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# Photovoltaic -Thermal systems (PVT): Technology review and future trends

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ABSTRACT

Combined solar photovoltaic-thermal systems (PVT) facilitate conversion of solar radiations into electricity and heat simultaneously. A significant amount of work has been carried out on these systems since 1970. Different PVT systems have been invented in the last thirty years. Several theoretical, mathematical, numerical and experimental models are introduced by many investigators across the world. The present article gives a broad classification and review of published research work on these systems. The article mostly covers the experimental work carried out on the different types of PVT systems in the last decade. The latest technology of liquid spectrum filters for PVT systems are also explored in depth.

## 1. Introduction

The Utilization of solar energy is increasing at a rapid pace. Many researchers around the world are developing the system based on solar energy. Terrestrial solar radiations consist of 43% IR, 48% VIS and 9% UV rays [1] The terrestrial solar radiations are in the wavelength range of 0.25–2.5 µm [2] This complete solar spectrum is not utilized by the solar PV system to generate the electrical power. Most of the solar cell materials, respond to the limited portion of the terrestrial solar spectrum. Fig. 1 shows the utilization of terrestrial solar spectrum for PV and thermal system. Only the radiations corresponding to the response range of the solar cell material are used by the solar cell to generate the electricity. The unused radiations of the solar spectrum will dissipate their energy as heat in the solar cell. This heat dissipation causes the thermal losses in the solar photovoltaic system, thereby reducing its performance. The output of the PV cells reduces when the operating temperature of the solar cell increases. Thus, for better performance, it is essential to maintain the low operating temperature of the solar cells [3].

## 2. Concept of PVT

Combined photovoltaic - thermal system (PVT) is considered as an appealing invention in solar technology. In these systems, the heat from the photovoltaic modules is extracted using various techniques. The extracted heat is utilized in thermal systems separately. Fig. 2 shows the simplest form of the PVT system. The concept of PVT was documented in the mid of 1970s [4]. Some theoretical and experimental works on these systems have been reported in the literature in the same decade [5–7]. To extract the heat from the PV modules, water and air were used extensively in the beginning. The technology has grown in the last three decades. Apart from extracting the heat from the PV modules, the PVT systems with spectrum filters are also in the recent research.

The concept of PVT systems is almost five decades old. But still, the technology is not much commercialized. It will always be beneficial to discuss the recent happenings in the technology to understand the development and to give the direction for future development. There are some review papers available in the literature describing the different aspects of PVT systems. Some of the published review papers during the year 2010–2017 are reported in Table 1.

The aim of the current article is to present a broad classification of the PVT systems, to discuss the experimental and theoretical work on different PVT systems carried out in the recent past. The paper also includes a review on the use of liquid based spectrum filters in PVT applications. A Comparative study of PVT technologies based on their major benefits, challenges and scope of future work is also discussed.

## 3. Classification of PVT systems

The PVT systems are broadly classified on the basis of heat

*Abbreviations:* AM, Air Mass; ANN, Artificial Neural Network; a-Si, Amorphous Silicon; BIPV, Building Integrated Photovoltaics; BIPVT, Building Integrated PVT; CdTe, Cadmium Telluride; CPV, Concentrated Photo Voltaic systems; CPVT, Concentrated type PVT; C-Si, crystalline silicon; EG, Band gap energy; Ge, Germanium; ID, Internal diameter of tube; InGaAs, Indium gallium Arsenide; InGaP, Indium Gallium Phosphide; IR, Infrared; mC-Si, Multi Crystalline Silicon; NIR, Near infrared; P3HT:PCBM, poly-3-hexathiophene-[6,6]-phenyl-C61-butyric-acid methyl-ester; PCM, Phase Change Material; PV cells, Photovoltaic cell; PV, Photovoltaics; PVT, Photovoltaic –Thermal (systems); Si, Silicon; Therminol VP-1, Fluid used to store heat, a special formulation of diphenyl oxide; TMS, Thin Metal Sheet; UV, Ultraviolet; VIS, Visible light

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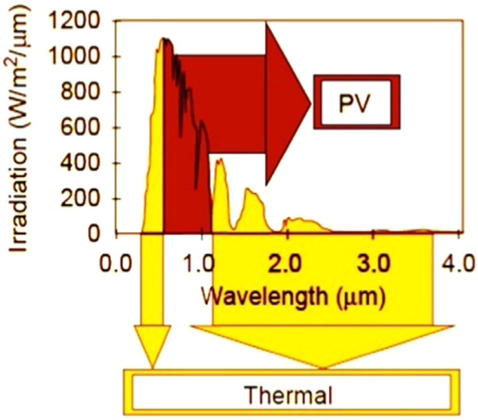


**Fig. 1.** Terrestrial solar spectrum for PV and Thermal systems [131].

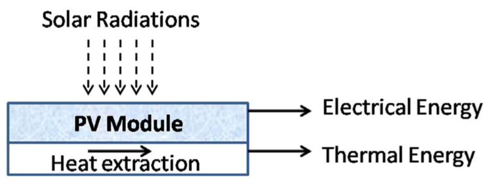


**Fig. 2.** Concept of PVT system.

extraction arrangement, working medium, and end applications. Further, the PVT systems can also be classified based on non concentration and concentration arrangements of radiations. A broad classification of PVT systems is shown in Fig. 3. The prominent work carried out on the PVT systems in the recent past is discussed in the subsequent text.

