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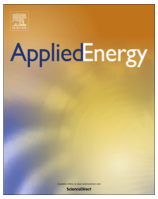

Fabrication and laboratory-based performance testing of a building-integrated photovoltaic-thermal roofing panel

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HIGHLIGHTS

- A BIPVT solar panel is designed and fabricated for energy efficient buildings.
- A high-speed manufacture method is developed to produce the functionally graded materials.
- Laboratory tests demonstrate BIPVT's energy efficiency improvement and innovations.
- The PV efficiency is enhanced ~24% through temperature control of the panel by water flow.
- The combined electric and thermal efficiency reaches >75% of solar irradiation.

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ABSTRACT

A building integrated photovoltaic-thermal (BIPVT) multifunctional roofing panel has been developed in this study to harvest solar energy in the form of PV electricity as well as heat energy through the collection of warm water. As a key component of the multifunctional building envelope, an aluminum/high-density polyethylene (HDPE) functionally graded material (FGM) panel embedded with aluminum water tubes has been fabricated through the vibration-sedimentation approach. The FGM layer gradually transits material phases from well-conductive side (with aluminum dominated) to another highly insulated side (with HDPE). The heat in the PV cells can be easily transferred into the conductive side of the FGM and then collected by the water flow in the embedded tubes. Therefore, the operational temperature of the PV cells can be significantly lowered down, which recovers the PV efficiency in hot weather. In this way, the developed BIPVT panel is able to efficiently harvest solar energy in the form of both PV electricity and heat. The performance of a prototype BIPVT panel has been evaluated in terms of its thermal efficiency via warm water collection and PV efficiency via the output electricity. The laboratory test results demonstrate that significant energy conversion efficiency improvement can be achieved for both electricity generation and heat collection by the presented BIPVT roofing system. Overall, the performance indicates a very promising prospective of the new BIPVT multifunctional roofing panel.

1. Introduction

The U.S. Department of Energy reported that building sectors consume more than 40% of the total energy and 73% of the total electricity produced in the U.S., and produce a significant fraction of non-renewable and non-recyclable building materials [1]. To reduce building energy consumption and greenhouse gas emissions, new technologies of efficient and renewable energy supply systems are in high demand. Solar energy is the most abundant renewable clean energy source, and modern technology can harness solar energy for a variety of uses, including generating electricity, providing light for a comfortable interior environment, and heating water for residential, commercial, or industrial use [2]. As solar energy technologies have advanced in recent years, integrated technologies for harvesting solar energy into building sectors, such as building-integrated photovoltaic (BIPV) systems [3–7], building-integrated solar thermal (BIST) systems [8–10], or building-integrated photovoltaic/thermal (BIPVT) systems [11–14], have evolved as viable technologies to improve building energy performance and to reduce environmental effects [15,16]. Those integrated systems replace parts of the conventional building materials and the components in the climate envelope of buildings, such as facades and roofs, and simultaneously serve as both a building envelope material and power generator [17–19].

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Nomenclature

A	total area of the BIPVT panel and the frame
C_{water}	specific heat capacity of water
ΔT_{water}	temperature increase of the outlet water over the inlet water
ΔT_{panel}	temperature decrease of the BIPVT surface
E_{IN}	absorbed irradiance by the BIPVT panel
E_{pv}	output electricity
E_{MAX}	maximum output electricity
E_T	theoretical electricity
P	electricity power
P_{max}	maximum electricity power
Q_{water}	useful collected heat by water
I_R	irradiance intensity
I_{MP}	max power current
I_{SC}	short circuit current
V_{MP}	max power voltage
V_{OC}	open circuit voltage
FF	fill factor
m_{water}	mass of the flowing water per second
$\eta_{thermal}$	ratio of the collected thermal energy with respect to the irradiance energy absorbed by the panel
η_{pv}	electricity conversion efficiency
η_T	total energy efficiencies

Abbreviations

Al	aluminum
BIPV	building-integrated photovoltaic
BIPVT	building integrated photovoltaic thermal
DPD	dissipative particle dynamics
FF	fill factor
FGM	functionally grated material
HDPE	high density polyethylene
IBC	International Building Code
I–V	current–voltage
NEC	National Electric Code
PV	photovoltaic
P–V	power-voltage
PVC	polyvinyl chloride
PVT	photovoltaic thermal
TE	thermoelectric

Compared with most conventional non-integrated systems, in addition to the power supply function, the integrated system offers several advantages: (1) there is no need for the allocation of land or facilitation of the PV system; (2) it does not require additional assembly components such as brackets and rails; and (3) it thus achieves significant savings in terms of the total building materials costs and associated labor fees [20,21].

