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Thermal Study of Hybrid Photovoltaic-Thermal (PVT) Solar Collectors Combined with Borehole Thermal Energy Storage Systems

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Abstract

This article reports on the evaluation of the short and long-term electrical performance of a photovoltaic-thermal (PVT) system coupled with borehole thermal energy storage (BTES). This assessment was conducted using a computer simulation of a PVT system installed on a small office building in two extreme climate zones in the United States. In each climate, two different scenarios were considered: (i) a PVT system coupled to a BTES with no ground-coupled heat pump (GCHP), and (ii) a PVT system coupled to a BTES with a GCHP. The system simulation results reveal significant improvements in PVT cell efficiency in the system without a GCHP compared with conventional PV panels. These improvements were reported to be as high as 4.1 and 4.7% in cold and hot climates, respectively. Moreover, a coupling GCHP showed a negligible impact on the PVT cell performance, which implies the feasibility of coupling the two technologies to the same BTES.

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Keywords: Photovoltaic-thermal; PVT; Thermal energy storage system; PV cells; Solar; Geothermal; TRNSYS

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1. Introduction

Photovoltaic-thermal (PVT) technology is a relatively new technology that comprises a photovoltaic (PV) panel coupled with a thermal collector to convert solar radiation into electricity and thermal energy simultaneously. It is well known that PV cell efficiency is a function of their temperature; increasing temperature reduces the photovoltaic conversion efficiency of sunlight to electricity. One of the central advantages of coupling a PV panel with a thermal collector is that the latter can reduce the former's temperature by circulating a coolant into the collector, thereby increasing the cell's efficiency. Many researchers have quantified the impact of a coolant on PVT cell performance. Most of this research is focused on the instantaneous impact of a coolant on PVT cells, which means that it only demonstrates the increase in PV cell performance when a relatively colder fluid is circulated into a thermal collector coupled with it. In real systems, in fact, the coolant usually is to be circulated in a closed loop

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between a heat source (PVT collector) and heat sink, especially when the coolant is an anti-freeze solution. Hence, coupling the PVT array to a suitably large heat reject sink has remained a challenge. A BTES systems can serve as a heat sink due to the stability of underground temperatures, which are usually lower than the working cell temperature, and thus, the objective of this study is to evaluate the short and long-term electrical performance of a PVT system coupled with BTES.

2. Literature Review

PV cells absorb 90% of incident solar radiation. However, only 15% is converted into electricity, and the remainder is wasted as heat [1]. This heat has been shown to have a negative impact on cell efficiency. The efficiency of a silicon (SI) cell, for example, decreases 15% for every 30°K increase in temperature [2]. Du et al. [3] reported a cell efficiency degradation at a rate of 0.45%/°C for SI cells. Kawajiri et al. [4] have developed a framework to "evaluate the effect of irradiation and temperature on crystalline-silicon PV potential" globally. They created a global distribution map of annual total irradiation on an equator-pointed tilted surface. The solar irradiation data were taken from NASA database [5] , averaged over 22 years. The solar irradiation map, after that, was applied to a global distribution of annual average temperature map to consider the performance of the PV cells as a function of the ambient temperature. Finally, a map of global annual energy generation potential was generated.

The first work on liquid-type PVTs was conducted from 1978 to 1981 [6]. This work was carried out by Wolf [7], who found that using a PVT system for heating and electricity generation is feasible and cost effective. Bergene and Lovvik [2] examined the cooling effect on solar cells with a rated efficiency of 10.4-12.7%. They found that a working cell temperature of 60-80°C is common and that this temperature resulted in an efficiency of 9.5-10.5%. However, after applying the cooling effect to the cells, they found a relative increase in electrical efficiency of about 10-30%. Fujisawa and Tani [8] compared the electrical energy of a PV, PVT (single cover), and PVT (coverless) with each other, all of which were mono-crystalline cells. They found that the PVT (coverless) produced 8% more energy than the PV on an annual basis, and that the single-covered had the lowest production. Tripanagnostopoulos et al. [9] tested the electrical performances of a free-to-ambient PV, back-insulated PV, and water-type PVT. Their results showed a performance increase of 3.2% in the PVT over the free-to-ambient PV, and a 13.3% increase in the PVT over the back-insulated PV. On the other hand, Zondag et al. [10] reported a reduction in cell efficiency when they built a prototype multi-crystalline PV-laminate combined with a conventional glass-covered sheet-and-tube collector. The electrical performance of their PVT dropped from 8.5% for a conventional PV to 6.7% for the PVT prototype. Daghigh et al. [11] simulated glazed and unglazed active PVT systems with different types of cells using TRNSYS. They found that all of the different types of cells with the glazed PVT collector produced less electricity than the unglazed.

Many researchers have sought to identify the parameters affecting the cooling process in PVT panels and their associated electrical efficiency improvement. The two most crucial parameters that have been identified are the PVT's working fluid inlet flow rate and temperature [2]. Daghigh et al. [11] reported an increase in the electrical performance of both glazed and unglazed PVT collectors when flow rate was increased from 0.001 to 0.02 kg/s, for all cells types; however, when the flow rate was increased further, the performance stayed constant. Jakhar et al. [12] conducted a TRNSYS model to analyze the electrical performance of a PVT collector coupled with an earth water heat exchanger (EWHE) as a function of different parameters. They found the optimum flow rate entering the PVT collector to be 0.018 kg/s. Bergene and Lovvik [2] studied the effect of tube geometry on PVT performance. They studied cell efficiency as a function of WD^{-1}, where W is the fin width and D is the tube diameter. They noticed that under a low flow rate, an increase in cell efficiency was associated with an increase in WD^{-1} and vice versa.

The feasibility of combining a PVT with a BTES, either with or without using GCHP, has been examined by few researchers. Bakker et al. [13] carried out a long-term TRNSYS model combining a PVT panel with a GCHP and concluded that the system was able to meet 100% of a one-family dwelling's heat demand and about all of its electricity demand, while keeping the long-term ground temperature constant. In the TRTNSYS model study by Jakhar et al. [12], they analyzed changing pipe material, length, and diameter of the U-tube to ensure maximum ground heat transfer and, hence, PVT electrical performance. They observed that changes in pipe materials and diameter hardly affected the (PVT + EWHE) system's performance, while changes in the pipe length from 10 to 50 m considerably reduced the PV cell temperature, especially during peak sunshine hours. Chiasson and Yavuzturk [14] describe the development of a publicly-available hybrid solar-geothermal simulator tool. Hybridizing a GCHP with solar thermal collectors is advantageous in realizing smaller, lower cost BTES, in addition to allowing achievement of a more sustainable geothermal system over the long term. The simulation tool accounts for the numerous, coupled dynamic processes of the building load, heat pump capacity, heat transfer in the Earth, and solar thermal processes. Each of these processes occurs over various time scales on the order of minutes up to many decades. For a heating-dominated school building in the northern United States, they showed a 62% reduction in BTES size with the addition of glazed-solar thermal collectors.