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EXPLORING THE POTENTIAL OF SOLAR FULL-SPECTRUM UTILIZATION WITH CONCENTRATED PHOTOCHEMICAL-PHOTOVOLTAIC-THERMOCHEMICAL (P-PV-T) SYSTEM

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ABSTRACT

Among various solar energy converting technologies, photovoltaic cells (PV) is the most widely used. However, the mismatch between the broad solar spectrum and the mono-energetic absorption of PV results in the non-absorption of photons with energy below the bandgap (*Eg*). Previous CPV-T systems were proposed to recycle the below *Eg* loss of PV. Another dominant loss, thermalization loss, could not be reduced in CPV-T systems. Moreover, CPV-T systems recycle all the energy loss as heat. In these systems, solar energy is converted to thermal energy firstly, which is further utilized to generate other products. Two converting processes increase the irreversible loss. In our opinion, the two different kinds of loss should not be treated equally without discrimination. So we proposed a solar cascade utilization system with concentrated photochemical-photovoltaic-thermochemical (CP-PV-T) processes to make the most use of the full spectrum of solar energy. The photons with energy far above *Eg* of PV are utilized in the photochemical process, and thus the thermalisation loss of PV cell is reduced. The below *Eg* loss of PV is recycled to provide heat for thermochemical process. Results show that the utilization rate of photon energy at the first 600 nm is increased to 80.68% from 44.01% with the addition of photochemical process in front of PV, and the total solar energy utilization efficiency of the proposed system is 64.24% on the design condition.

Keywords: solar energy; full spectrum; photochemical process; PV; thermochemical process

1. INTRODUCTION

With the rapid development of cities, the harvesting of sunlight for environmental remediation and traditional energy replacement has become more and more crucial. Among various solar energy converting technologies, photovoltaic cells (PV) have drawn much attention due to the fact that the product, i.e., electricity, is widely used. According to the research results from International Energy Agency (IEA), the electricity generated by PV is expected to account for 16% of the global electricity load by 2050. Concentrated photovoltaic technologies (CPV) are proposed to increase the electricity efficiency of per unit cell (in terms of %/cm2) and to reduce the life-cycle costing. The fundamental principle is that higher solar flux density is received in per photovoltaic cell, because optical collectors, such as mirrors and lenses, concentrate solar beams onto a small area. More electricity could be generated in per unit cell. In other words, less photovoltaic cells are needed with the same electricity load. The life-cycle costing is reduced by reducing the cell area, replacing the expensive solar cells with inexpensive optical collectors and tracking systems.

It is noteworthy that photovoltaic cells could convert only a small fraction of the full spectrum of solar energy into electricity. The fraction depends on the types of cells, because they have different spectral responses. The absorbed solar irradiation outside this spectral range is dissipated as heat, causing temperature increasing. Elevated temperature will put stress on material, and result in the decrease of solar-

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to-electricity efficiency. The decrease rate is -0.45%/℃ for typically polycrystalline (pc-Si) and monocrystalline silicon (c-Si) solar cells [1]. The effect is less for amorphous silicon (a-Si) cells, with the decrease rate of -0.25%/℃ depending on the module design [2]. The temperature-dependent efficiency decline becomes severity in CPV systems which always operate at elevated solar concentration level. To decrease the temperature of the photovoltaic cells, we should extract the dissipated heat from cells.

The heat extracted from cells could be further leveraged by integrating thermal systems with the photovoltaic cells, so the concept of photovoltaic-thermal (PV-T) systems is proposed. Researches in the PV-T could be traced back to 1970s [3, 4]. In the early years, researches mainly focused on conventional flat-plate PV-T system. They usually installed the thermal collectors on the backside of the silicon PV panels. The thermal collectors could not only serve as a cooling channel of solar cells, but also could recycle the heat for further utilization, such as domestic hot water or space heating. It is quite practical, especially for integrating with building rooftop and façade [5].

