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Comparative study and performance assessment of solar energy harvesting pavements

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ABSTRACT

Road pavements have tremendous potential in solar energy harvesting since they occupy a great share of urban surface and can absorb abundant solar radiation. Pavement-integrated photovoltaic (PIPV) module, pavement-integrated solar thermal (PIST) module, and pavement-integrated photovoltaic thermal (PIPVT) module are typical solar energy harvesting pavement modules that have emerged in the past few years. In this study, the performance of these modules was assessed and compared through numerical simulations on the weather conditions of four typical days representing different seasons in Shanghai. The results show that the PIPVT module can generate slightly more electricity than the PIPV module, while output less heat compared with the PIST module on all typical days. The PIPVT module can achieve the average overall energy efficiency of 37.31% considering both electricity and heat yields. Additionally, all three solar energy harvesting pavement modules have positive impact on mitigating the urban heat island (UHI) effect, and the PIPVT and PIST module can mitigate the UHI effect most and least significantly, respectively.

Keywords: Pavement-integrated photovoltaic (PIPV); Pavement-integrated solar thermal (PIST); Pavement-integrated photovoltaic thermal (PIPVT); Performance comparison; Urban heat island (UHI)

NONMENCLATURE

Symbols

A_c	Collector area (m^2)
L	Length of the module (m)
W	Width of the module (m)
E	Energy (J)
$\dot{E}$	Power (W)
$\ddot{E}$	Power per unit area (W·m^{-2})
V	Volume (L)
v	Velocity (m·s^{-1})

Greek number

α	Absorptivity
η	Energy efficiency (%)
ε	Emissivity
σ	Stefan-Boltzmann constant (W·m^{-2}·K^{-4})
ρ	Density (kg·m^{-3})
δ	Thickness (m)
β	Photovoltaic temperature coefficient (%/℃)
τ	Transmissivity
γ	Reflectivity

Abbreviation

PV	Photovoltaic
PIPV	Pavement-integrated photovoltaic
PIST	Pavement-integrated solar thermal
PIPVT	Pavement-integrated photovoltaic thermal
UHI	Urban heat island
CP	Conventional pavement

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1. INTRODUCTION

Nowadays, solar energy is an essential renewable energy resource that has been utilized in various applications. Conventional solar energy harvesting systems are installed in open ground areas, building roofs or facades, and thus either occupy vast land or increase building load. In recent years, pavements have emerged as a new promising scenario to harvest solar energy due to their extraordinary ability to absorb solar energy [3] and the great potential since they occupy huge urban surface [4]. Several pavement-integrated solar energy harvesting modules have been proposed, including pavement-integrated photovoltaic (PIPV) module, pavement-integrated solar thermal (PIST) module, and pavement-integrated photovoltaic thermal (PIPVT) module.

The PIPV module is a combination of the conventional asphalt pavement and the PV panel. Hence, this module can generate electricity besides the conventional function of withstanding the pedestrian and vehicle load. [5-7] The PIST module combines the conventional asphalt pavement and the solar thermal module, and thus can generate thermal energy. [8-10] The PIPVT module is another emerging solar energy harvesting module that can generate heat and electricity simultaneously with the integration of both PV cells and tubes. [11]

To have an overall understanding of solar energy harvesting pavement modules, the detailed comparisons among all these different modules are necessary. However, the vast majority of the existing studies only concentrate on one type of solar energy harvesting pavement modules currently, while the comparisons have not been conducted. Therefore, in this study, based on the simulated results, the performance of the PIPV module, PIST module, and PIPVT module is assessed and compared, aiming to provide a clear view of the performance characteristics of various solar energy harvesting pavement modules and their differences in performance.

2. CONFIGURATIONS OF DIFFERENT SOLAR ENERGY HARVESTING PAVEMENT MODULES

The configurations of different solar energy harvesting pavement modules are demonstrated in Fig 1. The main parameters of these modules are listed in Table 1.

