Renewable Energy 129 (2018) 419–430

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A novel hybrid energy system combined with solar-road and soil-regenerator: Sensitivity analysis and optimization

Bo Xiang [a], Xiaoling Cao [a], Yanping Yuan [a, *], M. Hasanuzzaman [b], Chao Zeng [a], Yasheng Ji [a], Liangliang Sun [a]

[a] School of Mechanical Engineering, Southwest Jiaotong University, Chengdu, 610031, Sichuan, China
[b] UM Power Energy Dedicated Advanced Centre (UMPEDAC), Level 4, Wisma R&D, University of Malaya, 59990 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 8 February 2018
Received in revised form
3 May 2018
Accepted 7 June 2018
Available online 8 June 2018

Keywords:
Solar road
Ground heat exchanger
Photovoltaic-thermal
Electrical efficiency
Thermal storage efficiency
Overall energy efficiency

ABSTRACT

To reduce the dependency of fossil fuels and greenhouse effect, the authors have proposed a novel solar-road and soil-regenerator hybrid energy system (SRSRHES), which utilizes a combination of Photovoltaic-Thermal (PVT) and soil heat storage technologies on the roadways. Design parameters and meteorological conditions affect the thermal storage performance of SRSRHES, which directly influences its annual performance and cost-effectiveness. Therefore, the study investigated the influence of flow rate, soil thermal properties, collector area, and borehole depth on electrical and thermal performance in three different cities with a numerical method to realize rational configuration of design parameters for the system. The results indicated that the recommended flow rates are 0.5, 0.3, and 0.3 kg/s in Beijing, Harbin, and Barkam respectively; Overall energy efficiency for different soils is different that is increased in the order of clay, sandy soil, sandstone, limestone, and granite. Collector area exerts a positive effect on total energy generation, but has a negative effect on overall energy efficiency. Borehole depth has a positive effect on both total energy generation and overall energy efficiency; Furthermore, the influence of various parameters on power generation performance is less than thermal storage performance, and overall energy efficiency mainly depend on thermal storage performance.

1. Introduction

Extensive consumption of fossil fuels has resulted in global energy shortage and environmental pollution. Fossil fuels based power generation system threatens the environment and the environmental sustainability. Nowadays, greenhouse gases (GHG) emitted by fossil fuels are serious issues and a global concern [1,2]. As the road transportation industry is a high energy consuming and pollution emitting sector, necessitating the implementation of energy conserving and emission reducing measures using renewable energy [3,4]. Consequently, national governments have issued policies for utilization of renewable energy to promote the sustainable development of society. Solar energy is regarded as a promising renewable energy source as it is inexhaustible, clean, and ubiquitous [5]. Currently, solar photovoltaic (PV) and photothermal processes are popularly employed to capture solar energy [6].

Road surfaces distributed throughout the world are exposed to the environment, provide sufficient area to capture solar energy, and can absorb about 40 MJ/m^2 of solar radiation per day during summer [7]. Use of pavements as solar collector for heat is a tested and mature methodology. It generally includes a piping heat exchange system installed under the pavement; the heat exchange medium in the pipes is heated and transferred to the heat reservoir for storage or direct application. Wu et al. [8] investigated the thermal response of an asphalt pavement as solar collector. In their study, copper pipes were placed under small slabs and thermal energy stored was collected by circulating water. The influences of circulating water flow rate, initial temperature distribution of the slabs, and the starting time for energy collection were studied during heat collection. The results showed that the temperature of pavement decreased significantly. The energy efficiency of the asphalt pavement as solar collector reached 33% and was limited by the reduction in the asphalt temperature by increasing flow rate. Chen et al. [9] investigated the use of an asphalt pavement as solar collector for melting snow. The design parameters during the snow

* Corresponding author.
E-mail address: ypyuan@home.swjtu.edu.cn (Y. Yuan).

https://doi.org/10.1016/j.renene.2018.06.027
0960-1481/

melting process were optimized using a numerical simulation method. The study reported that the optimal depth of the heat exchange pipe was 4–10 cm under the surface, and the optimal pipe spacing was 0.18–0.4 m. Gao et al. [10] conducted an experimental study to assess the heat transfer performance of the asphalt pavement as solar collector, and proposed that the heat collected during summer can be used for snow melting in winter. The experimental results showed that nearly heat 150–250 W/m^2 of heat could be obtained from the solar radiation intensity during natural summer conditions.

Similarly, PV panels in the pavement, called the ‘photovoltaic road’, can serve as solar collector, and used for electricity generation [4]. The PV road can be of two types namely, PV system using roadside facilities and the PV pavement. PV panels erected with roadside facilities also save space. For example, a tunnel built to protect trains from the falling trees is covered by solar panels in Belgium [11], a fully solar-powered highway has been constructed in Italy [12], and a PV array was laid on the roof of a long noise barrier tunnel on the A3 highway near Aschaffenburg, Germany [13]. In recent years, PV pavements, first proposed by an American engineer Scott Brusaw, and referred to as solar roads, have garnered interest globally [14]. In a solar road, the pavement is paved with PV cells, and is capable of supporting conventional transportation functions in addition to providing electricity for street lights, traffic lights, and residential households. And later the first solar bicycle path, solar road and solar-powered expressway were built in Netherlands, France and China respectively [15,16]. Shekhar et al. [17] established the operating temperature model of a solar road in Netherlands based on the energy balance principle, and the hourly operating efficiency was computed based on irradiance and temperature. The calculation revealed that the maximum operating temperature reached 85.98 °C, annual energy yield of the solar road was 84 kWh/m^2, and overall energy efficiency was 8.6%. However, the efficiency of solar road is lower than ordinary roof solar panels, due to the fixed installation angle and high operating temperature of solar cells. Many researchers investigated the effect of cell on the efficiency and found that the electrical efficiency decreased by 0.04–0.5% in different operating conditions for different PV modules with every 1 °C increase in solar cell temperature [18–21]. Efthymiou et al. [22] assessed direct and indirect effects of PV pavement on the microclimate and it is used to mitigate urban heat island. Measurement and simulation results showed that the temperature of PV pavements were 8 °C lower than conventional pavements, and the PV pavements contributed to about 0.8 °C decrease in the ambient temperature when compared to conventional pavements. Moreover, electricity generated by PV pavements can cater to the demand for lighting in city.

