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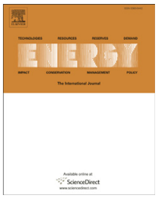

Optimized spectral splitting in thermo-photovoltaic system for maximum conversion efficiency

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Frequency conversion of the solar spectrum in thermo-photovoltaic systems improves the sunlight conversion efficiency by two means: moving the photovoltaic conversion to a different spectrum with better response, and the ability to recycle the frequency converted photons that exhibit insufficient conversion efficiency. In this work a theoretical optimization of the thermo-photovoltaic system was attempted in order to reach maximum conversion efficiency by an optimal choice of the emitter's operating temperature and the pass band wavelengths of the optical filter that is used to reflect the inefficient frequency converted photons back to the absorber-emitter unit to be recycled. We report that our optimization model, which accounts for the power leakage from the recycling process and the thermalization losses that associate the photovoltaic conversion, predicts for promising conversion efficiencies of sunlight to electricity which is as high as 44.3% for a thermo-photovoltaic system that employs absorber-emitter unit with 70% photon recycling efficiency and photovoltaic cell with 1.6 μm cutoff wavelength and is optimized at emitter's temperature of 3045 K and optical filter passband of (0.626–1.6 μm).

1. Introduction

Solar conversion to electricity is realized by different approaches. The photovoltaic PV cells present the most elegant method since no steam, moving parts, noise and pollution are involved. Nevertheless, the low conversion efficiency and the high cost of the PV cells limit their global deployment as a reliable source for energy. Solar concentrators can be used in order to control the cost issue. Nevertheless, high concentration causes undesired heating for the cell, which may cause degradation, low conversion efficiency or even damaging the PV system [1].

There are different reasons for the PV cell heating; one major factor is the thermalization process that comes from the photo-induced hot electors which dissipate their excess energy as heat inside the cell. Usually, hot electrons are produced by the absorption of shorter wavelength photons that are below the cell's cutoff wavelength λ_G, which corresponds to the bandgap energy of the cell. Therefore, in order to limit the thermalization, only photons with wavelength lower than λ_G, but sufficiently close, are allowed to take place in the photovoltaic conversion. Whereas, photons which exhibits relatively high thermalization and photons with longer wavelengths than λ_G could be either spectrally split and utilized differently [2–4]; or be recycled through a frequency convertor device, which is basically what the thermo-photovoltaic TPV system do. In the TPV the concentrated sunlight (or it can be any source of heat from fossil fuels or nuclear heat waste) is directed onto an absorber-emitter unit to reach high temperatures and emits a temperature-dependent power that is governed by the physics of the black body radiation. Therefore, the solar spectrum is frequency converted to different spectra that belongs to a cooler emitter than the sun surface 5800 K. For practical TPV system the operating temperature of the absorber-emitter should be below the melting temperature of the emitter's material; tungsten presents good choice for the emitter's material with melting point of 3695 K.

Interestingly, the concepts of spectral splitting and photon recycling in TPV systems were introduced first in the early 1960's [5], and gained special attention in the last decade because of advances in material science and photonic crystals technologies which realizes effective spectral control of the emitter's power. Different configurations and designs were proposed and tested in order to reach higher conversion efficiencies. Harder and Wűrfel optimized the operation of the TPV only from thermodynamic point of view [6]; their work resulted in defining the upper

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theoretical limits of the TPV systems efficiency by determining the optimal absorber temperature and the corresponding maximum efficiency; such result helps understanding the limitations on TPV performance, but cannot predict the real efficiency of TPV systems since they did not account for various factors to produce a realistic model of the conversion efficiency. Bermel et al. theoretical and experimental work was more detailed and they tried global optimization for the TPV operation by determining the optimal stack of dielectric multilayer of the optical filter with various configurations [7]. Interestingly, the previous modeling and optimization by proper spectral control of the TPVs did not address the thermalization losses in the photovoltaic conversion and the possible power leakage losses that associate the photon recycling process simultaneously. As matter of fact the thermalization losses effect is an important factor that should be accounted for in order to reach realistic optimal photovoltaic conversion efficiency. For instance, it was found even for an optimized three-junction PV structure that the thermalization losses are considerably significant since they are responsible for 23% of the solar power to be wasted as heat in the PV cell [8]. Indeed, some researchers addressed the necessity to have effective spectral control by narrowing the filtering pass band such that the lower cutoff of the pass band is made close as possible to the cutoff wavelength of the PV cell; such may suppress the thermalization losses but increases the leakage losses, therefore, the TPV system becomes not optimal. For example Rephaeli and Fan [9] proposed using an alternating multi-layer stack of SiO_2/Si in order to realize optical filtering at the emitter side such that the cutoff wavelength, where the photovoltaic response is the highest, is permitted to reach the photocell and underestimated the possible power could leak from the TPV system during the photon recycling process and such losses can become significant since it accumulates with every photon recycling round. To best of our knowledge none of researchers in TPV development has addressed that the pass band of the spectral control filter should be chosen optimally to compromise the thermalization losses and the leakage losses from photon recycling in order to maximize the conversion efficiency of the TPV system.