Table 1 Main parameters of pavement modules

Parameters	Values
Maximum PV power	85.72 W
Nominal PV efficiency	20.17%
PV temperature coefficient	0.35%/℃
Tube outer diameter	12 mm
Tube inner diameter	10 mm
Tube number	6
Tube spacing	8.33 mm
Length	0.85 m
Width	0.5 m
Slope	0°

3. METHODOLOGY

3.1 Energy balance equations

According to the energy transfer and conversion in different layers, the two-dimensional transient energy balance equations can be obtained for each solar energy harvesting pavement module. The energy balance equations and involved heat transfer coefficients are written in Ref. [11]. These energy balance equations can be solved in Matlab with thermophysical parameters of

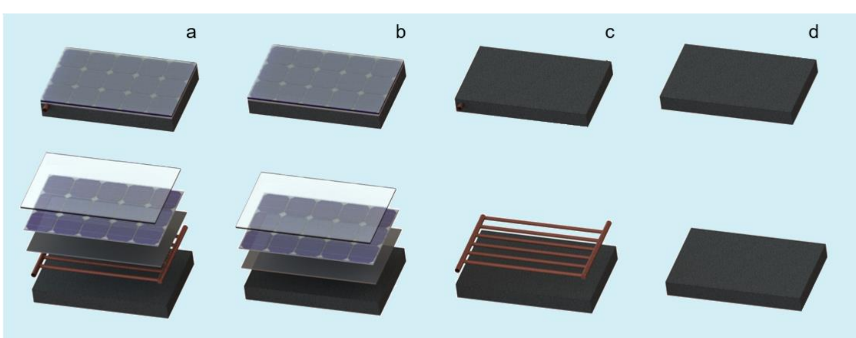

Fig 1 Physical configurations of different solar energy harvesting pavements. (a) PIPVT module; (b) PIPV module; (c) PIST module; (d) CP module

the modules and the weather data, and the results can be analyzed through some performance indicators.

3.2 Performance indicators

The relative error (RE) and root mean square deviation (RMSD) [12] are employed to compare the experimental and numerical results, defined as:

$$RE = \frac{R_{sim,i} - R_{exp,i}}{R_{exp,i}} \times 100\% \tag{1}$$

$$RMSD = \sqrt{\frac{\sum\left[\left(R_{sim,i} - R_{exp,i}\right) / \left(R_{exp,i}\right)\right]^2}{N_{exp}}} \times 100\% \tag{2}$$

where $R_{exp,i}$ and $R_{sim,i}$ are the experimental and simulated results at point *i*, respectively, and N_{exp} is the number of experimental points.

To assess the energy generation performance of different solar energy harvesting pavement modules, electrical efficiency η_{ele}, thermal efficiency η_{th}, and overall efficiency η_{all} are employed. [11]

UHI effect is a common phenomenon caused by human activities that the air temperature in urban areas is higher than that in surrounding rural areas. To quantify the influence of solar harvesting pavement modules on UHI effect, heat output intensity from pavement surface can be calculated as:

$$\ddot{E}_{th,out} = h_{r,sur-sky}\left(T_{sur} - T_{sky}\right) + h_{v,sur-amb}\left(T_{sur} - T_{amb}\right) + \ddot{E}_{rfl} \tag{3}$$

where $\ddot{E}_{rfl}$ is the reflected solar radiation.

