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Parallel experimental study of a novel super-thin thermal absorber based photovoltaic/thermal (PV/T) system against conventional photovoltaic (PV) system

Peng Xu [a,b], Xingxing Zhang [b,c,*], Jingchun Shen [b], Xudong Zhao [b], Wei He [d], Deying Li [a]

[a] Beijing University of Civil Engineering and Architecture, Beijing, 100044, China
[b] School of Engineering, University of Hull, Hull, HU6 7RX, UK
[c] Department of Architecture and Built Environment, University of Nottingham, Ningbo, 315100, China
[d] Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei, 230026, China

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ABSTRACT

Photovoltaic (PV) semiconductor degrades in performance due to temperature rise. A super thin-conductive thermal absorber is therefore developed to regulate the PV working temperature by retrofitting the existing PV panel into the photovoltaic/thermal (PV/T) panel. This article presented the parallel comparative investigation of the two different systems through both laboratory and field experiments. The laboratory evaluation consisted of one PV panel and one PV/T panel respectively while the overall field system involved 15 stand-alone PV panels and 15 retrofitted PV/T panels. The laboratory testing results demonstrated the PV/T panel could achieve the electrical efficiency of about 16.8% (relatively 5% improvement comparing with the stand-alone PV panel), and yield an extra amount of heat with thermal efficiency of nearly 65%. The field testing results indicated that the hybrid PV/T panel could enhance the electrical return of PV panels by nearly 3.5%, and increase the overall energy output by nearly 324.3%. Further opportunities and challenges were then discussed from aspects of different PV/T stakeholders to accelerate the development. It is expected that such technology could become a significant solution to yield more electricity, offset heating load freely and reduce carbon footprint in contemporary energy environment.

1. Introduction

Solar thermal and photovoltaic (PV) are the fundamental pillars to assist in transition from the traditional fossil fuel energy structure to a renewable energy system in contemporary built environment. PV semiconductor degrades up to 43% in efficiency performance with its temperature rise, leading to a subsequent reduction in annual electricity generation. The PV/Thermal (PV/T) technology was therefore developed to regulate the temperature of PV cells and make advanced utilization of the heat trapped from PV simultaneously. Such synergetic integration of PV and thermal absorber not only results in improved PV efficiency (Technology Roadmap-Solar photovoltaic energy, 2014), but also generates more energy per unit area whilst compared with stand-alone PV panel or solar thermal collector. Additional characteristics of the PV/T technology lie in potential saving in material use, reduction in installation cost and homogeneous facade appearance. It is now becoming a significant solution to yield more electricity and offset heating load freely in contemporary energy environment (Chow, 2010; Kalogirou and Tripanagnostopoulos, 2006; Sobhnamayana et al., 2014).

Technologies for this purpose have been developed substantially (Jie et al., 2011; Chow et al., 2007; Joshi et al., 2009; Sarhaddi et al., 2010a,b; Sobhnamayan et al., 2011) but meanwhile exhibited by some inherent problems, such as complex structure, high cost, low efficiency, unsafe operation and incompatibility between tubing absorber and flat-plate PV panel (Zhang et al., 2012). Currently, the most common way to develop a PV/T panel is to attach the PV panel onto a classical solar thermal collector, such as the author's previous work (Zhang et al., 2013, 2014, 2013; Zhao

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* Correspondence to: Department of Architecture and Built Environment, University of Nottingham Ningbo China, 199 Taikang East Road, Ningbo, 315100, China.

E-mail addresses: Xingxing.zhang@nottingham.edu.cn, Xing0520@gmail.com (X. Zhang).

