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An innovative urban energy system constituted by a photovoltaic/thermal hybrid solar installation: Design, simulation and monitoring

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HIGHLIGHTS

- The validation procedure (test bench) of a PVT panel simulation is presented.
- The 18-PVT system of a multi-housing building is presented as case study.
- The PVT system is modelled in Trnsys.
- The proposed model coincides with real monitored data with error below 6.4%.
- The model is available for design and diagnosis of PVT systems.

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ABSTRACT

The case study presented in this paper is an innovative urban roof-mounted energy system constituted by a hybrid solar system for domestic use. Utilizing this untapped energy is the key value for home renewable energy supply. It allows the improvement of the energy yield per area unit of roof or façade.

The Photovoltaic/Thermal (PVT) panel considered presents the particularity of the addition of a transparent insulating cover to reduce the heat losses on its front side. It has been developed by the manufacturer Endef Engineering in collaboration with the University of Zaragoza.

In this paper, the design of a PVT system to feed the domestic heat water requirements of multi-housing building is explained. The electricity production is also considered, in accordance with the Spanish regulation for self-consumption. The work developed began with the redesign of the hybrid solar plant, which individually supplies hot water to each dwelling and power for common consumption of the building, including a charging system for electric vehicles. Then, the PVT panel developed and manufactured by Endef Engineering and the complete thermal and electrical system are simulated in Trnsys. The monitoring of a real working installation is used in this paper to validate the proposed model. The presented case study is located in Zaragoza (Spain), in a residential apartment block, with an electrical installed power of 4.14 kWp and 20.5 kW of thermal capacity. The proposed model allows the calculation of the heat and electricity production and efficiency of the whole system with error lower than 6.5%.

1. Introduction

The hybrid photovoltaic/thermal (PVT) solar collectors constitute a very interesting renewable technology to be implemented in urban building, since they produce both electricity and heat from one integrated component. Photovoltaic (PV) systems convert, on average, less than 20% of the incident radiation into electricity, while the remainder 80% is turned into heat [1]. The capacity to utilize this untapped energy is the key value for hybrid systems, which enhances the energy yield per unit area of roof or façade [2]. Additionally, the versatility of the conversion allows optimizing electricity or heat depending on the demand requirements.

Solar technology has been developed mostly during periods in which the price of fossil fuels was increasing. Nevertheless, up to now, photovoltaic technology has required big plants and financial support to start its development. Despite the reduction or suppression of feed-in tariffs, the costs have been greatly reduced, from 4.5 €/W_p in 2008 to around 0.5 €/W_p in 2015 [3]. This reduction

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makes small plants profitable. On the other hand, solar thermal technology has been installed mainly in residential buildings where only installations with small dimensions are possible because the highest solar thermal generation occurs when the lowest heat energy is demanded. During summer months, only domestic hot water is consumed. Larger solar areas than those needed could cause high temperatures in collectors (over 100 °C), causing their deterioration. In contrast, small dimensions have long pay back periods due to high indirect costs (pumps, storage tanks, etc.). In the last years, both technologies have reduced their costs, and because of this, installations with similar sizes are available. On these installations, solar hybrid panels are adequate.

The European Directives 20-20-20 focus on the achievement of three goals by 2020: reduce greenhouse emissions by 20%, increase energy efficiency in order to save 20% of EU energy consumption, and reach a contribution of 20% of renewable energy in primary energy. From these three objectives, the last directive 2012/27/EU on energy efficiency insists on the goal of increased energy efficiency because it is the most difficult objective to achieve. Therefore, from the different actions proposed by this Directive, we would like to highlight two actions: distributed generation and the integration of renewable energy in buildings, which are responsible for 40% of the European Union's final energy consumption (Directive 2010/31/EU). Considering the different directives, the hybrid PVT panels currently present a great potential for implementation in the residential sector, hotels, and industry.

A significant amount of research and development on PVT technology has been done for the last four decades. Many innovative systems and products have been put forward and several publications focusing on PVT modules can be found in literature. Chow [4] published a very interesting review on this technology, although the contributions keep rising from then on. Since the mid-70s, solar hybrid technology has been researched by several authors, such as Wolf [5], Florschuetz [6], and Hendrie [7], who developed the first theoretical models and experimental studies to evaluate the efficiency and power generated by different types of hybrid panels. In the 1980s, there were several researches, such as Cox and Raghuraman [8], Braunstein and Kornfeld [9] or Lalović et al. [10], mainly focused on flat plate collectors (PVT). Some authors also developed concentrating hybrid collectors (CPVT), as in the case of the works conducted by Mbewe et al. [11] and Hamdy et al. [12]. In the 90s, some authors continued developing this technology for at least a decade, highlighting works such as that published by Garg [13]. The above mentioned authors worked in experimental and theoretical models of PVT cooled by air or water, standardizing the abbreviations of PVT/a and PVT/w, respectively. Authors such as Sopian et al. [14] worked in PVT/a with single and double pass. Prakash [15] developed some models comparing PVT/a with PVT/w, and he concluded that panels cooled by water reached higher efficiencies than those panels cooled by air. Bergene and Løvvik [16] developed a transient model and concluded that PVT/w can achieve global efficiencies between 60% and 80%. In 1998, De Vries [17] compared several hybrid panel typologies and included a combi-panel that used air and water.

