Applied Energy 217 (2018) 303–313

Contents lists available at ScienceDirect

Applied Energy

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

Co-producing electricity and solar syngas by transmitting photovoltaics and solar thermochemical process

Wanjun Qu[a,b,1], Hui Hong[a,b,1,*], Qiang Li[c], Yimin Xuan[d,*]

[a] Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing 210094, China
[d] School of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

HIGHLIGHTS

- Solar cogeneration system co-producing electricity and solar syngas is described.
- Full-spectrum solar energy is both converted into electricity and solar syngas.
- Infrared spectrum is converted into chemical exergy of syngas rather than waste heat.
- Total solar utilization efficiency can reach about 55% by using this cogeneration.
- In contrast to stand-alone CPV, high-grade energy conversion is enhanced by 50%.

ARTICLE INFO

Keywords:
Transmitting photovoltaics
Solar syngas
Cascade utilization
Energy conversion

ABSTRACT

In this paper, a solar co-producing electricity and solar syngas is originally proposed through synergistically combining a solar photovoltaic process and a solar thermochemical process. A transmitting photovoltaics is adopted and enables the ultraviolet and visible spectra to be converted into electricity. The infrared spectrum penetrates through the transmitting photovoltaics and is converted into high-grade chemical exergy of solar syngas through thermochemical reaction, rather than being converted into waste heat. The energy conversion models of the transmitting photovoltaics and solar thermochemical reactor are described. The total efficiency of solar-to-both electricity and solar syngas can be achieved to 55%. Furthermore, the influence of the key parameters on the solar cogeneration system performance is disclosed, such as the cut-off wavelength, solar cell types and production ratio. Our results would be expected to provide a new pathway of cascade utilization of the concentrating sunlight according to the spectrum distribution.

1. Introduction

Climate change and sustainable development represent the global challenges for humankind [1]. The large-scale application of renewable energy is a means to provide access to reliable and ample supplies of all forms of energy while ensuring environmental sustainability. Since 2010, the world has added more solar photovoltaic (PV) capacity than in the previous four decades, and the PV's share of global electricity is expected to reach approximately 16% by 2050 [2].

For achieving large scale application of solar energy, the efficiency gains of the roadmap of CPV could significantly reduce the number of modules required for a given capacity, thereby reducing soft costs. In the electricity generation process of concentrating photovoltaics, the ultraviolet and visible spectra generally excite and generate electron-hole pair; in most cases, the infrared spectrum does not contribute to electricity generation and contributes to heating the photovoltaics. Dissipation of this heat should be performed to maintain a reasonable operation temperature condition of photovoltaics; otherwise, the efficiency of generating electricity is impaired. The concentrating photovoltaic/thermal CPV/T method offers a viable approach to maintain the low-temperature electricity generation condition of a photovoltaics. In addition, from the standpoint of energy utilization, the dissipated heat of a photovoltaics can also be further used to provide heating, cooling, desalination and other heating related applications for domestic and

* Corresponding authors at: Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China (H. Hong); School of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China (Y. Xuan).

E-mail addresses: honghui@iet.cn (H. Hong), ymxuan@nuaa.edu.cn (Y. Xuan).

[1] These authors contributed equally to this study and shared first authorship.

https://doi.org/10.1016/j.apenergy.2018.02.159
Received 7 December 2017; Received in revised form 8 February 2018; Accepted 23 February 2018
0306-2619/

industrial processes [3,4].

The CPV/T approach can be employed in a distributing energy supply system, in which the electricity generation and waste heat recovery can satisfy the energy demand of a domestic house. For example, Deng et al. [5] proposed a solar photovoltaic/thermal integrating heat pump system, in which the electricity efficiency of a photovoltaics could be maintained a high level via a reasonable temperature operation condition while providing 30–70 °C heating water. Xu et al. [6] studied a concentration photovoltaic/thermal module which can produce electricity and heat simultaneously in a simple and reliable way. The water can be heated above 55 °C, and then was directly applied for domestic or industrial utilization. Renno et al. [7] designed a CPV/T system including an absorption chiller, and the energy gain can satisfy the variable energy demands of a domestic house by suitably varying the main system variables. Buonomano et al. [8] deigned a model of solar heating and cooling system combining with concentrating photovoltaic thermal collector and auxiliary chiller. The simulation results showed that the demand of heating and cooling for building space can be economically met. Calise et al. [9] investigated the dynamic performance of this type of polygeneration system; the simulation revealed that the system allowed the house to be independent from the cooling, heating and electric demands over a whole year.

The CPV/T approach can provide heat and electricity for combined desalination of water and electricity generation in domestic and industrial processes. Elsafi [10] studied the air heated Humidification-Dehumidification-Humidification cycle for desalinating water, in which the both required heat and electricity of the desalination unit were provided by the CPV/T system. Moreover, the exergy-costing evaluation indicated that the air-heated desalinating water process based on the CPV/T system could be a very competitive option at small-scale. Mittlman et al. [11] proposed an integration system combining with a CPV/T and a multi-effect evaporation desalination. Simulation results shown that this type of CPV/T desalination was cost-effective by exploiting the waste heat of the photovoltaics to desalinate water. Ong et al. [12] presented a concept of heat energy reuse from CPV/T by employing a multi-effect membrane distillation system for desalination. Experimental results indicated that this co-generation of both electricity and fresh water was applicable for isolated inland or coastal regions with high solar irradiation.