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Nomenclature

A_c	collecting area
C_f	conversion factor of the thermal power plant
I	solar radiation (W/m^2)
m	mass flow rate (kg/s)
Q	energy rate (W)
T	temperature (°C)
U_L	heat-loss coefficient ($W/°C\ m^2$)
X	testing factor

Greek

η	energy efficiency
η^*_{th}	characteristic thermal efficiency

Subscript

a	air
e	electricity
i	inlet of working fluid
o	overall
PV	photovoltaic
PV/T	photovoltaic/thermal
th	thermal
th,field	thermal performance in field
th,lab	thermal performance in laboratory

et al., 0000). This method is inconvenient and expensive by involving the classical manufacturing process of thermal collectors (Zhang et al., 2013, 2014). The conventional thermal absorbers are normally in the geometry of cylinder tubing which is absolutely unmatched with the flat-plate PV panel and therefore largely reduces the overall working efficiency. As a result, this article aims to develop a new flat-plate thermal absorber with high heat-transfer coefficient, low cost and low pressure drop that can easily retrofit the existing PV panels into the PV/T panels in a rapid way.

Moreover, an experimental evaluation of such PV/T system against the conventional PV system under the laboratory and the real climatic conditions has not yet been fully examined. This work retains certain challenges, however, as there are several uncertain factors, including dynamic weather conditions, thermal adaptability and system robustness, etc.

2. System description and experimental set up

Fig. 1 illustrates the schematic structure of the thermal absorber and its associated prototypes. The thermal absorber is made up by two parallel thin flat-plate metal sheets, one of which is extruded by machinery mold to formulate arrays of mini corrugations, while another sheet remains smooth to attach beneath PV panel through a series of U-shaped resilient metal clips. A laser-welding technology is applied to join them together, forming up the built-in turbulent flow channels. Such unique compact structure engenders not only high heat transfer capacity but also convenience in rapid PV/T transformation.

Such thermal absorber offers a very easy way to retrofit an existing PV panel by following steps as displayed in Fig. 2: (1) take off the installed PV panel from the roof; (2) insert the thermal absorber; (3) fix the absorber with the PV panel by the U-shaped clips (each clip can hold maximum pressure at about 1.8×10^6 Pa); (4) enclose the thermal insulation layer when needed; (5) install the retrofitted PV/T panel back to the roof surface and connect the standard piping system for thermal collection. All these procedures can be accomplished in just a few minutes.

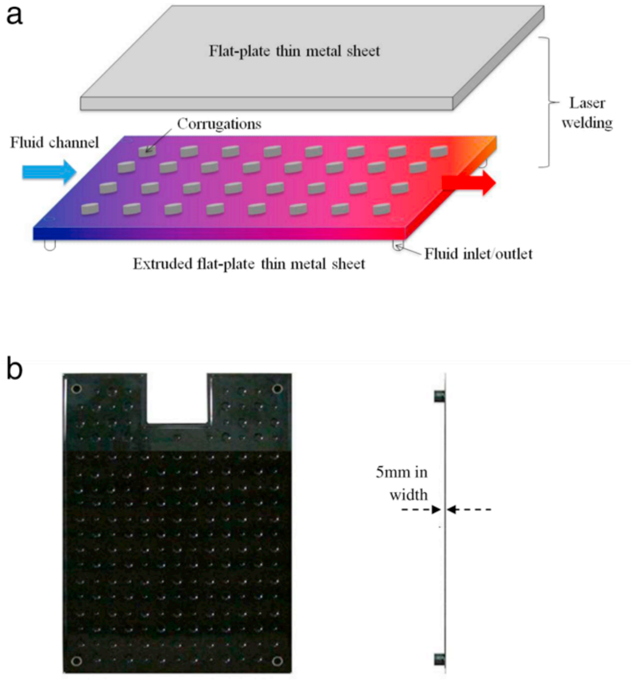

Fig. 1. (a) Schematic of thermal absorber and (b) the associated prototypes.

