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Original Research Article

Monitoring of solar cogenerative PVT power plants: Overview and a practical example

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ABSTRACT

This paper introduces the topic of management and monitoring of photovoltaic/thermal (PVT) systems, highlighting the differences respect to photovoltaic (PV) and solar thermal (ST) systems. A PVT module is a collector that produces at the same time both electrical and thermal energy. Thereby, the monitoring architecture of a non concentrating PVT system, realised with crystalline silicon cells liquid-cooled, is described.

In addition, a web application allows the on-line monitoring and control of that PVT system. Thus, daily reports of the remote PVT installations are elaborated and sent to the system operator. These data can be analysed off-line to calculate both energy performance indices and statistical values. Historical data analysis is useful not only to optimize the operation of the PVT system but also to design its retrofit. To check the effectiveness of the proposed remote monitoring system, the performances of two twin stand-alone systems a PVT plant, based on a patented PVT collector named TESPI, and a PV plant have been evaluated through an experimental campaign of measurements.

The two twin systems (one PV and the other PVT) are installed in Enna (Italy), where typical Mediterranean climate is present. During the survey both electrical and thermal critical operating conditions have been detected such as: deep discharge of batteries, optical losses and stagnation.

Introduction

In the last years, renewable energy sources are continuing to grow robustly all around the world, albeit from a low base, but not uniformly, in fact the importance of policy in the strength of renewable forms of energy in different countries has affected relevantly. In 2013 renewables account for more than 5% of global power output and nearly 3% of primary energy consumption. The challenge of sustaining expensive subsidy regimes, however, has become visible where penetration rates are highest, namely the below-average growth of Europe's leading renewable producers, who are grappling with weak economic growth and strained budgets [1,2]. Specifically, in the EU renewables represented the majority of new electric generating capacity for the sixth consecutive years. In this dynamic context, the possibility of building a solar hybrid system merging thermal and PV modules presents a strong practical interest [3–9]. The integration of the two systems increases the global efficiency (the efficiency of a PV module is 10–20% whereas a common flat plate collector can harvest up to 60% of the sun's energy) exploiting the same available surface and a reduction of the costs (compared with two separated systems that produced the same global energy).

A solar hybrid collector (PVT hereafter) typically consists of a PV module on the back of which an absorber plate (a heat extraction device) is attached. The purpose of the absorber plate is twofold. Firstly, to reduce the heating of the PV module, thus improving its electrical performance, and secondly for harnessing the thermal energy produced, which otherwise would be lost into the outdoor environment. The main parameters that affect the global PVT performance are the number of covers, the shape of the absorber plate and the operative design configurations (e.g. connections with thermal storage, mass flow rate, design temperature and so on). Anyway, the role of the fluid temperature is fundamental. Indeed, the domestic hot water (DHW) production requires thermal levels at least of 40÷50 °C that surely penalize the electric performance of the PV cells. On the contrary, lower temperatures would enable higher electrical efficiency but also would significantly reduce the thermodynamic quality of the recovered heat. The thermal hybrid collectors faces two main problems: (1) a high thermal efficiency requires good thermal insulation that unavoidably increases the

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Nomenclature

A_p	surface area of the absorber plate, m^2
A_{pv}	surface area of the PV module, m^2
C_{pw}	specific heat of the fluid under constant pressure, J/kg K
ΔE_T	difference of primary energy, kWh
I_{sol}	solar irradiation power, W/m^2
m_{ws}	mass flow rate, kg/s
P_{el}	electric power, W
P_{ref}	nominal electric power, W
P_{th}	thermal power, W
T_a	ambient temperature, °C
T_c	cell temperature, °C
T_{ref}	standard reference temperature, 25 °C
T_{out}	water outlet temperature, °C
T_{in}	water inlet temperature, °C
T_{red}	reduced temperature, °C W^{-1} m^2

Greek symbol

β	power temperature coefficient, °C^{-1}
η_{el}	electric efficiency
η_{th}	thermal efficiency
η_{power}	electric power generation efficiency
η_{PVT}	overall energetic efficiency of a PVT module
η^{II}_{PVT}	efficiency of a PVT module according 2nd law of Thermodynamics
η^{ex}_{PVT}	exergy efficiency of PVT module

PV cell temperature, as a consequence, the thermal drift decreases the conversion efficiency of PV system and (2) the heat transfer to the thermal fluid vector can be hindered by the presence of the PV cells.

