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# Performance analysis of a solar-powered solid state heat engine for electricity generation

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ABSTRACT

A hybrid system consisting of a CPC (compound parabolic collector) system, a SOE (solid oxide electrolyzer) system and a PEMFC (proton exchange membrane fuel cell) system was proposed to harvest solar energy. And a sensitivity analysis was conducted to evaluate the system performance. The impacts of operating temperatures of the SOE and PEMFC system, and the direct irradiation intensity of the sun on the performance characteristics were systematically analyzed. Results revealed that there exists an optimal SOE operating temperature leading to the maximum power output and maximum electrical efficiency simultaneously. Larger operating temperature of the PEMFC resulted in larger power output and higher efficiency. There also existed optimal direct irradiation intensities leading to the maximum power output and maximum electrical efficiency. Furthermore, the performance of the proposed solar energy harvesting system for practical use in real-life was also simulated. This may serve a clean technology for electricity generation.



## 1. Introduction

The environmental pollution and global warming due to the depletion of fossil fuels have attracted rising attention. The adverse exhaust such as sulfur oxides, particles (PM 2.5) has caused severe catastrophe for human beings and the nature. Clean and sustainable technologies for generating electricity, substituting the coal/oil-based plant offer methods to relieve such issues. Solar energy is a clean and nearly inexhaustible energy, and has been utilized in many applications, i.e. supplying hot water, generating electricity.

Photovoltaic conversion is the direct conversion of the sunlight into electricity without any heat engine to interfere. They are widely used for power sources, water pumping, remote building, solar home systems, and satellites. A photovoltaic power generation system consists of multiple components like cells, mechanical and electrical connections. The peak power output varies in size from a few kW for residential purpose to solar power stations up to tens of GW [1]. However the electrical efficiency is usually about 14%–19% for commercially available multi-crystalline silicon solar cells. Many technologies have been invented to improve the electrical efficiency such as organic and polymer cells [2,3], hybrid photovoltaic cell [4] and thin film technology [5]. The state-of-art solar cells achieve an efficiency over 19%. But the cost is much higher, and in present is not practical for industrial applications.

Another way for solar energy utilization is that combining solar heating system and traditional thermodynamic cycles. The CPC (compound parabolic collector) system provides an efficient way for collecting solar energy to produce high temperature thermal energy [6]. The bottom installations based on Stirling engine [7], Steam Rankine cycle [8], or organic Rankine cycle [9] absorb heat from the CPC system and generate electricity. The traditional thermodynamic cycles involves moving parts. The maintenance is kind of complicity. And the stability cannot be guaranteed. Solid state heat engines could relieve such problem. The core technology is to explore a thermodynamic cycle as a heat engine based on electrochemical processes. The TREC (thermally regenerative electrochemical cycle) where net energy is produced by the voltage difference that originates from heat absorbed at the higher temperature, shows an efficiency of 40–50% of the Carnot limit for high-temperature applications [10]. Ericsson pyroelectric cycle, which consists of two isothermal and two isoelectric processes is also investigated [11,12]. Another technology is the regenerative fuel cell which consists of an hydrogen producing system and a fuel cell system [13]. Acetone can be thermally decomposed at 400 °C to release hydrogen which is cooled to 100 °C for use in a polymer electrolyte fuel cell. The reaction product is again acetone, such that

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the system creates electric power from the acetone decomposition/recombination occurring respectively at the hot and cold reservoirs [14]. Besides water can be decomposed into hydrogen and oxygen which react electrochemically and water is reproduced. Hybrid electricity generating systems based on regenerator $H_2/O_2$ fuel cells have been also conceived [15,16]. In above systems, electricity need to split water should be supplied by external source. And photovoltaic systems have been widely explored to meet this demand [17–19].

Based on the fact that most of the aforementioned regenerative fuel cells involves external electricity and the photovoltaic systems can supply that electricity, the cost is much higher. Here we adopted a new solid state heat engine to convert the solar energy into electricity [14]. The solid state heat engine consists of a SOE (solid oxide electrolyzer) and a PEMFC (proton exchange membrane fuel cell) system. In the SOE system water is decomposed into hydrogen and oxygen while heat and electricity are supplied. In the PEMFC, the hydrogen and oxygen from the SOE react electrochemically. Meanwhile the electricity is generated, some of which support the SOE system, the other could be used to do external work (net power output). Therefore no external electricity is need. Besides, the heat maintain normal operation of the SOE system comes from a CPC system. In all, the hybrid system converts solar energy into electricity.

Recently several generic system-level concepts for the solar collecting system, solid oxide electrolyzer system and the proton exchange membrane fuel cell have been present in sufficiently specific detail to enable a systematical analysis on the proposed solar-powered solid state heat engine. In this paper, the analysis is conducted based on semi-empirical models of the CPC, SOE and PEMFC systems. The operating conditions of the solid heat engine on the performance of the proposed solar energy harvesting system have been analyzed. Furthermore, the sun's impact on the overall electrical efficiency has also been considered. And for practical simulation, the relation of the net power output with time in one day is also investigated. This paper may serve as a guidance for designing solar energy utilizing systems.