## 4. Non concentrated PVT systems

The non concentrated PVT systems are the simplest PVT systems. The natural radiations without any concentrating arrangements are used in the PVT systems. Based on the medium used for the heat extraction from photovoltaic module, these systems are classified as water type and air type of systems, discussed in the subsequent text.

### 4.1. Water type PVT systems :

In these types of PVT systems, water is used as a medium for extracting heat from the PV modules. The available literature mostly includes theoretical and experimental performance analysis of the water type PVT systems. The work includes, PVT systems with glazing [33,35,37,40,41], without glazing [38,42,163], different arrangement of water channels [43,44,47–49], fully covered and partially covered collectors by PV modules [39,42,45], collector surface covering arrangement [64,69], Semitransparent PV modules [46,52], use of selective coating [57], systems with multi fluid [58–61], use of PCM 53,54]. The available literature also describes the work on the end use of the heated water from PVT system. The hot water from the PVT system is used for domestic needs in most of the cases. The end use includes hot water [34,66,71,73], feed water for solar still [69]. The summary of some of the recent prominent literature on water type PVT system is discussed in the subsequent text.

Santbergen et al. [33] analyzed the performance of a single glazed water PVT system. The system consists of PV laminates attached to absorber surface and water tubes to extract the heat from the PV module (Fig. 4). Water is circulated using pumps. To improve electrical and thermal performance, use of anti reflective coating and solar cell with low temperature coefficients are suggested.

He et al. [34] carried out a comparative study for performance assessment of the PVT system in natural circulation of water. A conventional flat plate collector, a PVT collector and a mono crystalline PV module were considered. PV modules were mounted on absorber plate and water tubes were attached beneath the plate (Fig. 5). The daily thermal efficiency recorded was 40%, which is about 75% of that of a conventional solar thermosiphon collector system. The daily average electrical efficiency was found about 10%, which was a little lower than the conventional mono crystalline silicon photovoltaic module in the same conditions. However, the primary-energy saving efficiency was found about 60–75%, which was much higher than the efficiency of the conventional system.

Rommel et al. [35] investigated the performance of single glazed

**Table 1**
Summary of review papers available on PVT systems (2010–2017).

| S.N. | Contents of Review paper | Year of publication | Ref. |
|---|---|---|---|
| 1 | Water and Air type PVT systems | 2010 | Hasan et al. [8] |
| 2 | Water + Air + Refrigerant type PVT systems | 2011 | Daghigh et al. [9] |
| 3 | Flat plate PVT systems | 2011 | Ibrahim et al. [10] |
| 4 | Liquid + air type PVT, Applications of PVT systems | 2012 | Tyagi et al. [11] |
| 5 | Air type PVT systems, Water Type PVT systems, use of refrigerants in PVT systems, environmental aspects of PVT | 2012 | Zhang et al. [12] |
| 6 | Air type PVT systems | 2013 | Hussain et al. [13] |
| 7 | Standards of PVT systems | 2013 | Kramer et al. [14] |
| 8 | Spectral beam splitting for PV systems | 2013 | Mojiri et al. [15] |
| 9 | Semitransparent BIPVT systems | 2014 | Ng et al.[16] |
| 10 | Water type PVT, Air Type PVT, BIPVT, Heat pump assisted PVT systems | 2014 | Shan et al. [17] |
| 11 | Water flat plate PVT systems | 2014 | Aste et al. [18] |
| 12 | Air type PVT systems, Water Type PVT systems, BIPVT - special focus on case studies in India. | 2015 | Kumar et al. [19] |
| 13 | Flat plate PVT, Special focus on materials and end applications of PVT systems | 2015 | Michael et al.[20] |
| 14 | Concentrated PVT systems | 2015 | Omar et al.[21] |
| 15 | Environmental impact of PVT systems | 2016 | Good [22] |
| 16 | BIPVT systems | 2016 | Yang et al.[23] |
| 18 | Environmental issues of PVT systems | 2016 | Lamnatou et al. [24] |
| 17 | Thermal absorbers for PVT systems | 2017 | Wu et al.[25] |
| 19 | PVT absorption cooling systems | 2017 | Alobaid et al. [26] |
| 20 | Air type PVT systems, Water Type PVT systems, use of PCM in PVT, Use of Heat Pipe in PVT | 2017 | Al-Waeli et al. [27] |
| 21 | BIPVT systems, summary of BIPVT System design software | 2017 | Debbarma et al. [28] |
| 22 | Air type PVT systems, Water Type PVT systems, use of PCM in PVT, Use of Heat Pipe in PVT | 2017 | Sathe et al. [29] |
| 23 | Use of Nanofluids in PVT | 2017 | Yazdanifard et al. [30] |
| 24 | Series connected PVT systems | 2017 | Sahota et al. [31] |
| 25 | Concentrated PVT systems with spectral beam splitting | 2017 | Ju et al. [32] |