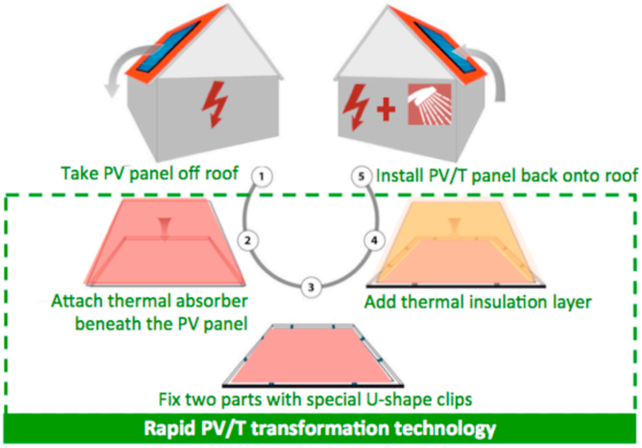

Fig. 2. Approach to retrofit the existing PV panels.

There are respectively two fluid inlets at the bottom and two fluid outlets on the top with the standard piping joints for a symmetrical fluid distribution. The overall thickness of the thermal absorber is less than 5 mm with a flexible dimension subject to the sizes of PV panels in practice. The absorber has a weight at about 10 kg m^{-2} which can contain the fluid at nearly 3.5 L m^{-2}. The entire loop was filled with water/glycol mixture (95%/5%) as working fluid for the prevention of potential freezing problem. The nominal flow rate is designed at 130 L h^{-1} m^{-2} and the maximum operating pressure is design at approximately 3×10^5 Pa (3 bar). The laboratory evaluation consisted of one PV and one PV/T panel respectively. During the field testing, the overall system involved 15 stand-alone PV panels and 15 retrofitted PV/T panels. The total electric installation capacity was around 6 kWp and all the PV or PV/T panels were connected with the national grid through an electric inverter. Table 1 presents the electrical parameters of single PV panel under the standard testing conditions and Table 2 lists some experimental instruments in the laboratory testing. Each PV or PV/T panel has an effective area of 1.28 m^2. Fig. 3 shows the schematic design of the field testing system. The demonstration project was continuously operated and recorded in real climate

Table 1
Photovoltaic characteristics of single PV panel under standard testing conditions.

At short-circuit current	$I_{SC} = 8.67$ A, $V_{SC} = 0$ V
At open-circuit voltage	$I_{OC} = 0$ A, $V_{OC} = 30.24$ V
At the maximum power point	$I_{mp} = 8.1$ A, $V_{mp} = 24.7$ V ($P_{mp} = 210$ W, $\eta_o = 16.1\%$)

Table 2
List of the experimental testing and monitoring devices.

Devices	Specification	Value
OEM pressure sensor—Model: Tecsis-P3297	Accuracy	≤1.0%
Thermocouple T type	Min/max temperature sensed [°C]	−200–350
Data logger DataTaker-TD500	Record data with computing unit	–
Power sensor WB1919B35-S	DC output	≤0.2%
Pyranometer—Model: Hukseflux-LP02-TR-05	Calibration uncertainty	<1.8 %
	Sensitivity [μV/(W m^{-2})]	14.45
	Transmitted range [W/m^2] / [mA]	0–1600/(4–20)
Pocket anemometer—Model: Skywatch-Xplorer 1	Air velocity resolution [kph]	0.1
	Best air velocity accuracy	±3%
	Maximum air velocity [kph]	150
Solar simulator system—Model: SolarConstant4000	Similar global radiation to CIE Publ.85, IEC 60904-9/Class B	
	Radiation intensity [W/m^2]	1000/ [280–3000 mm]
	Homogeneity	±10% or better (class C)
	Control system	Control with touch panel