## 2. System description

The schematic figure of the solar-powered solid-state heat engine is present in Fig. 1. The hybrid system consists of a CPC system, a SOE and a PEMFC system. Both the SOE and PEMFC also function as heat exchangers, thereby they can exchange heat with external heat source. The solar collector is chosen to supply thermal energy to the SOE system for its high collection temperature and intermittent sun-tracking. The thermal oil is heated to high temperature, and then goes to the SOE system, where the water cycled from the PEMFC system absorb heat from the CPC system and electrical power from the PEMFC system, then is split into hydrogen and oxygen. The gases produced (hydrogen and oxygen) then flow into the PEMFC system, where they react electrochemically and the electricity is generated. The electrical potential is sufficient to drive the SOE system, and produce external work as shown in Fig. 2. Furthermore, in order to enhance the efficiency, a regenerator is applied to heat the water produced in the PEMFC, which react electrochemically in the SOE system.

### 2.1. CPC model

Neglecting the work loss due to the pump, the collected energy rate from a single collector is

$$\dot{Q}_r = \dot{m}_{oil} c_{p,oil} (T_1 - T_2) \tag{1}$$

where $c_{p,oil}$ is the specific heat of the oil; $\dot{m}_{oil}$ is the mass flow rate in the receiver; $T_1$ and $T_2$ are receiver inlet and outlet temperatures. The collected energy rate $\dot{Q}_r$ can be also calculated as

$$\dot{Q}_r = F_R A_{ap} \left[ S - \frac{A_r}{A_{ap}} U_L (T_{ro} - T_0) \right] \tag{2}$$

where $F_R$ is the heat removal factor; $A_{ap}$ is the aperture area; $A_r$ is the receiver area; $U_L$ is the solar collector overall heat loss coefficient. $S$ is the effective flux absorbed by the receiver, which is given by Refs. [20];

$$S = G_b \tau \rho_c \alpha \gamma K_\gamma \tag{3}$$

where $G_b$ is the direct irradiation intensity; and $\rho_c$, $\gamma$, $\tau$, $\alpha$, $K_\gamma$ are the reflectance of the mirror, intercept factor, transmittance of the glass cover, absorbance of the receiver, and incidence angle modifier, respectively.

The heat removal factor can be expressed as

$$F_R = \frac{\dot{m}_{oil} c_{p,oil}}{A_r U_{lo}} \left[ 1 - exp\left( \frac{-F' U_L A_r}{\dot{m}_{oil} c_{p,oil}} \right) \right] \tag{4}$$

where $F'$ is the collector efficiency factor.

The total amount of solar irradiation that shines upon the collector, denoting the heat into the system, is defined as

$$\dot{Q}_{solar} = A_{ap} F_R S Col_r Col_s \tag{5}$$

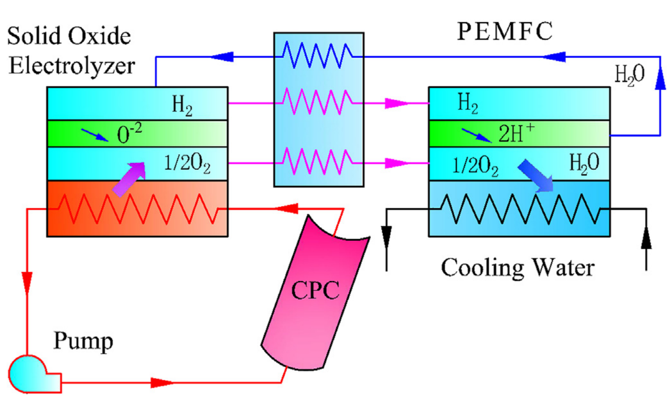


**Fig. 1.** Schematic diagram of the solar-powered electricity generation system.

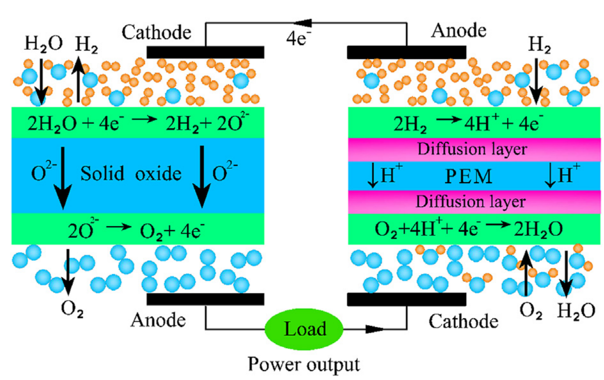


**Fig. 2.** Schematic diagram of the solid state heat engine consisting of SOE and PEMFC systems.