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Thermodynamic analyses of a solar-hydrogen energy system based on SBS PV-T and SOEC/SOFC technologies

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ABSTRACT

Spectral-beam splitting (SBS) hybrid photovoltaic-thermal (PV-T) collectors are able to generate, from the same aperture area, both electricity and thermal energy, at a temperature high enough to make this useful in a wide range of applications. This is a promising technology, especially in area-constrained environments, as it can achieve very high overall (electrical plus thermal) efficiencies. Combining SBS PV-T collectors with reversible solid oxide electronic cell/solid oxide fuel cell (SOEC/SOFC) systems can help address the intermittent nature of the solar resource, since the collected solar energy by the SBS PV-T collectors can be converted to and stored as hydrogen by the SOEC module. If and when needed, the hydrogen can later be converted back to electricity by the SOFC module. In this paper, we present numerical models that has been developed for the SBS PV-T collector and SOEC/SOFC system. Parametric analyses based on these models have been performed in order to identity operational characteristics and optimal designs, looking to integrated systems that maximize overall energy efficiency. It is found that the water vapor temperature and flow rate through the SOEC/SOFC module are crucial for the performance of this component, but that this leads to a reduced SBS PV-T collector thermal efficiency. Based on the results, we propose a novel hybrid solar-hydrogen system concept that involves combining SBS PV-T collectors, a Rankine cycle engine and a reversible SOEC/SOFC module.

KEY WORDS: energy efficiency, fuel cell, photovoltaic-thermal, spectral-beam splitting

1. INTRODUCTION

Global economic development continues to drive an increase in the world's demand for energy. Global primary energy consumption grew by 2.9% in 2018, nearly double the average growth rate (1.5%) over the past decade, and the highest growth rate since 2010. At the same time, carbon emissions increased by 2% in 2018, the highest growth rate over the past seven years. Clean, low-carbon, and renewable energy have become important transformation directions for future energy systems. In 2018, the world's renewable energy generated a total of 2480 TWh, at an annual growth of 14.5%, of which wind power generated 1270 TWh and solar power generated 590 TWh, with annual growth rates of 12.6% and 28.9%, respectively [1].

High costs remain a major barrier for the wider uptake of solar technologies [2,3], and in this context, improving the efficiency of solar energy utilization efficiency appears as an important solution [4,5]. In addition, the time-varying ('intermittent') nature of the solar energy resource, as well as any mismatch between generation and demand, are obstacles that act to increase the required installation areas and to introduce requirements for energy storage capacity, both which act to increase system cost and complexity. Therefore, it becomes crucial to propose high-efficiency, low-cost solar-energy generation systems that are able to deliver useful power and

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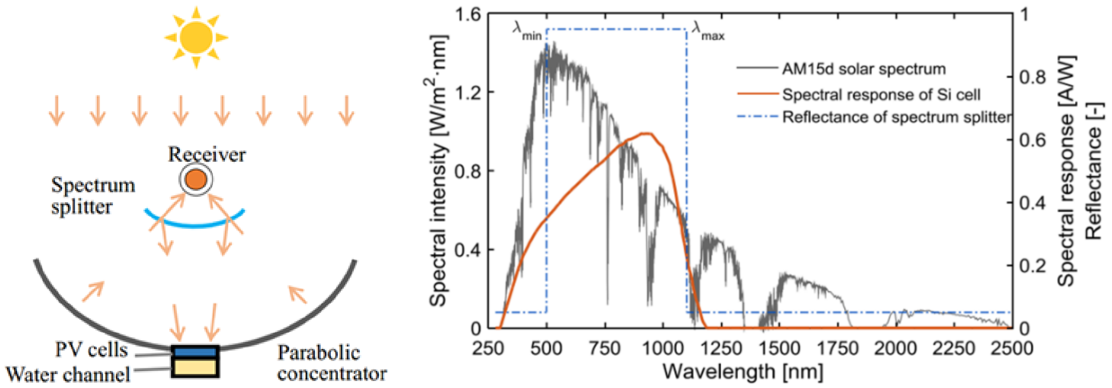
heat across a range of sectors (domestic, commercial, industrial, etc.) [6-8]. In this paper, we purpose and examine a new solar-hydrogen energy system based on SBS PV-T collectors and SOEC/SOFC modules.

2. SYSTEM DESCRIPTION AND METHODOLOGY

2.1 SBS PV-T collector: The design of the proposed SBS PV-T collector is shown in Figure 1. Sunlight with wavelengths between $\lambda_{\min}$ and $\lambda_{\max}$ is reflected by the spectrum splitter and received by the PV cells. The remaining part of the incident sunlight is received by the receiver after being projected by the spectral separator. The receiver uses high-pressure water vapor as the working medium. The water channel below the PV is used to keep the PV cells at a low working temperature, in order to ensure a high electrical efficiency from the cells.



(a) (b)

Figure 1: (a) Geometrical design, and (b) spectral design of the SBS PV-T collectors.