Photovoltaic-thermal (PVT) technology produces electricity and heating energy simultaneously, and is effective in maintaining solar cell efficiency [23–25]. The heat generated by the PVT collector is between 40 and 60 °C and is generally applied in low-temperature heating systems such as the PVT hot water system [26,27], PVT preheating/heating system [28], and PVT heat pump system [29]. The PVT system can attain an energy efficiency of 60–80% [30]. Sun et al. [31] studied the effects of PVT module tilt angle and connection mode on the energy efficiency of a hot water system, and the optimal tilt angle was 40°. Yuan et al. [32] investigated the hourly performances of five connection modes for the PVT forced circulating hot water system. The modes differed in the collector numbers in series, which were 1, 2, 3, 4, and 6. The study found that increasing the number of series increased the temperature difference between the inlet and outlet of the collector, and increased the pump running time. Further, Ouyang et al. [33] investigated the influence of optimized connection modes on the performance of PVT hot water system in different radiation regions. The results showed that the connection modes corresponding to the maximum electric generation were 2 and 3 in the regions II and III respectively. Slimani et al. [34] compared the energy performance of one PV and three PV/T modules that were basic solar PV/T air collector, glazed solar PV/T air collector and glazed double-pass solar PV/T air collector. The results indicated overall daily average energy efficiencies of 29.63%, 51.02%, 69.47%, and 74%, respectively on a typical summer day in Algiers with airflow of 0.023 kg/s.

Ground source heat pump (GSHP) is a technology that uses the soil as heat source and sink, and has been widely studied and applied in the past few decades, especially in heating, ventilating, and air conditioning [35]. The ground heat exchanger (GHE) is an important component of the GSHP system as it affects the performance of the entire GSHP system directly [36,37]. Yang et al. [38] proposed a two-region vertical U-tube GHE analytical model for GSHP system dynamic simulation. The heat transfer region of GHE which presented as a quasi-three dimensional steady-state heat transfer model was divided into two parts at the boundary of borehole wall, and the two parts were coupled by the borehole wall temperature. Cao et al. [39] and Yuan et al. [40] improved the two-region model by adopting a numerical simulation method in the soil area and a steady-state analytical method on the basis of energy conservation for the borehole area, and investigated the restoration performance of vertical GHE and thermal interaction of multi-GHEs under various intermittent ratios and spacing of boreholes. Limited soil temperature recovery ability eventually led to deterioration in the heat transfer performance of the GHE. In cold regions, the heating load in winter is larger than the cooling load in summer, which causes the soil temperature to decrease gradually over prolonged running time [41]. The solar assisted ground source heat pump (SAGSHP) can effectively address this problem. Previous research have indicated that the SAGSHP can compensate for the mismatch between heating load and cooling load, realize seasonal heat storage of solar energy and make full use of solar energy throughout the year [42–44]. Bakirci et al. [45] built and tested a SAGSHP system during the heating season, and concluded that this system was suitable for cold areas in Turkey. The COP of the heat pump was 3.0–3.4, while the comprehensive COP of the system was 2.7–3.0, about 10% smaller than the heat pump. Chen and Yang [46] completed the optimization process on a TRNSYS-based platform by simulating the influence of solar collector area on the total borehole length and system performance. The simulation results indicated that the optimized collector area and borehole length were 40 m^2 and 264 m respectively. Solar energy could provide the total heat extraction in addition to 75% of hot water requirement under the optimized design per year. Moreover, the energy balance of the optimized design was confirmed with a minor difference of 0.75%. Pärisch et al. [47] discussed the running characteristics of the SAGSHP system under non-standard conditions; higher source and lower sink temperatures, various flow rates, and complicated control strategies were considered. The study found that the system COP could be increased by raising the heat source temperature, and if the heat source temperature was 10–20 °C, COP depended on the temperature lift between source and sink. In addition, the flow rate had little impact on the exergetic efficiency. Ozgener and Ozgener [48] used the drive-way as solar collector and coupled it with a GSHP system to heat a greenhouse. The exergy efficiency of this system reached 68%.

Xiang and Yuan et al. [49] proposed a novel solar-road and soil-regenerator hybrid energy system (SRSRHES) that was the first of its kind to use a combination of PVT and soil heat storage technologies on the roadway. The SRSRHES undertakes transportation functions, outputs electricity, and stores solar thermal energy to the soil. In this study, a dynamic mathematical model of the SRSRHES was developed, validated, and applied to cold regions, and thermal