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Efficient path of distributed solar energy system synergetically combining photovoltaics with solar-syngas fuel cell

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ABSTRACT

Solar energy system is compatible with the ever-rising demands to switch from fossil fuels to renewable energy sources. Here, a concentrating solar power system integrating photovoltaics and a solar-syngas-fuelled solid oxide fuel cell is proposed. The concentrated sunlight is first absorbed by a spectrum selective nanofluid. The ultraviolet and infrared solar spectrum bands of the concentrated sunlight are absorbed and converted into solar syngas through a thermochemical reaction. The upgraded solar syngas is converted into electricity through solid oxide fuel cell. The visible and near-infrared sunlight band un-absorbed by nanofluid is transmitted and directly converted into electricity through concentrator photovoltaics. In contrast to individual concentrator photovoltaics, this solar hybrid system can convert the ultraviolet and infrared solar spectrum bands to solar syngas instead of waste heat. The nanofluid has the function of adjusting the output electricity share between the solid oxide fuel cell and the concentrator photovoltaics. The simulation method of this type of solar hybrid system is described. The conversion performance of the full spectrum solar energy converted into electricity is analysed for a typical system. In particular, the complementary feature of the spectrum response is disclosed for the selected nanofluid. The solar-to-electricity efficiency would be expected to be approximately 31.5% at a direct normal irradiation of 900 W/m^2. An optimal particle size and volume fraction of the nanofluid are provided. The results may provide a possibility of a new pathway to the high-efficiency of full solar spectrum utilization.

1. Introduction

The growing world economy has brought about the ever-rising demand and consumption of fossil fuels, which aggregates the concern of global warming. To solve the dilemma of development and environmental protection, it is recommended to switch to clean, low-carbon and renewable energy sources. Among all the energy sources, the solar energy is abundant and widespread, raising much interest.

For solar-to-electricity conversion, photovoltaic (PV) and concentrator photovoltaic (CPV) technology have great potential in both microgrids and centralized power plants [1]. However, commercial PV modules usually exhibit relatively low efficiencies of 14–20% [2]. The reason is that not all photons in sunlight suit the bandgap energy of PV cells [3]. For photons at 600–1100 nm wavelengths, their energy is comparable to the PV bandgap energy and is almost totally converted to electricity. The energy of ultraviolet energy (UV) and near-UV photons is too high for PV bandgap energy, and the excessive part goes to heat through relaxation [4]. Furthermore, the energy of infrared photons is not high enough for the PV bandgap and relaxes into heat instead of exciting electrons. Consequently, approximately 20% of full-spectrum sunlight is converted to electricity in a single-junction PV cell, while the other 80% UV and infrared sunlight goes to low-temperature heat.

The solar chimney is also feasible in solar-to-electricity conversion. Whereas, a large area of land, usually a mountain, is required to provide enough hot air for the turbine [5]. To reduce the need for large area, the flexible floating solar chimney has been proposed [6]. Whereas, the solar-to-electricity efficiency of the floating solar chimney is still at 0.6%. More improvements are needed.

To improve the efficiency of the solar-to-electricity conversion, a photovoltaic/thermal (PV/T) system has been proposed by Wolf in the 1970s [7]. In this PV/T system, the low-temperature heat generated by the PV cell can be recovered to provide hot water. From the viewpoint of the first law of thermodynamics, the efficiency converting sunlight into both electricity and heat is usually 60–80%. However, from the

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Nomenclature

Symbols

A	area of the quartz windows, m^2
C	concentration ratio
$I(\lambda)$	spectral energy of concentrated sunlight spectrum, W/nm
$I_0(\lambda)$	spectral energy of incident sunlight in the system, W/nm
CI_{ab}	sunlight energy absorbed by nanofluid, W
CI_{sc}	sunlight energy scattered by nanofluid, W
CI_{CPV}	sunlight energy absorbed by CPV cell, W
y	nanofluid layer thickness, cm
k	thermal conductivity of quartz, W/(m K)
q_v	volume flow rate, L/s
h_f	convective heat transfer coefficient between the nanofluid and quartz window, W/(m^2 K)
T_{sky}	sky temperature, K
ρc_p	specific heat of nanofluid
T	temperature, K
T_m	nanofluid mean temperature, K
T_{out}	outlet nanofluid temperature of solar receiver, K
T_{in}	inlet nanofluid temperature of solar receiver, K
R	thermal-conduction resistance of quartz window, K/W
h_{air}	convective heat transfer coefficient between the quartz window and air, W/(m^2 K)
$Q_{rad,i}$	radiation heat loss in the *ith* control volume, W
$Q_{conv,i}$	convection heat loss in the *ith* control volume, W
Q_{ab}	total heat gain of nanofluid, W
P_e	electricity consumption in nanofluid pump, W
$P_{sol\text{-}SOFC}$	contribution of absorbed sunlight in SOFC electricity output, W
m	molar flow rate, mol/s
PleaseCheck	standard molar reaction heat, kJ/mol