Figure 2 shows the structure of a PV receiver in more detail. Energy conservation equations and heat transfer relations are used to describe the distribution of temperature perpendicular to the surface of the receiver [9-11]. The temperature of the PV layer will directly affect its conversion efficiency. Our simulation results indicate that the PV electrical efficiency is 18.1% at an operating temperature of 362 K. The thermal efficiency of the receiver depends on the temperature of its thermal output, which is coupled to the SOEC/SOFC module; of particular note is that our model estimates show that this temperature is sufficient to drive the module (Section 3).

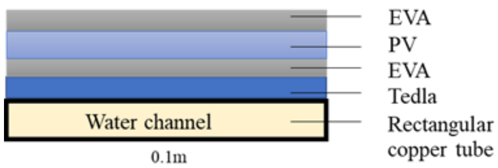


Figure 2: Structure of the PV receiver.

2.2 SOEC/SOFC module: Figure 3 shows the design of SOEC module proposed in this study, which can split (electrolyze) high-temperature water vapor into streams of hydrogen and oxygen. This device can also be run in reverse as a fuel cell [12-15]. The hydrogen can be then stored or delivered downstream of the module.

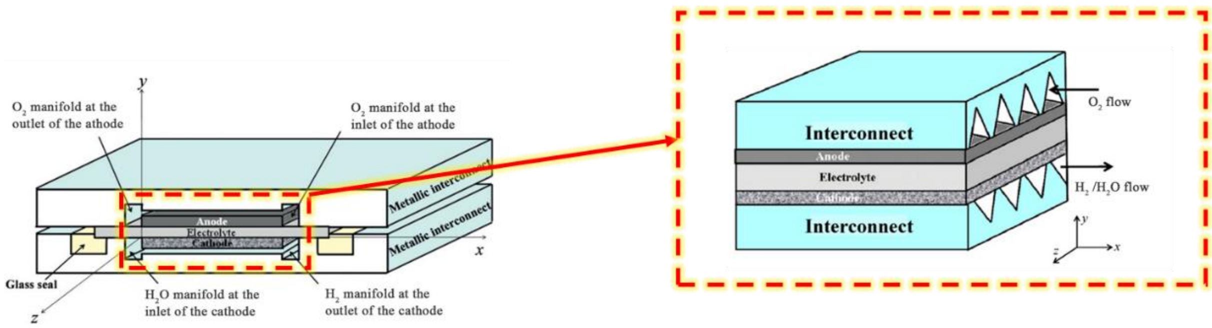
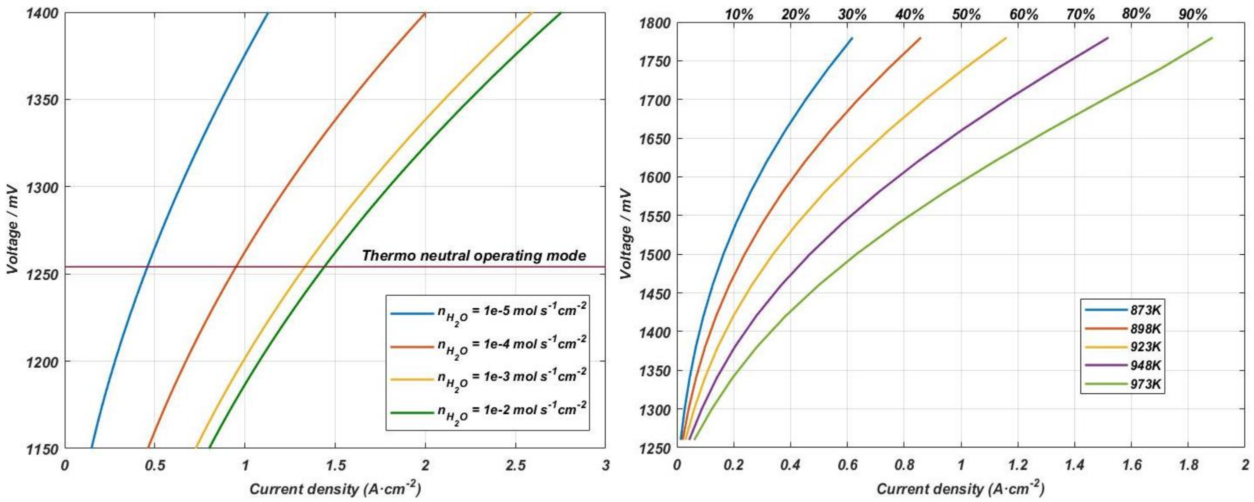


Figure 3: Design details of the reversible SOEC/SOFC system as proposed in this work.

3. RESULTS AND DISCUSSION

We now turn to the key results of this present study. The influence of the water vapor flow rate through the reversible SOEC/SOFC module on the performance of the module are shown in Figure 4a. It can be seen from this plot that, for a given voltage, the current density increases as the flow rate increases, leading to a higher conversion efficiency. However, a larger flow rate is not conducive to the separation of hydrogen.

The temperature of the water vapor is another key parameter that controls the operation and performance of the SOEC/SOFC module. It can be seen from this plot that, again for a given voltage, increasing the operating temperature significantly increases the current density as shown in Figure 4b, thus improving the module's conversion efficiency. However, a higher operating temperature requirement for this flow also requires a higher temperature and lower thermal efficiency in the SBS PV-T collector, which suggests a non-trivial trade-off between the performance of the collector and that of the SOEC/SOFC module.