In the last decade, several advances in solar hybrid collectors have been published [18] that proposed theoretical models and experimental validations [19], compared different solar hybrid typologies [20], proposed improvements [21], proposed new models [22], and showed the last recent advances. Then, some authors have integrated these advances into other more complex installations, such as heat pumps [23] or cooling machines [24]. The field of CPVT has also been further explored by authors such as Li et al. [25], Al-Alili et al. [26] or Buonomano et al. [27], attending both to their performance as well as to their direct application in heating and cooling systems. Amori and Taqi Al-Najjar [28] analyzed the thermal and electrical performance of a hybrid air based solar collector which, obviously, present less efficiency than the water-cooled ones. In the comparison between PVT and CPVT coupled with absorption and adsorption machines made by Del Amo et al. [29], a remarkable conclusion showed that PVT/w thermal efficiency significantly decreased when high temperatures were demanded (e.g. absorption machines). Therefore, the aim of that paper was to propose advances that improve the thermal efficiency of the PVT/w in high temperature conditions.

As mentioned, hybrid panels can achieve a better overall efficiency because they convert a greater amount of incident radiation in useful energy. This overall efficiency may be high at low temperatures, up to 60% and 80% [16]. However, electrical and thermal performances reduce significantly when the operating temperature increases [30]. This fact has been analyzed in detail in this study. It is worth stressing that in uncovered PVT solar panels, as the operating temperature increases, thermal efficiency decreases at a higher rate than in thermal collectors. The reason is the glass cover, which reduces convection losses in thermal collectors. A previous study considered covered and uncovered collectors by analyzing the appropriateness of glass cover on a thermo syphon-based water-heating PVT [31].

Moreover, the coproduction of two different energy types, heat and electricity, in the same panel makes relevant the study of the system from the Second Law of Thermodynamics that is, considering both its energy and exergy [32]. Several authors faced this matter and provided equations to evaluate the exergy efficiency of the PVT [33,34]. As remarked by different authors, the achievement of better thermal efficiencies in PVT panels is a key issue to further develop this hybrid technology [35]. Such improvement can be faced by reducing the thermal losses in the front side of the panel through an additional layer over the PV module.

The I + D area of Endef Engineering, in collaboration with the Mechanical Engineering Department of the University of Zaragoza, developed a second generation photovoltaic thermal panel. The second generation name comes from the incorporation of a transparent insulating cover (TIC) which contains an inert gas that improves the thermal efficiency of the panel. This improvement is achieved through the proper combination of the physical properties (dynamic viscosity, conductivity, density, etc.) that minimize the losses by natural convection. The upper glass cover is completely sealed by the photovoltaic module by means of adhesives resistant to solar irradiation and temperature changes.

After reviewing the existing literature, the authors of this paper evaluated different transparent insulation covers (TIC) which improve thermal performance at high temperatures and consequently achieve greater useful energy per square meter. From all the results obtained it is worth highlighting the thermal efficiency improvement achieved. Comparing the different TIC proposed with an uncovered hybrid panel the thermal efficiency is three times higher in domestically hot water applications.

As a first step in the development of the PVT panel, the study was aimed to improve on convective losses in pane spacing in a covered panel by substituting the inside air with different gases and also optimizing the distance between panes. Although a striking improvement of up to 50.4% in the convective heat loss coefficient was observed for Xenon gas with optimized spacing, the overall heat loss coefficient only improved by 8.1%, due to the significant radiative losses in comparison to convective losses in that compartment. The Xenon/Argon photovoltaic–thermal panels outperform air panels in most operating conditions, up to 3.5%. However, considering economic/environmental issues, Argon appears as the most suitable filling gas [36].

As a result, the PVT-TIC-Ar was considered as the better option to be manufactured by Endef Engineering. The detailed procedure of the mentioned study was published [36]. That work includes an electronic annex where the complete EES code with the PVT

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