Since the emitter's radiation spectra is temperature dependent, the goal of this research is to optimize the spectral control of TPV systems mainly by choosing a proper filtering band [λ_m-λ_M] and emitter's temperature T. Moreover, different from what researchers and engineers usually do in optimizing solar systems that incorporate a PV component, our optimization avoids searching the maximum power point on the I-V curve of the photo cell in order to maximize the fill factor which is a major one in the overall conversion efficiency. Instead, we are more concerned here in maximizing the produced photocurrent by efficient recycling of the inefficient photons; this would lead to the largest possible area under the I-V curve that is confined between the lines of V_{oc} and I_{sc}. As a matter of fact, the issue of maximizing the fill factor in order to deliver maximum electricity to a certain load can be handled independently by using DC-DC convertor that controls the impedance matching between the output of the TPV system and a specific load.

As mentioned above, we shall search for the optimal emitter's operating temperature T and the optical filter passband [λ_m-λ_M] which maximize the TPV conversion efficiency. Nevertheless, we assume that the type of the used PV cell is decided; this defines the cutoff wavelength λ_G which should equal the upper wavelength λ_M of the optical filter pass band as a first step toward optimization, since photons with longer wavelengths cannot contribute to the photovoltaic conversion, hence, better be recycled.

In the coming sections the task is to model the conversion efficiency η with respect to the optimizing parameters λ_m and T by accounting for the thermalization and photon recycling associated losses. Then suitable numerical optimization method is applied in order to determine the optimal operating parameters and the corresponding maximum conversion efficiency.

2. Theory

In order to model and optimize TPV system we refer to Fig. 1, which shows the system configuration and operation. Usually, photons that emits from the emitter are likely to be recycled between the absorber-emitter unit and the optical filter more than once before they are transmitted to the PV cell through the pass band of the optical filter, or be lost by the power leakage of the recycling subsystem in the form of infrared radiation or by conductive and convective means from the hot emitter since it is not isolated perfectly against thermal leaks. Consequently, it would be useful to introduce the concept of photon recycling efficiency μ_{rec} in order to account for the ability of the absorber-emitter unit to absorb the frequency converted photons and then re-emitting them to the optical filter. In fact, μ_{rec} depends on the absorptivity and emissivity of the absorber-emitter unit, the geometrical configuration of the emitter and the optical filter, and the heat isolation of the recycling subsystem.

Starting with basic physics of the blackbody radiation, an emitter at temperature T (in Kelvins) emits power with spectral density (Watt.m^{-2}.Sr^{-1}.nm^{-1}) as follow [10]:

$$p(\lambda, T) = \frac{2hc}{\lambda^5}\left(\frac{1}{\exp\left(\frac{hc}{k_B\lambda T}\right) - 1}\right) \tag{1}$$

where h is Planck's constant, c is the speed of light in free space, λ is the wavelength and k_B is Boltzmann's constant.

Practically, the photon recycling efficiency through the non ideal absorber-emitter unit is usually less than unity, i.e. $\mu_{rec} < 1$, because

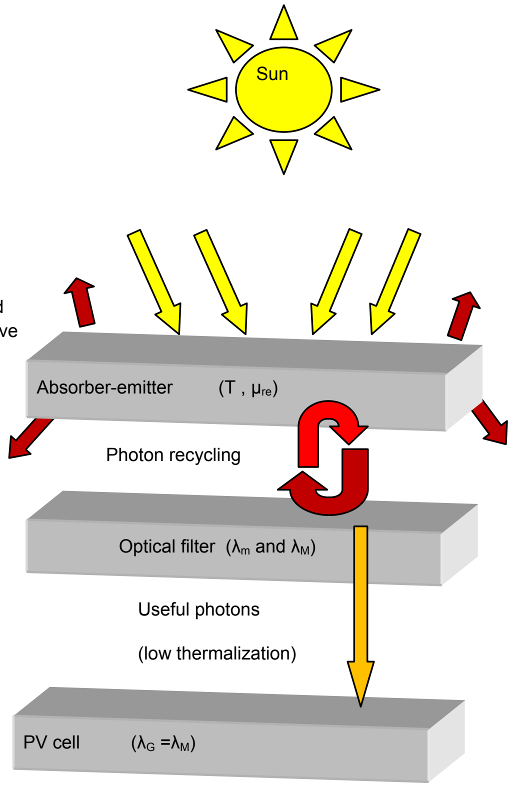

Fig. 1. Thermo-photovoltaic system operation and parameters of interest.

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