However, it suffers from the fact that the thermal medium must be kept well insulated to avoid heat losses. A further development of this technique is solar driven thermally activated reactions, such as cracking of methane. But the flat-plate PV-T systems could only generate low-temperature heat (lower than 100℃), which limit applications to some extent. As an alternative, the concentrated photovoltaic-thermal system (CPV-T) was studied by O'leary and Clements in 1980s [6]. Concentrators could increase the solar irradiation density on the PV surface, and improve the temperature of the heat in thermal subsystem as well. Besides the superiority of CPV, there are two other advantages for CPV-T. For photovoltaic subsystem, since the area of solar cells is reduced, more expensive III-V multi-junction cells could be adopted to achieve higher solar-to-electricity efficiency (14%–20% for commercial silicon cells and 25%–30% for commercial III-V multi-junction cells [7], 46.0% for laboratory III–V multi-junction solar cells [8]). For the thermal subsystem, higher temperature heat could be obtained, expanding its application scope. For example, the thermal subsystem could provide cooling for domestic houses by integrating an absorption chiller with photovoltaic cells. Some researchers used nanoparticles in heat transfer fluids to obtain higher temperature heat (up to 300℃) for providing process heat for industry or distributed generation [9]. The dissipated heat could also be utilized to generate electricity to improve the overall solar-to-electricity efficiency. For instance, the dissipated heat is recycled for organic Rankine cycle (ORC) to be further converted into electricity [10]. According to the simulation results by Kosmadakis, the efficiency was increased to 11.83% from 9.81% [11]. The relative low efficiency is derived mainly from the low temperature heat source for ORC (~140℃), and the cell efficiency of Si here is 12% at 25℃. Moreover, thermoelectric (TE) converter could also be attached into the backside of the photovoltaic. The previous research results show that integrating a TE converter with a GaAs cell with 50X solar concentration ratio could theoretically contribute an extra 6% efficiency and increase the overall solar-to-electricity efficiency to about 30% [12]. The dissipated heat could also desalinate seawater and provide heat for thermochemical reaction and so on.

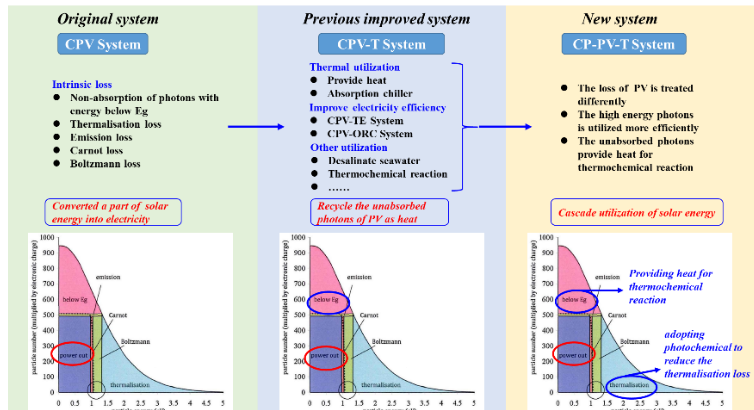

Fig. 1 Existing systems and the problem the proposed system aims to solve.

However, most of existing CPV-T systems only exploit unabsorbed photons with energy below the bandgap (i.e., below *Eg* loss). The photons with energy far above *Eg* introduce thermalization loss as carriers cool to the bandgap edge, which is also the dominant loss of PV. Increasing the number of absorbers in a multi-junction device can decrease the thermalization loss and below *Eg* loss, but most PV cells are single junction and the junctions of all PV cells are less than four. Some systems recycle all the dissipated heat. But in all the thermal subsystem in CPV-T systems, solar energy is converted into heat firstly, which is further utilized to drive various thermal processes, such as absorption chiller, ORC, TE, etc. Two converting processes lead to the increase of irreversible loss. In our opinion, the untapped photons should not be treated equally without discrimination. So we proposed a solar cascade utilization system with concentrated photochemical-photovoltaic-thermochemical (CP-PV-T) processes to make the most use of the full spectrum of solar energy. The basic principle is that photons with high photonic energy (short wavelength) are converted to chemical energy by photochemical process, photons with middle photonic energy are converted to electricity by PV, and photons with low photonic energy (long wavelength) are converted to chemical energy by thermochemical process. In this paper, photo-induced molecular isomerization is chosen in the photochemical process, conventional Si is used as a case study in PV process, and methanol decomposition reaction is used in the thermochemical process.