The Organic Rankine cycle (ORC) [13] has been considered to be a suitable waste heat recovery system for the concentrating photovoltaic/thermal CPV/T, in which the low-temperature releasing heat of photovoltaics can be further converted into work. Tourkov et al. [14] examined the feasibility of a combined CPV/T and ORC. Many organic working fluids were investigated for obtaining the highest operating efficiency and meeting design criteria for expanders in ORC, in which alkanes were observed to have the greatest potential for high efficiency. Al-Nimr et al. [15] conducted a parametric analysis to investigate the effect of some key parameters on the total conversion performance; therein, the simulations showed that when the inlet turbine temperature was less than 61 °C, the increase of this temperature resulted in the increase of the overall efficiency.

In the aforementioned CPV/T systems, cogenerating such products as heating energy and electricity, the full solar spectrum utilization rate could be above 55%. There is approximately 15% of solar energy input that is converted into electricity, and approximately 40% of the incident solar energy is directly converted into recovery heat of photovoltaics [16]. In practice, from the standpoint of the quality of energy, there exists an irreversible loss. Although combined CPV/T and ORC generation offers an approach to explore the working potential of full-spectrum solar energy; the performance of the thermal cycle is lower in contrast to that in the solar power tower plant. Reducing the energy conversion of solar radiation into low-temperature waste heat of photovoltaics can realize a high-efficiency and high-grade solar energy conversion.

Combination with CPV/T system and chemical reaction can be as a pathway of cascade utilization of solar energy. Abdelhamid et al. [17,18] designed a double stage CPV/T collector. Therein, the lower energy photons are concentrated on the surface of absorber tube by a secondary concentrator and the maximum outlet temperature of absorber tube can reach about 360 °C. This temperature level of solar heat can be reused in pyrolysis process of biomass. Bicer et al. [19] constructed a concentrating photovoltaics and photonic hydrogen production application, in which the lower wavelength of the spectrum is directed to reactor for water splitting, and then the electricity and hydrogen acted as final solar products. As indicated in previous works, the mid-temperature solar thermochemical process was feasible, in which solar energy can be converted and stored in the solar syngas with high conversion efficiency. This process [20–22] can achieve conversion of solar radiation to solar syngas. Li et al. [23–25] proposed a hybrid solar PV-thermochemical exergy conversion device combining a photovoltaics and a methanol thermochemical reactor. The high efficiency and the flexibility in application scale could make the proposed device a promising means for effective solar energy utilization. Differing from the abovementioned CPV/T methods, the waste heat recovery was achieved using a thermochemical reaction, and the energy transfer process of solar radiation that was not converted into electricity was converted from sunlight to heat to solar syngas.

In this paper, we focus on the direct and efficient thermochemical conversion of the infrared spectrum and the high-efficiency electricity generation via conversion from the ultraviolet and visible spectra of solar light. A combined electricity and solar syngas generation is proposed to achieve better matching of full-spectrum solar energy conversion. The interactions are analyzed among cut-off wavelength, transmissivity of the transmitting photovoltaics, electricity efficiency of the transmitting photovoltaics and production of solar syngas. Finally, a method is proposed to explore the high-grade energy conversion of full solar spectrum.

2. Cogeneration system description and methodology

2.1. Description of the concentrated solar cogeneration system

Fig. 1 presents a schematic diagram of the full-spectrum solar energy conversion system, which primarily consists of a solar photovoltaic process and a solar thermochemical process.

2.1.1. In the solar photovoltaic process

The concentrated sunlight (full spectrum) first reaches the surface of transmitting photovoltaics, as shown in Fig. 1. A transmitting photovoltaics is adopted in this study. High-energy photons are absorbed by the excitation of an electron from a filled state in the valence band to an empty state in the conduction band, while low-energy photons pass through transmitting photovoltaics. The mechanism and feasibility of transmitting photovoltaics have been confirmed in the research of stacked tandem photovoltaics reported by Refs. [26,27]. As a result, the light in the ultraviolet and visible spectra excite and generate electron-hole pairs, and the light in the infrared spectrum passes through the transmitting photovoltaics. Finally, the electricity generated by light from the ultraviolet and visible solar radiation is dispatched to the grid. It is worth noting that part of solar energy from the ultraviolet and visible spectra is converted into waste heat caused by the inner recombination loss of photovoltaics. A cooling passage can be mounted beneath transmitting photovoltaics to collect this waste heat releasing from photovoltaics. For reutilizing the waste heat of photovoltaics, preheating the reactant of thermochemical reaction is a practical way.

2.1.2. In the solar thermochemical process

The transmitted infrared solar radiation reaches the surface of the solar thermochemical reactor and provides the heat for driving an endothermic reaction of hydrocarbon fuel. Based on the feedstock, the endothermic reaction of the hydrocarbon fuel can include cracking and