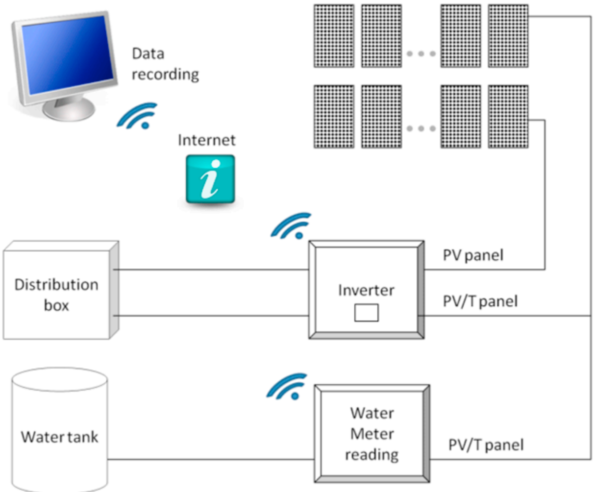

Fig. 3. Schematic design of the field testing system.

over two weeks from 1st May to 18th May 2014 in Jiangsu, China (32.9° N, 119.8° E). The testing was fully operated and the testing data were recorded automatically at 5 s interval. The on-site project is displayed as Fig. 4.

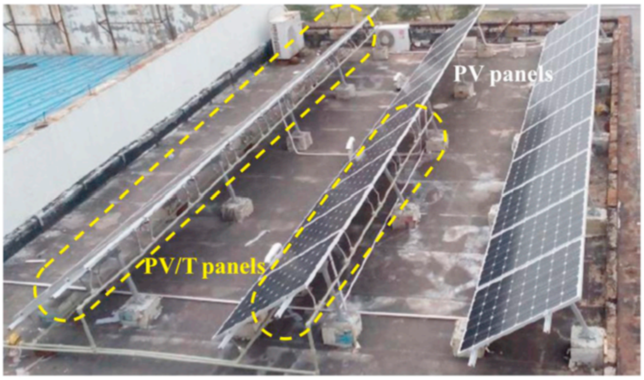

Fig. 4. One-site diagram of the field testing.

3. Results and discussion

3.1. Definition of performance metrics

Thermal efficiency of a PV/T panel is defined as the ratio of useful thermal energy (Q_{th}) to incident irradiation (I) striking on the collecting area (A_c)

$$\eta_{th} = Q_{th}/IA_c. \tag{1}$$

As a type of solar thermal system, the panel thermal efficiency can be alternatively derived from the following semi-empirical efficiency model to correlate with external weather and operational conditions (Chow et al., 2007)

$$\eta_{th} = \eta_{th}^{*} - U_L\left(T_i - T_a\right)/I \tag{2}$$

where, η_{th}^{*} is the characteristic panel thermal efficiency and could be interpreted as the panel when the working-fluid inlet temperature (T_i) is equal to the mean air temperature (T_a). U_L is the overall heat-loss coefficient of the panel. With the measured weather and operational conditions, the values of η_{th}^{*} and U_L for a specific solar collecting system can be determined by linear regression analysis. Larger η_{th}^{*} and the lower U_L would result in a more efficient solar thermal panel.

Electrical efficiency of a PV/T or a PV panel is the ratio of electricity generated from PV cells (Q_e) to the overall incident irradiation on the collecting area

$$\eta_e = Q_e/IA_c. \tag{3}$$

As such a PV/T panel yields not only solar heat but also electricity, to make a parallel comparison with a standard PV panel, the overall equivalent electrical efficiency of a PV/T panel is given by the following equation, in which the solar heat is converted into the equivalent electricity through the use of average conversion factor of the thermal power plant (C_f) with commonly 0.38 (Sarhaddi et al., 2010b; Zhang et al., 2014) for a typical coal-fired power plant in China.

$$\eta_o = \eta_{th}C_f + \eta_e. \tag{4}$$

To compare the effect of the thermal absorber to the PV panels (baseline), the varying percentage is defined as the equation below.

$$X = \frac{X_{PV/T} - X_{PV}}{X_{PV}} \times 100, \tag{5}$$

where, X represents the varying element such as temperature, power and thermal energy.

Table 3
Testing results of the thermal absorber based PV/T panel.