2. **PROPOSED SYSTEM AND METHODOLOGY**

2.1 Solar full-spectrum utilization system

Previous CPV-T systems were proposed to recycle the below *Eg* loss of PV. Another dominant loss thermalization loss could not be reduced in CPV-T systems. Moreover, the thermal subsystem in CPV-T systems recycle all the energy loss as heat. In these systems, solar energy is converted to thermal energy firstly, which is further utilized to generate other products. Two converting processes increase the irreversible loss. To address these problems, the CP-PV-T system is proposed to realize the cascade utilization of solar energy.

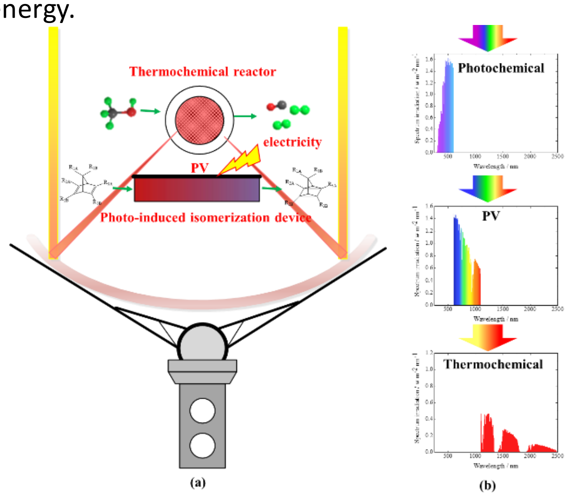

Fig. 2 (a) Sketch of the CP-PV-T system (b) Sketch of the cascade utilization of sunlight.

The CP-PV-T system consists of four main parts, i.e., a parabolic trough collector, a photon-induced isomerization device, PV cell and a thermochemical reactor. Sunlight is concentrated by the parabolic trough collectors. The concentrated light is incident upon the photon-induced isomerization device. The reactants, i.e., norbornadiene derivatives (NBDs), in the device absorb high energetic photons, to be converted to the related structural isomers, i.e., quadricyclane (QCs). Simultaneously, the high energetic photons are stored in the chemical bonds of QCs. The rest of sunlight is transmitted to the PV cell, which can adsorb the photons with energy above *Eg*. This part of solar energy is converted to electricity in PV cell. The thermalisation loss of PV cell is reduced because the photons with energy far above bandgap are adsorbed by the reactants in the photochemical process. The photons with energy below *Eg* are utilized in the thermochemical process, providing heat for methanol decomposition. Methanol is decomposed into CO and H_2, and the rest part of solar energy is stored in the products.

A CP-PV-T system is proposed to realize the cascade utilization of the full spectrum of solar energy efficiently. The advantages of the proposed system are summarized as follows.

(1) The system can use the full spectrum of solar energy. The photons with energy above *Eg* are utilized in the photochemical process or PV cell, and the photons with energy below *Eg* provide heat in the thermochemical process.

(2) The system realizes the cascade utilization of solar energy. In existing CPV-T systems, the energy that cannot be used in the PV cell all be recycled to provide heat for other thermal subsystems, such as absorbed chiller, ORC, TE and so on. This treat increases irreversible loss due to two converting processes in these systems. Different from previous systems, the dominant losses of PV are reduced in different ways. The photons with energy far above *Eg* of PV cell are utilized in the photochemical process, and thus the thermalisation loss of PV cell is reduced. The below *Eg* loss of PV cell is recycled to provide heat for methanol decomposition.

(3) The products of the system are all in high energy level, and the products can be easily transported. The high energetic photons are stored in the form of chemical bonds. The middle energetic photons are converted into electricity. The photons with energy below *Eg* are stored in the chemical energy of syngas (CO and H_2).

(4) The system is environmentally friendly. Solar energy is the main energy input of this system. Moreover, there is no CO_2 emission in the photochemical process and PV cell, and there is little CO_2 emission in the thermochemical process.