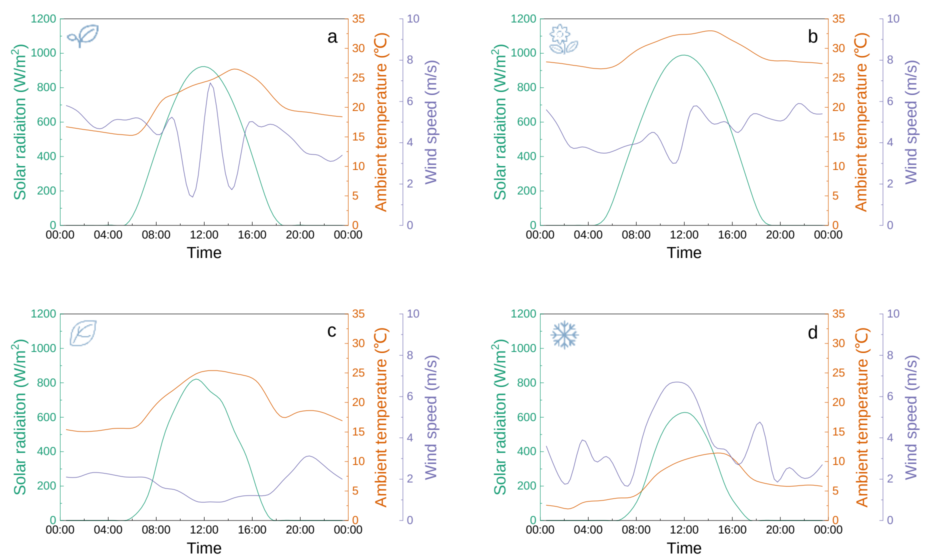

Fig 3 Weather conditions on four typical sunny days
(a) 10th Apr. (spring); (b) 14th Jul. (summer); (c) 2nd Oct. (autumn); (d) 14th Jan. (winter)

Pavement surface temperature T_{sur} is the other employed indicator of the UHI effect, defined as the average of simulated points' temperatures on the pavement surface.

4. RESULTS AND DISCUSSIONS

4.1 Validation

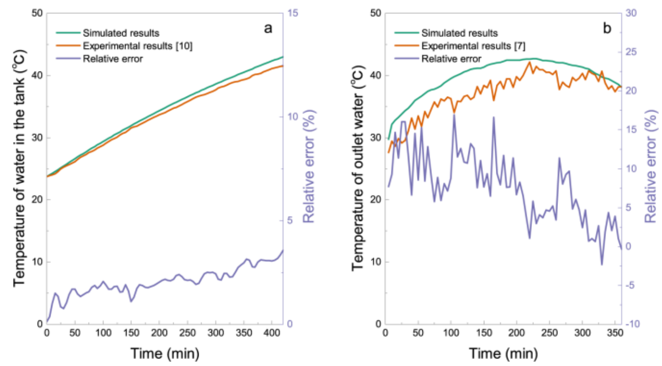

Fig 2 Comparisons between experimental results [1, 2] and simulated results of PIPVT (a) and PIST (b) modules.

For validation, the simulations are conducted for both PIPVT modules and PIST modules using the developed mathematical models. As shown in Fig 2, the simulated results are compared with experimental results for PIPVT modules and PIST modules, respectively. For PIPVT modules, RE ranges from 0.12% to 3.57% and RMSD is 2.18%. For PIST modules, RE ranges from –2.32 % to 16.94 % and RMSD is 8.79 %. Considering the error of measurement devices and the simplified assumptions of the model, the deviations are acceptable. As illustrated in Fig 2, for these modules, the simulated results exhibit good agreement with experimental results. Thus, it is believed that the proposed models can be used to predict the performance of typical solar energy harvesting pavement modules with adequate accuracy.

4.2 Performance simulation and assessment

As shown in Fig 3, four typical days representing four seasons were selected for simulations to investigate the operating performance of solar energy harvesting pavements in different seasons. All the weather conditions were measured at the campus of Shanghai Jiao Tong University in Shanghai, China (31.17 °N / 121.43 °E). All the systems operate from 8:00 to 16:00.

As shown in Fig 5, both the electrical efficiency and the electricity yield of the PIPVT module are higher than that of the PIPV module on each day. The better electrical performance of the PIPVT module can be attributed to the flowing water inside its tubes that can extract the heat continuously and make the temperature of PV cells in the PIPVT module lower than that in the PIPV module. Specifically, the PIPVT module can output and 0.59 – 1.02 kWh/m^2 electricity on different typical days. The electricity yield of the PIPVT module is 1.39% – 3.37% higher than that of the PIPV module on different typical days.