Parameters	Symbol	Value	Parameters	Symbol	Value
Initial thermal efficiency	η_0	73.5%	Fluid volume	V	4.5 L
Linear coefficient	U_L	15.8 W m^{-2} K^{-1}	Pressure drop	ΔP	19.7 Pa
Collecting area	A	1.28 m^2	Nominal mass flow	m	50 L h^{-1} m^{-2}
Thermal output	Q_{th}	890 W	Maximum mass flow	m_{mx}	230 L h^{-1} m^{-2}
Electrical output	q_{th}	168 W	Joint diameter	D	0.022 m
Thermal efficiency	η_{th}	65%	Outlet temperature	T_o	42 °C
Electrical efficiency	η_e	16.8%	PV temperature	T_{PV}	45 °C

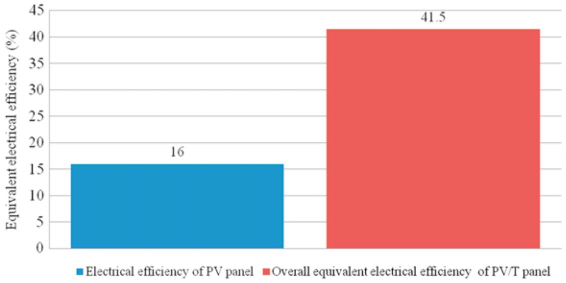

Fig. 5. Comparison of the operating efficiency between the PV/T panel and standard PV panel.

3.2. Laboratory evaluation

The experimental evaluation of one PV panel and one PV/T panel was carried out respectively in the laboratory. The solar simulator was adjusted upwards or downwards to evenly simulate the solar radiation on either the PV or the PV/T panel. Table 3 gives some results under the standing testing conditions, i.e. 1000 W/m^2 of solar radiation, 25 °C of air temperate and 30 °C of inlet temperature. The electrical efficiency of the PV/T panel was about 16.8%, increased relatively 5% when comparing the PV panel. The initial optical thermal efficiency and the linear coefficient were determined by the linear regression analysis of the testing results, respectively at 73.5% and 15.8 W m^{-2} K^{-1}, leading to the thermal performance of such thermal absorber as Eq. (2). The linear coefficient (heat loss coefficient) was a little bit high mainly because there was no thermal insulation attached at the absorber back. This needs to be considered especially at cold climate regions in the future. The temperature difference between the PV layer and absorber outlet was only about 3 °C, which demonstrates that such thermal absorber had a very small contact thermal resistance when applying onto the back of PV panels. Owing to the special design of flow channel, the pressure drop in the thermal absorber was less than 20 Pa, consuming only little energy from the pump. The comparison of the operating efficiency between the PV/T panel and standard PV panel is addressed in Fig. 5. It is seen that the equivalent electrical efficiency of the combined PV/T panel was around 41.5%, which were much higher of the tested value of the standard PV panel at around 16%, indicating an advanced overall performance achieved by such PV/T panel.

$$\eta_{th,lab} = 0.735 - 15.8\,(T_i - T_a)\,/I. \tag{6}$$

In addition to the standard testing conditions, the impact of the fluid flow rate to the thermal efficiency of the PV/T panel was also investigated as displayed in Fig. 6. It is seen that increasing the fluid flow rate leads to higher thermal efficiency of the PV/T panel. By increasing the flow rate from about 50 to 230 L/h/m^{-2}, the thermal efficiency correspondingly enhanced from 46% to nearly 71%. To remain a high efficiency above 60% of such PV/T panel, it is therefore recommended that the fluid flow rate should be no less than 100 L/h/m^{-2} during future operation. The impact of the fluid flow rate to the thermal efficiency is expressed by Eq. (3):