Today, most photovoltaic (PV) modules in production are based on crystalline silicon wafer technologies. The electricity conversion efficiency of silicon solar modules available for commercial application is about 12–20% [22]. However, more than 85% of the incoming solar energy is either reflected or absorbed as heat energy [23]. Consequently, the working temperature of the solar cells increases considerably after prolonged operations. Solar panel temperature is one of the important factors that affects electricity conversion efficiency, most solar cells show a heat-related performance loss of about 0.4–0.5%/°C [24]. Without a cooling system, in-service surface temperatures are commonly 40–50 °C above ambient temperature, resulting in 16–25% reductions in electricity generation or malfunction beyond the operational temperature range [25]. The rise in PV temperature not only reduces electricity generation, but also reduces the life-span of the module itself. Therefore, a technique that is able to cool the solar panel is in high demand in order to improve both the energy efficiency and service-life of the solar panels.

If a BIPV system is properly designed, the cooling load of the building envelope in which PV modules are integrated into can be eliminated, and the heat energy can be collected by the flow of air or a liquid, this is the fundamental design concept of a BIPVT system. The BIPVT system appears as an exciting new technology as it merges photovoltaic and thermal systems, simultaneously harvesting both electrical and the thermal energy [16]. The most common BIPVT systems are realized through a heat transfer fluid in an open-loop (usually air) [26–28] or closed-loop (usually liquid) configuration [29–32]. Chen et al. [33] designed an air-based open-loop BIPVT system that was thermally coupled with a ventilated concrete slab. Their field test results indicated that a typical efficiency of about 20% for thermal energy collection can be obtained, and as a result the annual space heating energy consumption of the house is about 1600 kW h, which is about 5% of the national average. A prototype open loop air-based BIPVT system with a single inlet [27] was experimentally studied in a full scale solar simulator. It was found that, in an open-loop air-cooled BIPVT system with large-scale PV areas covering complete roof or façade surfaces, the temperature of PV arrays can rise to high values (exceeding 70 °C), resulting in a significant decrease in electrical efficiency and degradation of PV panels with time. Thus it is desirable to enhance heat removal from the PV panels by using multiple inlets instead of a single inlet. For this purpose, they further designed a two-inlet BIPVT system [28]. Their test results indicated that an equivalent two-inlet system with frameless PV panels can increase the thermal efficiency by 5% compared to a conventional one-inlet system.

Generally, the closed-loop configuration with liquid is more efficient than the open-loop with air as heat transfer fluid due to the high thermo-physical properties of liquid compared to air [34]. Within the category of rooftop or roof added BIPVT systems, based on the closed loop configuration, Corbin and Zhai [31] designed a BIPVT with thermal and combined (thermal plus electrical) efficiencies of about 19% and 34.9%, respectively. Their test results showed that the PV efficiency of their BIPVT can be raised by 5.3% and the collected warm water was suitable for domestic utlization. Ibrahim et al. [35] developed a BIPVT roof system with a spiral flow copper absorber attached at the bottom of the PV modules on the roof. It was reported that an energy efficiency of about 55–62% can be achieved for a BIPVT system. Buker et al. [36] recently developed a BIPVT roof collector combined with a liquid desiccant enhanced indirect evaporative cooling system. Their experimental results showed that the BIPVT roof collector is capable of providing about 3 kW of heating, 5.2 kW of cooling power and 10.3 MW h/year of power generation, respectively. In addition, the overall power efficiency data also shows that the power energy performance of PV modules can be improved by 10.7% due to achieved collector cooling as the cold water flow creates a passive cooling effect and partially removes the waste heat from the PV modules. Currently, most closed-loop BIPVT systems employ water tubes for cooling and thermal energy collection. Normally, the water tubes are embedded in insulation materials and covered by absorber materials in contact with the PV elements above [37]. These designs commonly exhibit poor heat conduction due to the small contact area between the absorber and water pipes.