(a) (b)

Figure 4. Evolution of cell voltage with current density for different: (a) water vapor flow rates (P_{Total} = 1 atm, T = 1073 K), and (b) water vapor temperatures (P_{Total} = 1 atm, $n_{\text{H2O}} = n_{\text{H2}} = 1\times10^{-5}$ mol.s^{-1}.cm^{-2}), as per the legends.

4. CONCLUSION AND FUTURE WORK

In this study, we developed thermodynamic and electrochemical models of a SBS PV-T collector design and a SOEC/SOFC module design in order to consider how these would operate and perform in an integrated system for solar-hydrogen generation. The PV module in the PV-T collector is able to deliver electricity at a high efficiency owing to SBS technology. Furthermore, the thermal absorber of the SBS PV-T collector is shown to be able to generate thermal-energy at a high enough temperature to drive the SOEC/SOFC module downstream. Simulation results show that the water vapor pressure, temperature and flow rate through the SOEC/SOFC module need to be carefully controlled in order to maximize the performance of this component, and can have a significant influence on the conversion efficiency (to hydrogen). Specifically, increasing the operating temperature of a module improves its conversion efficiency, but also leads to a requirement for a higher-temperature thermal output from the SBS PV-T collector, lowering this component's thermal efficiency and leading to trade-off between the performance of the collector and that of the SOEC/SOFC module.

Based on this insight, we proceed to propose the novel solar-generation system shown in Figure 5, which is mainly composed of SBS PV-T collectors, a reversible SOEC/SOFC module, and a Rankine cycle power sub-system. In this system, part of the high-temperature heat that is generated in the SBS PV-T collector field is sent to and used to generate electricity by the Rankine cycle sub-system, while the rest is applied for hydrogen generation by the SOEC/SOFC module. The waste heat of the hydrogen and oxygen is then recycled by a steam generation module. A system-level simulation is now proposed, along with outdoor tests [16]. The proposed hybrid solar-hydrogen system can be an interesting integrated energy generation and storage solution for off-grid distributed applications.

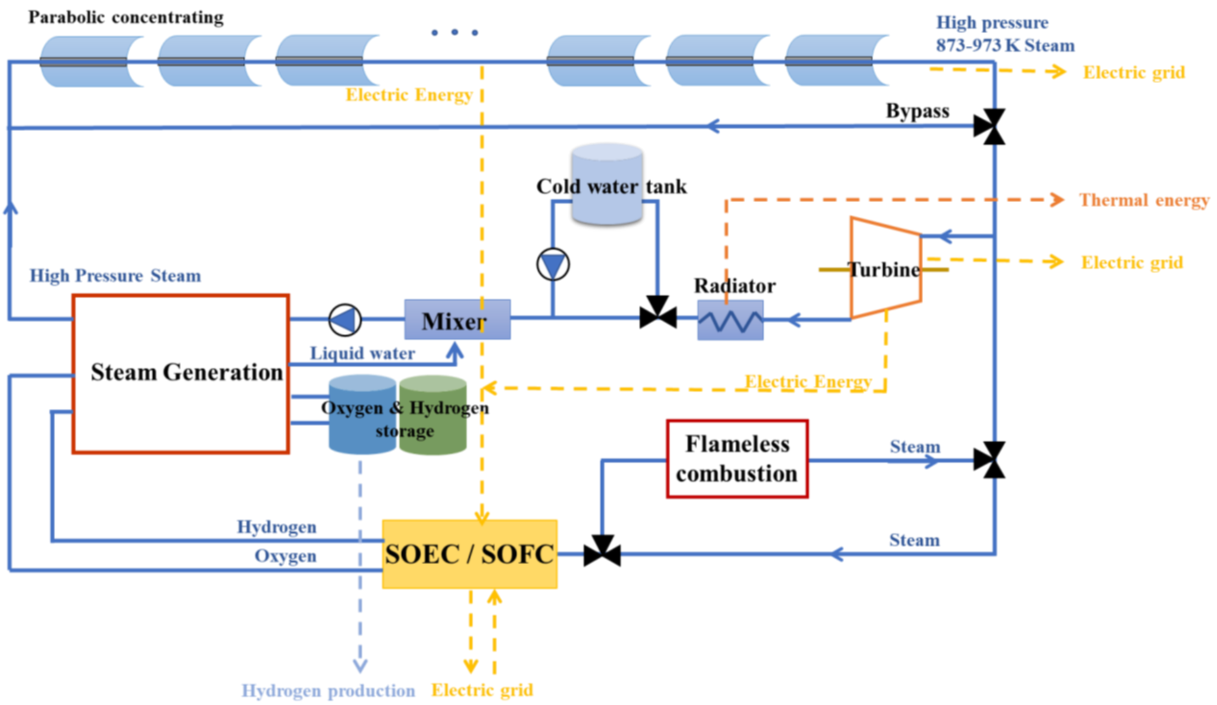


Figure 5: Proposed concept of novel solar system.

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