$$\eta_{th,lab} = 0.1642\,\ln(m) + 1.1558. \tag{7}$$

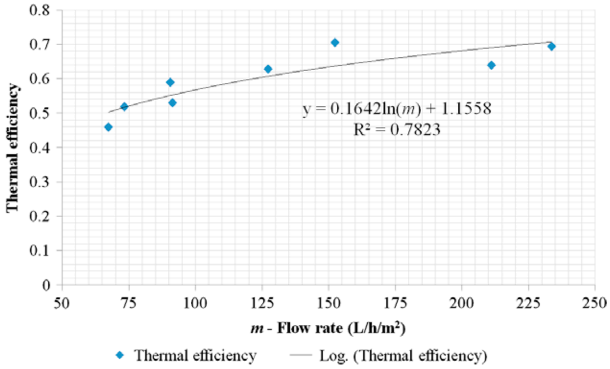

Fig. 6. Thermal efficiency against the parameter of flow rate (m).

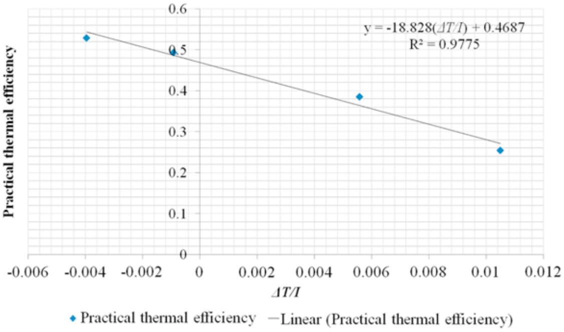

Fig. 7. Practical thermal efficiency against the $\Delta T/I$ parameters.

3.3. Field testing

A parallel field testing between the 15 PV panels and the 15 PV/T panels were implemented and the comparative results were discussed from the aspects of temperature at PV cells, electrical power output and additional thermal output by the PV/T panels. In practice, the initial optical thermal efficiency and the linear coefficient were determined by the linear regression analysis of the testing results, respectively at 46.9% and 18.8 W m^{-2} K^{-1}, resulting in the thermal performance of such thermal absorber as in Eq. (4) and Fig. 7. The practical results were a little bit poorer than that in the laboratory mainly due to varying climate conditions and the lower incident solar radiation angle.

$$\eta_{th,field} = 0.4687 - 18.828\,(T_i - T_a)\,/I. \tag{8}$$

Figs. 8–10 respectively illustrated the parallel comparison results of the PV and the PV/T panels during the two-weeks field-testing period. The mean daily PV temperatures of the PV panels and the PV/T panels were approximately 41.1 °C and 39.8 °C respectively, and therefore the thermal absorber decreased the PV temperature at about 3.0% daily in average. However, the temperature difference was not too large mainly due to the moderate solar radiation in May and the thermal insulation layer at the back of the PV/T panels. Thanks to the temperature reduction of the PV layer, the mean daily power of the PV panels and the

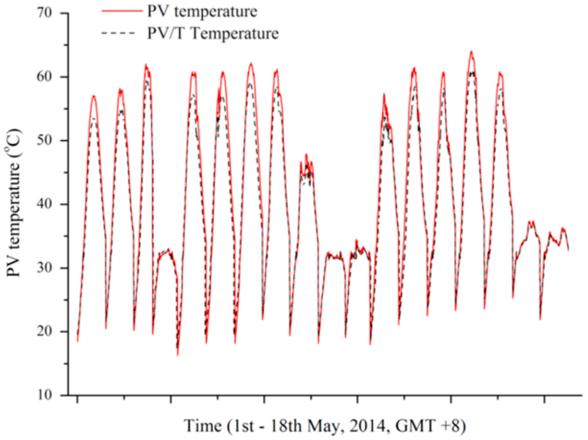

Fig. 8. Daily PV temperature of the PV and PV/T panels.