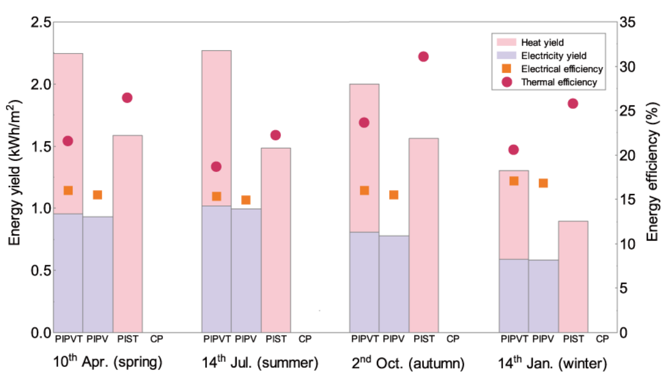

Fig 5 Energy yield and efficiency of solar energy harvesting pavements on four typical days

The PIPVT module can convert the absorbed solar radiation into electrical and thermal energy simultaneously. Compared with the PIST module that only generates heat, the PIPVT module has relatively lower thermal efficiency. The thermal efficiency of the PIPVT module ranges from 15.80% to 23.87%, which is lower than that of the PIST module. Specifically, the PIPVT module can output 0.71 – 1.29 kWh/m^2 heat on different typical days. The PIPVT module can achieve the average overall energy efficiency of 37.31% that takes both electricity and heat yields into account.

For both PIPVT and PIST modules, compared to the other typical days when the heat output is abundant and stable, the heat yield is significantly less on the typical winter day when the solar radiation and ambient temperature are both the lowest.

Besides, to investigate the solar energy harvesting pavement modules' influence on the UHI effect, heat output from pavement surface and maximum pavement surface temperature are employed as indicators. As exhibited in Fig 4, the PIPVT module has the least heat output from the pavement surface and has the lowest temperature on all typical days, showing that it can mitigate the UHI effect most effectively. In comparison with the CP module, the PIPVT module can reduce the heat output from pavement surface and the maximum pavement surface temperature by 38.48 – 43.96% and 4.48 – 9.37℃ on different typical days, respectively.

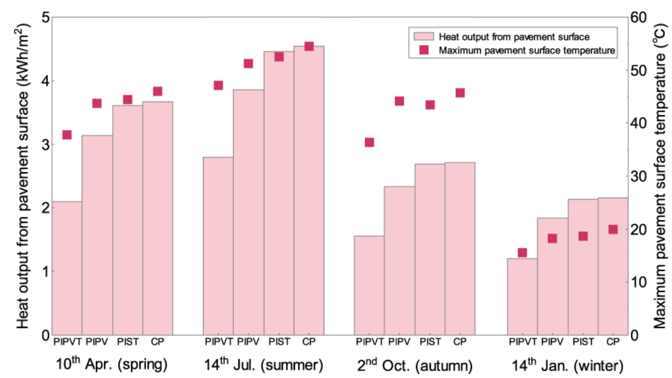

Fig 4 Heat output from pavement surface and maximum pavement surface temperature of solar energy harvesting pavements on four typical days

The PIPV module's heat output from the pavement surface and maximum pavement surface temperature are both significantly less than those of the CP module, meaning that the PIPV module can also apparently mitigate the UHI effect on all typical days. However, according to the above two indicators, the PIST module only has a very slight influence on the UHI effect mitigation.

5. CONCLUSIONS

To investigate and compare the performance of three typical solar energy harvesting pavement modules, namely, pavement-integrated photovoltaic (PIPV) module, pavement-integrated solar thermal (PIST) module, and pavement-integrated photovoltaic thermal (PIPVT) module, two-dimensional transient models were developed and validated in this study. Simulations were conducted with the developed mathematical models on the weather conditions of four typical days representing four seasons in Shanghai.

The simulated results show that the electricity yield of the PIPVT module is slightly higher than that of the PIPV module, while its heat yield is lower than that of the PIST module on all typical days. When considering both electricity and heat yields, the PIPVT module can achieve the average overall energy efficiency of 37.31%. All three solar energy harvesting pavement modules have positive impact on the mitigation of the UHI effect, among which the PIPVT module has the most significant influence on UHI effect mitigation with the least heat output from pavement surface and the lowest maximum pavement surface temperature on all typical days. Specifically, in comparison with the CP module, the PIPVT module can reduce the heat output from pavement surface and the maximum pavement surface temperature by 42.01% and 7.35℃ on average, respectively. However, the influence on UHI effect mitigation of the PIST module is very slight.

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