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A novel hybrid energy system combined with solar-road and soil-regenerator: Dynamic model and operational performance

Bo Xiang[a,1], Xiaoling Cao[a,1], Yanping Yuan[a,*], Liangliang Sun[a], Hongwei Wu[b], Fariborz Haghighat[c]

[a] School of Mechanical Engineering, Southwest Jiaotong University, Chengdu 610031, Sichuan, China
[b] School of Engineering and Technology, University of Hertfordshire, Hatfield AL10 9AB, United Kingdom
[c] Department of Building, Civil and Environmental Engineering, Concordia University, Montreal H3G 1M8, Canada

A R T I C L E I N F O

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A B S T R A C T

Solar roads are emergent and huge energy source in traffic domains. To improve the energy utilization efficiency of a solar road, a novel solar-road and soil-regenerator hybrid energy system in combination with conventional photovoltaic-thermal and soil heat storage technology was proposed. A mathematical model of the solar-road and soil-regenerator hybrid energy system was developed, validated, and applied to evaluate the thermal storage and power generation performance of the proposed system in cold regions. The results indicated that for critical thermal storage temperatures of 20, 30, and 40 °C, the proposed system decreased maximum photovoltaic cell temperatures by 24.09, 25.84, and 24.42 °C and increased electrical efficiencies by 6.85, 6.68, and 4.53%, respectively, compared with conventional solar roads. By storing heat in the soil and elevating soil temperatures, the proposed system also increased the average borehole wall temperatures by 2.93, 2.26, 1.87 °C. The proposed system produced overall energy efficiencies of 48.42, 55.47, and 66.58%, while conventional solar road efficiencies approximate 10.75%.

1. Introduction

Energy is important for economic and social development. Fossil-fuel-based energy shortages and environmental pollution have spurred interest in solar energy as a promising renewable energy source [1]. Solar energy must be captured, converted, and stored in a cost-effective fashion to promote the application [2]. Nowadays, primary methods of capturing solar energy include photovoltaic (PV) and thermal processes [3]. Solar energy is gradually applied to transportation sector with the development of solar energy utilization technology. Efthymiou et al. [4] investigated the impact of PV pavements in the urban environment. Nasir et al. [5] expanded the investigation of the road pavement solar collector system based on four tested parameters. Literature [6] reported that the Italy government is getting ready to begin construction on what is to be the world's first totally solar highway. Literature [7] reported that solar panels produce energy for high-speed trains.

First proposed by Scott Brusaw, an American engineer, solar roads have garnered interest recently [8]. A solar road is a low-carbon, environmentally friendly alternative that supports conventional transportation functions while providing output electricity for street lights, traffic lights, and residential household electricity. In 2014, the Netherlands built the world's first solar bicycle path, and in 2016, France built the world's first solar road, *Wattway*, in Normandy [9].

Analysis of the solar bicycle path indicated a photoelectric conversion efficiency of 8.6%, which is lower than the efficiency of ordinary roof solar panels. The fixed installation angle and high operating temperature of the solar cell contribute to this reduced efficiency. The highest operating temperature measured was 85.98 °C [10]. For each 1 °C increase in solar cell temperature, electrical efficiency decreases approximately 0.5% [11].

Photovoltaic-thermal (PVT) technology, which produces electricity and heating energy simultaneously, has proven effective in maintaining solar cell efficiency [12]. The PVT technology produces heating energy temperatures of 40–60 °C, and has been applied in low-temperature heating systems [13]. Pei et al. [14] analyzed the performance of heat pipe PVT systems for domestic hot water throughout the year. Izquierdo and Agustín-Camacho [15] carried out an experimental research with a PVT micro grid feeding a reversible air–water heating capacity heat pump for radiant heated floor. Chen et al. [16] proposed a heat-pipe solar (HPS) PVT heat pump system which combined the HPS PVT

* Corresponding author.
E-mail address: ypyuan@home.swjtu.edu.cn (Y. Yuan).
[1] Joint first authors.