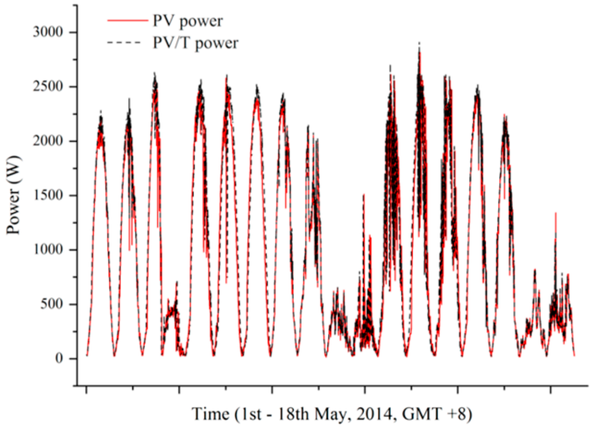

Fig. 9. Daily power of the PV and PV/T panels.

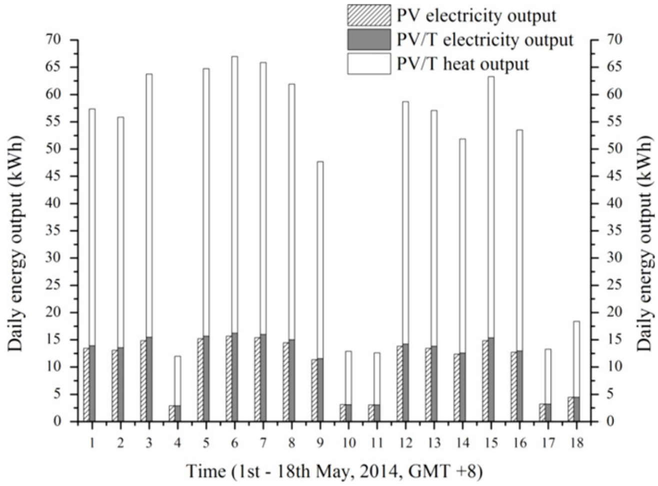

Fig. 10. Daily energy output of the PV and PV/T panels.

PV/T panels were nearly 926.7 W and 959.2 W respectively. As a result, the thermal absorber increased the power output by 3.5% in average, which was slightly lower than that in the laboratory mainly owing to the varying weather conditions and the impact of incident solar angle. The PV/T panels could generate 11.3 kW h electricity and 35.3 kW h heat daily (46.6 kW h energy in total) while the PV panels could only produce 10.9 kW h electricity in total. Thus, an increase of the overall energy output by nearly 324.3% was achieved by the PV/T panels whilst compared with the PV panels.

3.4. Opportunities and future work

PV/T stakeholders

To enable a widespread deployment of such hybrid solar technology, the explicit benefits and challenges for PV/T stakeholders have been identified as summarized in Table 4 (Technology Roadmap-Solar photovoltaic energy, 2014), which needs to be elaborated during the coming years. The establishment of an interdisciplinary working group seems necessary, which can attain a sound information exchange of results related to R&D, design specifications, design tools, test methods, installation barriers, market surveys, and policy development. This interdisciplinary cooperation may lead to a clear understanding of various problems over the PVT developments.

Evaluation standards

Currently, no published legal standards are found in the PV/T field, while common standards need to be developed as soon as possible. So far, evaluation of PV/T systems in laboratories is conducted according to the researchers' own procedures or standards for solar thermal collectors. Neither of these methods is ideal for comparing PV/T with other energy systems equally, for the results will differ from case to case (i.e. types of PV cell, testing conditions). As a result, new test procedures should be developed to establish their relevant suitability on basis of the existing standards of stand-alone PV panels and solar thermal collectors.

Long-term reliability measurement

Although a short-term evaluation of the PV/T system in a real climate has been carried out, a long-term (seasonal or annual) scheme is still essential to resolve different uncertainties in practice. This work retains certain challenges, including seasonal dynamic weather conditions, thermal adaptability in different climate zones, and system robustness.