Greek Symbols

λ	sunlight wavelength, nm
δ	quartz window thickness
α	absorption coefficient
ε	emissivity of quartz window
τ	transmittivity of quartz window
σ	Stefan-Boltzmann constant
η_{fuel}	solar thermochemical efficiency
η_{heat}	solar thermal efficiency
η_{SOFC}	SOFC efficiency
η_{sys}	solar-to-electricity efficiency of the proposed system
$\eta_{CPV/Carnot}$	solar-to-electricity efficiency of the reference CPV/Carnot cycle reference system
$\eta_{CPV,ref}$	solar-to-electricity efficiency of the individual CPV reference system
η_{opt}	optical efficiency of solar collector
$\eta_{opt,total}$	optical efficiency of the proposed system

Subscripts

i	number of control volume
ii	the inner surface of inner quartz window
io	the outer surface of inner quartz window
oi	the inner surface of outer quartz window
oo	the outer surface of outer quartz window
ref	reference system
p	nanoparticle
amb	ambient
r	thermochemical reaction
carnot	Carnot cycle

Abbreviations

SR	spectral response, A/W
LHV	molar lower heating value, kJ/mol
PV	photovoltaics
CPV	concentrator photovoltaics
CPV/T	concentrator photovoltaics/thermal
NCS	nanofluid-thermochemical-SOFC converter
SOFC	solid oxide fuel cell
UV	ultraviolet sunlight
Vis	visible sunlight
NIR	near-infrared sunlight

viewpoint of the second law of thermodynamics, Ref. [8] reported that the exergy efficiency converting sunlight into electricity and heat is still about 14%.

Since 2008, the electricity is produced from the PV heat by the organic Rankine cycle [9]. The solar-to-electricity efficiency is increased to 31% at 110 °C. However, a contradiction appears. There is a thermal coupling between the PV operation temperature and the initial temperature of the organic Rankine cycle. The efficiency of PV can be decreased with the increase of operation temperature, due to the negative temperature coefficient. Whereas, the organic Rankine cycle needs high initial temperature to work efficiently. Such contradiction restricts the solar-to-electricity efficiency from further improvement.

One solution to the contradiction is the multi-junction photovoltaic cell. In a multi-junction photovoltaic cell, the different photon energies of sunlight spectrum are matched with 2–4 single junctions with different bandgap energies [10]. Thus, the UV and near-infrared sunlight produce electricity instead of heat, and the solar-to-electricity efficiency can achieve 46% [11]. Due to the limited photo current and low light transmission to the underlying junction, the multi-junction photovoltaic cell still faces challenge in scale application.

Spectrum selection is another solution to the contradiction. In spectrum selection solar energy systems, the concentrated sunlight is split into several wavelength bands. Each wavelength band is respectively utilized by the most efficient energy conversion pathway [12]. One type of spectrum selector is the selective mirror. It can transmit the visible and near-infrared sunlight band suitable for the PV bandgap, while reflecting the rest sunlight [2]. In the reflected spectrum, the infrared sunlight has thermal effect and can be utilized in a thermodynamic cycle or thermoelectrical unit [13]. Moreover, the UV spectrum contains high energy photons and is suitable for a photo-thermal chemical reaction, producing solar fuel [14]. With selective mirrors the solar-to-electricity efficiency can be promoted to 30% under one sun illumination [15].

The selective mirror have problems when the conditions change. When the reaction temperature rises, the photochemical or thermochemical reaction may become more effective than the PV module. To maintain the system efficiency, different selective mirrors are required to reflect more sunlight to the reactor. In this situation, there may be much complexity for operation.

Another type of spectrum selector is the liquid spectral filter. Liquids such as water, ethylene glycol and heat transfer oils have special chemical bonds and function groups that absorb infrared light. Looser et al. [16] took experimental study on the absorption spectra of eligible pure liquids, suggesting the heat transfer oil as one of the most suitable liquid spectral filters. Furthermore, when nanoparticles are dispersed in a liquid to form a stable nanofluid, the absorption may further include visible or UV sunlight. A nanofluid is both a spectrum selector and volumetric absorber. To date, the research on nanofluid