According to Baker et al. (2004), these species, when exposed to supraoptimal, sublethal temperatures above 40 °C, experience the most negative impact on photosynthesis (Farrar and Williams, 1991). Supraoptimal temperatures inhibit photosynthesis by decreasing the efficiency of photosynthetic enzymes (Huxman et al., 1998; Rokka et al., 2000; Crafts-Brandner and Salvucci, 2000) and increasing photorespiration (Law and Crafts-Brandner, 1999; Jordon and Orgen, 1984). Supraoptimal temperatures also increase growth and maintenance respiratory costs (Van Iersel and Linstrom, 1999), lower water-use efficiency (Martin et al., 1995), and the lower evapotranspiration, cooling potential of urban vegetation (Martin and Stabler, 2002). Because much of the horticulture utilized in the region has been recently introduced, similar to the population, these plants have not adapted to the regional climate, and the stress of the increased heating days reduces evapotranspiration (Baker et al., 2004).

Celestian and Martin (2003) studied effects of parking lot location on size and physiology of four regionally common landscape tree species in the Phoenix region over a 2 year period. Parking lot trees must contend with a number of microenvironmental stresses that might adversely affect their growth. In addition to restricted rooting volumes and limited access to water and nutrients, some parking lot trees are exposed to elevated rhizosphere and canopy air temperatures caused by intense sunlight and the absorptive and reradiated properties of asphalt and concrete surface covers (Kjelgren and Montague, 1998). Continuous exposure of trees, especially those within parking lot landscaped medians, to these conditions might adversely impact tree performance by either direct injury of tissues or by indirect inhibition of physiological processes like nitrogen and carbon assimilation. In their study, Celestian and Martin (2003) examined four common tree species: (1) *Brachychiton populneus* (bottle tree), (2) *Fraxinus velutina* Torr. (Arizona ash), (3) *P. alba* Griebach (South American mesquite), and (4) *Ulmus parvifolia* Jacq. (Chinese elm). Bottle trees were located at two parking lots, Arizona ash at three parking lots, South American mesquite at three parking lots, and Chinese elm at four parking lots. At each parking lot, the researchers collected samples of rhizosphere soil [15–30 cm (6–12 in) depth] from under the canopy drip line at both the median and perimeter locations for analysis of soil chemical properties.

Their research revealed trees located within the landscaped medians were smaller than those within the landscaped areas along the parking lot perimeter, though the extent and significance of this difference was species specific.

The UHI as represented in the Phoenix region has caused an increase in the re-occurring heat stress days which can reduce the potential effectiveness of an urban forestry mitigation strategy. Because of the increased stress, plant viability will require increased rates of water. This has to be considered for a region like Phoenix which is arid and presently in a drought (Baker et al., 2004).

5.2. Use of photovoltaics

The use of PV canopies as a mitigation strategy would be most appropriate for the large volume of school, retail and commercial parking lots. The power generated from the PV will depend on the rating of the system and the available electricity generating potential hours. PV canopies can be used to provide supplemental base load and peak power electricity for buildings, signage and municipal needs in the immediate area.

By providing photovoltaic canopy coverage as a means to mitigate the surface temperatures of pavements, there is the potential for microscale and mesoscale reduction in the Urban Heat Island. By reducing the UHI, there will be a corollary reduction in the need for mechanical cooling which in fact reduces the anthropogenic heat flux. Photovoltaics as a renewable energy resource, requires less than 1 gallon of water per kW h for both withdrawal and consumption (Energy Foundation, 2003).

Mesoscale utilization of photovoltaics in parking areas and over paved areas needs to be modeled to understand the regional mitigation benefits.

6. Discussion

This study was undertaken to evaluate mitigation options for UHI as a result of impacts from surface pavements. The findings identified sustainable engineering opportunities which utilize renewable solar energy photovoltaic systems to mitigate UHI at the microscale. The research area of Phoenix is experiencing its 7th straight year of drought conditions in an already arid region. Conventional urban forestry campaigns to mitigate UHI will most certainly have an initial net increase in water use consumption within a region as plants try to establish and overcome elevated rhizosphere temperatures.

Conversely, the utilization of photovoltaics as a mitigation strategy can result in a reduction of water usage by minimizing the need for water-intensive thermoelectric power generation sources to meet base energy needs as well as having the compounded benefit of potentially reducing mechanical cooling needs by reducing the hysteresis lag effect. Photovoltaics provide for an alternative source to meet the increasing peak energy demand in the Phoenix region, and unlike urban forestry, the PV canopy coverage reaches maximum microscale mitigation potential immediately upon construction in comparison to the years it takes for trees to mature.

Further research is needed to quantify the life cycle benefits of this renewable energy mitigation scheme by examining the costs associated with construction and operation of these units primarily in commercial and retail zones. A sustainable engineering mitigation approach could include the incorporation of engineered pavements such as porous pavements with the use of PV canopy coverage to provide a more effective and more sustainable mitigation strategy in regards to UHI. Because trees planted in parking lots require large diameter dirt wells, the footprint of a parking lot must be increased to accommodate the vehicles per retail or commercial square footage. Future research is being undertaken to examine how photovoltaic parking canopies maximize can potentially increase the number of vehicles per square foot by eliminating tree wells and thus reduces the footprint of the parking lot. Additionally, porous pavements can have an added benefit of reducing the size of parking lots by more effectively managing storm water, which is one of the criteria for sizing a parking lot (Field et al., 1982).

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