Market analysis

Analysis of the market potential is crucial for the development of PV/T products. It is well known that solar technology is expected to provide nearly 50% of the low-and-medium temperature heat within the EU (ESTTP, 2009) and 5% of global electricity demand (Technology Roadmap-Solar photovoltaic energy, 2014) by 2030. A market investigation of PV/T products is suggested in terms of conducting the following: (1) case studies of existing PV/T products to identify their applicability for end users, climatic regions, market positions, and recommendations; (2) a feasibility study of PV/T application in various locations, building types and energy systems; (3) a market survey of customers' preferences; and (4) establishment of a generic extrapolating methodology for the market analysis of PV/T systems.

Manufacturing cost

Current fabrication of such PV/T systems is achieved by separate production lines of PV panels and thermal absorbers. Future large-scale product implementation should combine those two separate manufacturing lines and establish effective upstream/downstream supply chains. Thus, the capital cost would be reduced to some extent. These products also need to be optimized to suit energy specifications, production aspects, and installation and mounting requirements. This part of the work would play an important role in pushing PV/T towards the market, while in synergy with market players and local authorities, the manufacturing cost could be further reduced.

Dissemination activities

In order to motivate the use of PV/T technology, more dissemination activities should be presented to the public using various approaches, including the publication of roadmaps, showcases, workshops, on-site visits, open days and conferences. The events

Table 4
Opportunities and challenges for PV/T stakeholders.

Stakeholders	Opportunities	Challenges
R&D institutes	Quest for new technological solutions	• Performance and reliability standards • Increased system performance
Engineering consultants	Innovative and high profile technology	• Design tools development • New system concepts development
Architects	New solutions for integration	• PV/T integrated with building design • New building concepts
Installers	Reduced installation effort	• Plug-and-play integration in comfort systems • Combination of two professional specialisms
Building industry	Increased energy performance	• Integration of panel into building facade • Prefabrication possibilities
Manufacturers	Enlarged markets	• Cost-effective production • Plug-and-play systems
Policy makers	More effective path to renewable targets	• Building regulations, market and R&D support

should invite both local and national media (television, newspapers, etc.) to conduct live reports throughout the regions, nations and all over the world.

Policy support

Public energy agencies are the catchers of all the initiatives in building energy saving and environmental pollution reduction, and also connect the actions of the different players. Local authorities and decision makers have a central role in lowering market barriers by proposing public subsidies and financing mechanisms to make PV/T solutions competitive with conventional systems. Action should be taken to support PV/T development by the integration of local building regulations. The PV/T payback time would be significantly reduced if additional policy support came from governments. However, there is currently no policy issued particularly for this technology. Specific policies should be published to encourage the deployment of such technology and subsidize the corresponding financial benefits for end users.

4. Conclusion

This article developed a super thin-conductive thermal absorber suiting to retrofit the existing PV panel into the PV/T panel with multiple benefits, including dual outputs of increased electricity and additional hot water, and potential savings in installation cost and space. It compared the PV panel and the PV/T panel in parallel through both laboratory and field testing. The laboratory testing results demonstrated that the PV/T panel could achieve an electrical efficiency of PV cells at around 16.8% (with relatively 5% increase), and produce an extra amount of heat at thermal efficiency of nearly 65% under the standing testing conditions. The nominal mass flow rate of working fluid was recommended above 100 L h^{-1} m^{-2} in order to achieve the thermal efficiency of more than 60%. The thermal absorber was measured with an extremely low pressure drop at less than 20 Pa. The field testing results indicated that the PV/T panel could essentially improve the electrical return of PV panels by nearly 3.5% in practice, and meanwhile increase the overall energy output (both electricity and heat) by nearly 324.3%. Such synergetic integration of PV and thermal absorber not only results in improved PV efficiency, but also generates more energy per unit area whilst compared with stand-alone PV panel. Explicit benefits and future challenges were discussed for PV/T stakeholders to accelerate the development of such technology. An interdisciplinary working group was suggested to be established in the future to attain a sound information exchange in R&D, design specifications, design tools, test methods, market surveys and policy development. The dedicated technology is expected to promote the development of solar driven heating system and enable the relevant reduction of carbon emissions.

Acknowledgments

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