2.2 Calculating model

The energy flow and matter flow of the system are shown in Fig. 3. It can be seen that the full-spectrum solar energy is incident to the system, and it is concentrated by the parabolic trough collectors. The concentrated light is adsorbed by the photochemical process, PV cell and thermochemical process in turn. The energy input of the system is only solar energy and the matter input is only methanol. The products are energy stored in the chemical bonds of photo-isomers in the photochemical process, electricity and syngas. It can be concluded from the matter flow that the reactants and photo-isomers in the photochemical process are isomerized to each other by internal rearrangement, which is an internal reaction. There is no matter flowing into or out of the photochemical system. The heat loss in the photochemical process, and the Joule heat in PV cell are recycled by the heat exchanger to provide thermal energy for thermochemical reaction.

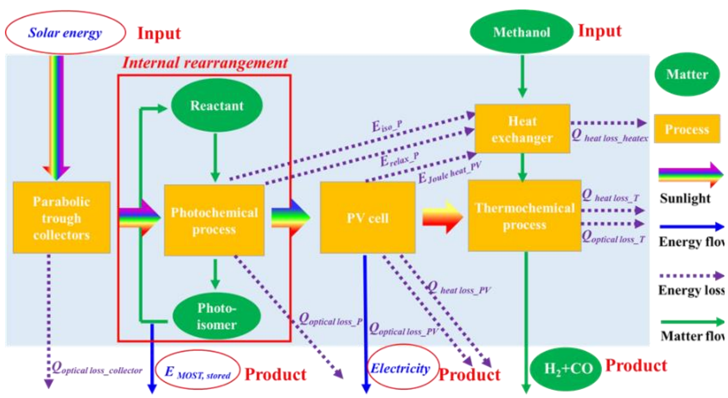

Fig. 3 Energy flow and matter flow of the system.

3. RESULTS AND DISCUSSION

Figure 4 compares the efficiency of photon energy utilization between the photochemical process and photovoltaic process. In figure 4, the higher the photon energy is, the lower the photon utilization rate will be in the photochemical and photovoltaic processes, because the energy that is higher than the bandgap energy is dissipated as heat in the both processes. For photons with photon energy higher than *Eg*, the utilization rate in photochemical process is greater than that of the photovoltaic process. It can be concluded that adding photochemistry process in front of PV cells can enhance the utilization rate of photons, further to improve the utilization rate of solar energy.

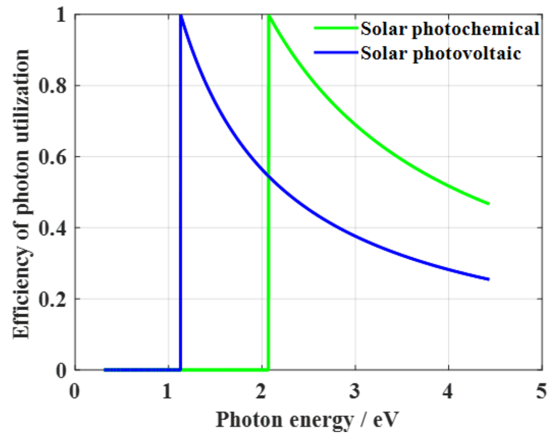

Fig. 4 Comparison of photon utilization efficiency between solar photochemical process and solar photovoltaic cells.

Figure 5 compares solar energy utilization by photochemistry and photovoltaic cells at different wavelengths. In Figure 5, the red line represents the change of solar energy with wavelength at AM1.5, the green line is the solar energy utilized by photochemical process, and the blue line stands for the solar energy utilized through photovoltaic cells. It can be concluded that the energy stored by photochemical process is always higher than the electricity generated by photovoltaic cells in the first 600 nm. The utilization rate of photon energy at the first 600 nm is increased to 80.68% (photochemistry) from 44.01% (PV) with the addition of photochemical energy storage process.

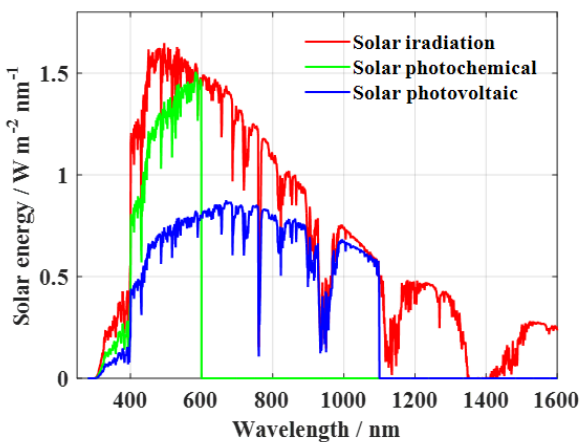

Fig. 5 The comparison of the utilization of solar energy between solar photochemical process and solar photovoltaic cells.