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Nomenclature

PV	photovoltaic
PVT	photovoltaic-thermal
SRSRHES	solar-road and soil-regenerator hybrid energy system

Symbols

A	solar road area [m^2]
C	specific thermal capacity [J/(kg·K)]
$d_{sr,i}$	internal diameters of pipe in solar road [m]
$d_{sr,o}$	external diameters of pipe in solar road [m]
G	solar irradiance [W/m^2]
H	borehole depth [m]
h_c	convective heat transfer coefficient [W/(m^2·K)]
h_o	convective heat transfer coefficient between the outside and the transparent [W/(m^2·K)]
h_r	radiation heat transfer coefficient [W/(m^2·K)]
$h_{sr,f}$	heat transfer coefficient from pipe in solar road to fluid [W/(m^2·K)]
l	thickness [m]
Q_e	electric energy production [J]
Q_{th}	heat storage capacity [J]
q_1	heat flow between the left pipe and the borehole per microelement [W/m]
q_2	heat flow between the right pipe and the borehole per microelement [W/m]
q_{12}	heat flow between the left and right pipe per microelement [W/m]
R	thermal conductive resistance [K/W]
Ra	Rayleigh number
R_1^{Δ}	thermal resistance between the left pipe and borehole [K/W]
R_2^{Δ}	thermal resistance between the right pipe and borehole [K/W]
R_{12}^{Δ}	thermal resistance between the adjacent pipes [K/W]
S	source term
T	temperature [°C]
T_{f1}	fluid temperature in the left leg [°C]
T_{f2}	fluid temperature in the right leg [°C]
T_{st}	Critical thermal storage temperatures [°C]
t	time [s]
V	flow rate [m/s]
v_r	wind speed [m/s]
M	mass fluid flow [kg/s]
w	width [m]
x,y,z	Cartesian coordinates

Greek symbols

α	absorptivity
β	title angle [°]
σ	Stefan-Boltzmann constant [W/(m^2·K^4)]
ε	emittance
η_e	electrical efficiency of proposed system
η_f	primary energy-saving efficiency
η_p	electric power generation efficiency of conventional power plant
η_{pv}	electrical efficiency of PV cell
η_r	reference energy efficiency of PV cell
η_{th}	thermal storage of proposed system
η_t	overall energy efficiency
λ	thermal conductivity [W/(m·K)]
ρ	density [kg/m^3]
τ	transmissivity

Subscripts

a	air
c	thermal absorber
g	ground
in	isolating layer
B	bond
b	borehole wall
oa	outdoor air
p	photovoltaic cell
si	silicone gel
sky	the sky
so	soil
sr,f	fluid in solar road's pipe
t	transparent surface
tw	pipe wall
U-in	inlet fluid of U-pipe
U-out	outlet fluid of U-pipe

collector with heat pump. The authors investigated the performance of the system with numerical and experimental method. Systems using PVT technology have demonstrated efficiencies of 60–80% [17].

To compensate for the seasonal dispersion and instability of solar energy, energy produced in the summer must be stored and used to supplement the winter heat demand, especially in cold regions [18]. The shallow stratigraphic soil supporting a solar road, with good heat storage properties, may serve as a regenerator [19]. The ground heat exchanger (GHE) is an advisable design for storing heat in soil. Cao et al. [20] developed a heat transfer model of the GHE by combining the analytical solution and numerical solution, and investigated on the restoration performance of vertical ground heat exchanger with various intermittent ratios. Yuan et al. [21] investigated the thermal interaction of multiple boreholes, the soil hear transfer properties of a large soil area is the focus.

Moreover, some studies have considered solar energy-soil thermal storage using a combination of solar energy technology and ground source heat pump systems [22]. Liu et al. [23] designed and implemented an experiment of solar seasonal storage coupling with ground-source heat pump system. Aim at this system, thermal equilibrium of soil was studied; relationship between solar energy radiation quantity and thermal storage quantity was discussed. Results showed that solar energy utilization efficiency achieved 50.2% and soil temperature raised by 0.21 °C. Wang et al. [24] studied a solar-assisted ground-coupled heat pump system with solar seasonal thermal storage installed in a detached house in Harbin using experimental method. The results show that the system can meet the heating–cooling energy needs of the building. The average coefficient of performance (COP) of the system was 6.55 in winter and that was 21.35 in summer, and the heat directly supplied by solar collectors accounted for 49.7% of the total heating output in winter. After a year of operation, the heat extracted from the soil by the heat pump accounted for 75.5% of the heat stored by solar seasonal thermal storage. Dai et al. [25] empirically investigated the effects of operation mode on the heating performance of a solar-assisted ground source heat pump system (SAGSHPS) and found that the solar energy accelerated soil temperature recovery when the heat pump system was not operational. In addition, the solar energy storage time was optimized to reduce the energy consumption of the circulating water pump according to storage tank temperature. Chen and Yang [26] used the Transient System Simulation Tool (TRNSYS) to