Over the last 35 years, a large amount of research on PVT collectors has been carried out [7,8]. Limiting our analysis to PVT collectors that use liquid heat-transfer media, the main technique is to glue either PV cells or an entire commercial PV laminate to the absorber of a commercial thermal collector. The drawback of gluing PV cells is the fact that the PV will not be sufficiently protected from the ambient (in particular from moisture), which makes this technique problematic for commercial application. In addition, problems may result due to insufficient electrical insulation. The hybrid electrical and thermal energy generation implies a tradeoff between the electrical and the thermal energy production. An appropriate monitoring and control system allows an assessment of such a tradeoff.

Although data on PVT tested in laboratories are available, experimental tested on PVT plants are nearly missing: only a few PVT systems have been tested under real operating condition and for a relatively long times.

Further, nowadays, the web can tell you the instantaneous watt output of an individual PV module, so it shouldn't be too hard to do something similar for solar thermal energy, but it is surely harder to monitor a PVT due to the interaction of both electrical and thermal parts [9,10]. What follows is an appeal to advance toward modern and efficient PVT systems by implementing monitoring and control technologies. This will be the key to the continued development of PVT as one of the most effective means of displacing fossil fuel use, driven in part by the prospect of monetizing electrical and thermal output.

The paper is organized in three main sections (excluding introduction and conclusions): in the first section, entitled solar technology diffusion, some figures about the increase of solar installations in Europe are reported and discussed. The aim is to prove the rapid and not uniform spread that such systems can cause, in an urban or suburban context, to a competition in the exploitation of the sites that have the best solar potential.

The second section, entitled Monitoring systems for solar power plants, develops an overview of the main features, standards and references of PV, ST and PVT systems. This section has been divided in three subsections each treating such solar systems. The aim is also to highlight the overlapping points and differences of monitoring strategies applied to PV, ST and PVT systems. In this context the different definitions of efficiency for PVT systems are remarked. Finally, in the third section, named Experimental PVT power plant, a modular and general purpose monitoring and control system architecture developed for a PVT system is presented. To check the effectiveness of the proposed remote monitoring system, the performance of an experimental stand-alone PVT power plant based on a patented PVT collector named TESPI [11] (Thermal Electric Solar Panel Integration) has been evaluated.

Solar technology diffusion

In 2012, the International Energy Agency (IEA) evaluated an installed capacity of 269.3 GWth, which corresponds of about 384.7 million square meters of collector area, installed in 58 countries (an estimated 95% of the worldwide market). The vast majority of the total capacity in operation was installed in China (180.4 GWth) and Europe (42.8 GWth) [12]. Of this, 88.3% comprised flat-plate collectors (FPC) and evacuated tube collectors (ETC), 11% unglazed water collectors and 0.7% glazed and unglazed air collectors [13].

The estimated total capacity of solar thermal collectors in operation worldwide by the end of 2013 is 330 GWth, or 471 million square meters of collector area. This corresponds to an annual collector yield of 281 TWh [12].

Compared with other forms of renewable energy, the contribution of solar heating in meeting global energy demand is, besides the traditional renewable energies, like biomass and hydropower, second only to wind power. Moreover, solar thermal is the leader in installed capacity. In 2013, the solar thermal sector registered a slowdown with installed collector surface of 3,027,532 m^2, i.e. 13.2% less than in 2012 [13]. The solar thermal market contraction was particularly serious in the key European markets: Germany (−11.1%), Italy (−18.2%), France (−19.1%), Greece (−13.1%), Austria (−13.5%) and Portugal (−37.0%). The cumulated solar thermal collector surface area in service in the European Union was about 44.8 million square meters at the end of 2013, equating to 31.4 GWth of capacity [14]. Germany (17,222,000 m^2), Austria (5,045,000 m^2), Greece (4,164,025 m^2) and Italy (3,700,000 m^2) are the four countries with the highest collector surface area in service. Using the per capita surface indicator, Cyprus is the European country leader with 0.787 m^2/p.c. ahead of Austria (0.598 m^2/p.c.), Greece (0.376 m^2/p.c.) and Germany (0.214 m^2/p.c.). Italy is in twelfth position with 0.062 m^2/p.c. The solar thermal operators underline that the solar thermal technology has become less fashionable because its return on investment time is seen very unfavorably when compared with that of other renewable energy sources, especially respect to the PV technology. Another limit to a higher expansion of the solar market is that the public information and recommendation campaigns on heating systems are not high on the public agenda. In this context, it is interesting to underline that the heat production from the solar thermal sector reached