Figure 6 shows the energy sankey diagram of the proposed system on the design condition. As shown in Figure 6, 7.98% and 42.82% of incident solar energy are stored by photochemical process and thermochemical process, respectively. The photovoltaic cell efficiency is 13.44%. The optical loss and heat loss in thermochemical reactor account for the largest of all losses, and the total utilization efficiency of solar energy is 64.24%.

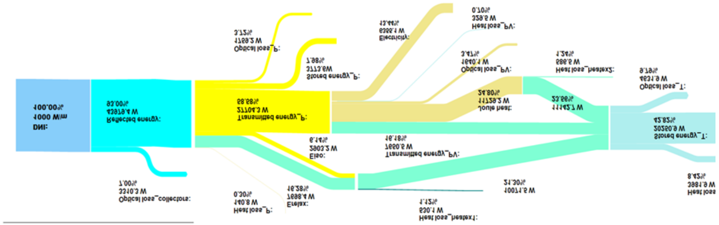

Fig. 6 Energy flow of the proposed system.

4. CONCLUSIONS

The CP-PV-T system is proposed to realize the cascade utilization of the full spectrum of solar energy efficiently. The main research outcomes are summarized as follows.

(1) The system realizes the cascade utilization of the full spectrum of solar energy. The photons with energy far above *Eg* of PV are utilized in the photochemical process, and thus the thermalisation loss of PV is reduced. The below *Eg* loss of PV cell is recycled to provide heat for methanol decomposition.

(2) The utilization rate of photon energy at the first 600 nm is increased to 80.68% from 44.01% with the addition of photochemical energy storage process in front of PV.

(3) The total utilization efficiency of solar energy in the proposed system is 64.24% on the design condition.

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REFERENCE

[1] Looser R, Vivar M, Everett V. Spectral characterisation and long-term performance analysis of various commercial Heat Transfer Fluids (HTF) as Direct-Absorption Filters for CPV-T beam-splitting applications. Appl Energ 2014;113:1496-511.

[2] Kalogirou SA, Tripanagnostopoulos Y. Hybrid PV/T solar systems for domestic hot water and electricity production. Energy Conversion and Management 2006;47:3368-82.

[3] Wolf M. Performance analyses of combined heating and photovoltaic power systems for residences. Energy Conversion;16:79-90.

[4] W. FL. Extension of the hottel-whillier model to the analysis of combined photovoltaic/thermal flat plate collectors. Solar Energy 1979;22:361-6.

[5] Chemisana D. Building Integrated Concentrating Photovoltaics: A review. Renewable and Sustainable Energy Reviews 2011;15:603-11.

[6] J.; OM, L DC. Thermal-electric performance analysis for actively cooled, concentrating photovoltaic systems. Solar Energy 1980;25:401-6.

[7] R. WS, A. GM, E. WM, R. C, A. S. Applied photovoltaics: Routledge; 2013.

[8] Kribus; A, Mittelman G. Potential of polygeneration with solar thermal and Photovoltaic Systems. J Sol Energ 2008;130:11001-5.

[9] Otanicar T, Dale J, Orosz M, Brekke N, DeJarnette D, Tunkara E, Roberts K, Harikumar P. Experimental evaluation of a prototype hybrid CPV/T system utilizing a nanoparticle fluid absorber at elevated temperatures. Appl Energ 2018;228:1531-9.

[10] Rahbar K, Riasi A, Khatam Bolouri Sangjoeei H, Razmjoo N. Heat recovery of nano-fluid based concentrating Photovoltaic Thermal (CPV/T) Collector with Organic Rankine Cycle. Energy Conversion and Management 2019;179:373-96.

[11] Kosmadakis G, Manolakos D, Papadakis G. Simulation and economic analysis of a CPV/thermal system coupled with an organic Rankine cycle for increased power generation. Solar Energy 2011;85:308-24.

[12] Analysis of Potential Conversion Efficiency of a Solar Hybrid System With High-Temperature Stage.