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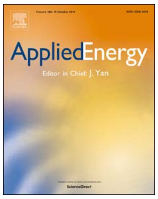

Heat recovery potential and electrical performances in-field investigation on a hybrid PVT module

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HIGHLIGHTS

- PV and hybrid PVT modules thermal behavior in-field characterization.
- Temperature distribution in solar cells monitoring through infrared thermography.
- Electrical efficiency/environmental conditions correlation.
- Water cooled PVT design/implementation/validation (model-based/experimental).
- Heat recovery assessment in PV and PVT prototypes via bottoming ORC plant.

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ABSTRACT

The aim of the present study is the characterization of PVT modules electrical performance in real operating conditions, as well as the investigation of thermal recovery via a cooling circuit integrated with a third generation PV module.

The approach combines both theoretical and experimental tools: a MatLab® simulation model provides a reliable theoretical basis, whose validation is performed on experimental evidences from in-field PV module tests. The model represents the module energy balance, under unsteady operating conditions; a full set of measurements allowed to validate the theoretical approach, thus offering the possibility to evaluate the effects of both variable outdoor air temperature and pressure and wind speed.

Water-cooled PV modules electrical performance increases by as much as 33%, with respect to the situation in which no cooling is performed and up to a 20% electric efficiency is achieved, with a 2.0 L/min water flow rate on the back. A major drawback is that thermal recovery for cogeneration purposes is not effective, due to a low thermal gradient (10 K maximum) on the water. When a 10 mm thick glass cover was integrated in the PV module along with a frame to reduce wind circulation over exposed surfaces, a 100–500 W thermal recovery on a day basis could be achieved. Furthermore, a 15–30 K increase in water temperature assures about the higher quality of the recoverable heat. The suitability of organic fluids instead of water to reduce the power absorption by the pump, is addressed as the most effective way to increase PVT electric output: the absorption with R236fa and R245fa is a 60% and 75% lower than with water, respectively.

The novelty of the present study lies in the dual theoretical and experimental approach, leading to a validated non-steady-state mockup, easily adjustable to extend the analysis to PV modules arrays for residential applications. Furthermore, the use of an infrared camera, typically confined to post-manufacturing quality control, allows here a continuous monitoring of the module thermal field, key to evaluate the temperature effect on the module performances both in steady and unsteady conditions.

1. Introduction

In the present industrial practice, PV modules are mainly based on either the sc-Si or the mc-Si cells technology, the advantage of the former being a higher efficiency in electrical conversion, whereas the latter shows a higher durability. As the investment cost of mc-Si modules is lower, this technology, despite yielding up to 35% less electric energy per unit of surface area, is preferable when there are no strict space constraints for the installation and soft costs (design, installation and permits) represent an unimportant share of the total life-cycle cost.

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Nomenclature

h	convective heat transfer coefficient [W/m^2 K]
C	thermal capacity [J/kg K]
H	pump hydraulic head [m]
Nu	Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
k	thermal conductivity [W/m K]
S	surface [m^2]
T	temperature [K]
c	specific heat [J/kg K]
g	standard gravity acceleration [9.086 m/s^2]
σ	Stefan-Boltzmann constant [$5.67 \cdot 10^{-8}$ W/m^2 K^4]
X	measured value
V	variance
a	sensitivity
PVT	PV thermal
$conv$	convection
irr	irradiation
mod	PV module
p	constant pressure
rad	radiative
th	thermal
w	water
$\dot{Q}$	thermal power [W]
P	power [W]
Δ	variation
f	flow rate [m^3/s]
M	mass [kg]
p	pressure [mbar]
u	speed [m/s]
ε	emissivity
η	efficiency
μ	dynamic viscosity [kg/m s]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
N	number of values
s	standard deviation
U	uncertainty
air	air
el	electrical
m	motor
out	output
$pump$	pump
sky	sky
v	constant volume
i	i-th measured value

Less common, but still commercially available, are the PV modules based on a-Si cells, whose efficiency is the lowest among all available technologies, not to mention its sensitivity to ambient conditions. The characteristics of three main types of PV modules are in Table 1. Since, for any of them, efficiency is relatively low and not expected to significantly increase in the near future, the electrical yield can be maximized using add-on technologies, such as concentrating devices and cooling devices. The former increase the amount of solar energy collected by a given PV module, whereas the latter reduce the PV module operating temperature, hence increasing its efficiency and making heat available for cogeneration purposes as a side effect.

In this paper the authors examine both a bare PV module and a PV module equipped with a tailored cooling system (PVT) and compare the efficiency of the two under same operating conditions.

An extensive literature investigates all aspects related to PVT systems, from manufacturing to operation: the first attempt to define optimal configurations dates back to 1970 and it is due to Wolf [2] and Florschuetz [3], who aimed to provide a reliable modelling platform which could guide future research and development. Kern and Russel [4] and Garg and Agarwal [5] have investigated both air- and water-cooled PVT systems, and Tripanagnostopoulos [6–8] has come to the conclusion that the former lead to an efficiency of 38–45% in c-Si and a-Si modules, whereas the latter lead to a much higher efficiency of 55–60%. Tonoui and Tripanagnostopoulos [9] have studied the improvement in performance achievable by adding a suspended metal sheet in the middle of the air channel or by implementing finned surface to boost the heat exchange. Among the main findings of both theoretical and experimental studies is that water-cooled PVT systems have greater efficiency and also greater margins for improvement than air-cooled PVT ones. Nonetheless, major advantages of the latter are in the lower financial investment required and the more favorable life cycle cost, as shown in Raman and Tiwari [10]. Detailed studies by Chow et al. [11] aim to model PVT collectors behavior under a variety of environmental conditions, in addition to investigating the optimal configurations in terms of collector design [12,13], glazing [14,15] and fluid circulation [16]. Three types of uncovered PVT collectors are investigated in [17], with an extensive experimental campaign supporting both model calibration and validation, thus allowing a safe estimation of the annual yield for each specific PVT type. An enhanced configuration for a PVT system is features a thin flat copper sheet instead of Tedlar as the bottom layer and a single water channel, as in [18]: a 35.3% primary energy saving efficiency is appreciated on a 20.9% efficiency PV module. Kalogirou [19–21] has examined the effect of control parameters, such as water inlet and outlet temperatures, operating pressures and mass flow rate, on PVT performance, whereas the effect of temperature reduction on thermal and electric efficiency has been directly evaluated by Krauter and Ochs [22]. A similar sensitivity analysis, investigating both dependence of electric and thermal performance of a sheet-and-tube PVT collector for DHW production, on control parameters (e.g. pump operation, thermostat controller, flow rate), climate data and cells optical properties is performed in [23]. Ehsan Fadhil Abbas Al-Showany [24] recently investigated the impact of weather conditions on PV module performance by performing experiments on identical PV modules in a given location. The reduction in electric yield by unclean panel due to natural pollution deposition over a 3-month period was about 3.8% compared with the clean panel, and 13.8% compared to the water-cooled clean panel. Other studies assessing the performance of PVT systems are due to Tiwari and Soda [25,26], not to mention Chow studies focused on a PVT/thermal water-heating hybrid system [27,28] and Ben cheikh el Hocine et al. [29] who created a model for PVT collectors, though not explicitly providing a direct comparison between the model results and experimental measures. A comprehensive financial analysis of a PVT system for residential and commercial applications is in [30], where a sensitivity analysis clearly shows how both the net present value and the discounted payback period encourage the installation of a PVT system instead of a conventional side-by-side PV and solar thermal system. The environmental impact of hybrid PVT systems is discussed in [31], where a review of the published results aims at the definition of a common ground to address in the design phase and market

Table 1
PV modules main characteristics [1].

	a-Si	mc-Si	sc-Si
Cost [€/kW]	1375	1562	1750
Efficiency [%]	9	15	20
Lifespan [years]	20	20	20