Energy Conversion and Management 156 (2018) 264–268

Contents lists available at ScienceDirect

Energy Conversion and Management

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

The maximum theoretical performance of unconcentrated solar photovoltaic and thermoelectric generator systems

R. Bjørk*, K.K. Nielsen

Department of Energy Conversion and Storage, Technical University of Denmark – DTU, Frederiksborgvej 399, DK-4000 Roskilde, Denmark

ARTICLE INFO

Keywords:
Thermoelectrics
Photovoltaics
Thermal
Efficiency
Carnot

ABSTRACT

The maximum efficiency for photovoltaic (PV) and thermoelectric generator (TEG) systems without concentration is investigated. Both a combined system where the TEG is mounted directly on the back of the PV and a tandem system where the incoming sunlight is split, and the short wavelength radiation is sent to the PV and the long wavelength to the TEG, are considered. An analytical model based on the Shockley-Queisser efficiency limit for PVs and the TEG figure of merit parameter zT is presented. It is shown that for non-concentrated sunlight, even if the TEG operates at the Carnot efficiency and the PV performance is assumed independent of temperature, the maximum increase in efficiency is 4.5 percentage points (pp.) for the combined case and 1.8 pp. for the tandem case compared to a stand alone PV. For a more realistic case with a temperature dependent PV and a realistic TEG, the gain in performance is much lower. For the combined PV and TEG system it is shown that a minimum zT value is needed in order for the system to be more efficient than a stand alone PV system.

1. Introduction

Conversion of solar radiation directly to electricity with as high efficiency as possible is of immense interest to society. Photovoltaic devices (PV) that can directly convert parts of the solar spectrum to radiation receive a significant amount of attention, but recently additional energy conversion technologies that can utilize the remaining part of the solar spectrum have come into focus. The part of the solar spectrum not converted by a PV is typically turned into heat, and this has lead to an increased focus on coupling a PV with a thermoelectric generator (TEG), which can convert a flow of heat directly to electrical energy through the Seebeck effect.

A combination of a PV and a TEG could potentially have a higher efficiency, i.e. be able to convert a larger fraction of the incoming solar radiation into electricity, than a PV alone. There are two ways to realize a system containing both a PV and a TEG device. In a combined system, the TEG is mounted directly on the back of the PV. The heat absorbed by the PV is transferred through the TEG, generating electricity. In a tandem system, the incoming sunlight is split in wavelength by a wavelength separating device (beam splitter/dichroic prism), and the short wavelength radiation is sent to the PV while the long wavelength goes to the TEG. The two kinds of PV and TEG systems are illustrated in Fig. 1.

The tandem system has been studied previously [1–3], and experimental systems have also been realized, but only with small gains in open circuit voltage and efficiency [4,5]. A review of the field from an experimental point of view was presented in Sundarraj et al. [6]. The combined system has also been considered in some detail [7–12], with a number of studies focussing on the effect of concentration on the performance of the combined system. Recently, Beeri et al. investigated an experimental setup with a PV and a Bi_2Te_3 TEG and found that a concentration factor of 200 was needed before the TEG electrical contribution started to dominate [13]. However, the overall system efficiency did not increase as the concentration was increased. In another experimental study Kossyvakis et al. examined a PV and TEG system, where the PV was either poly-Si or dye-sensitized based. The authors observed that only for the lower efficiency dye-sensitized cell was the resulting system performance similar to the operation of the PV alone [14]. Finally, in a numerical study Lamba et al. modeled a combined PV and TEG system and found that increasing the concentration from one to five decreased the total system efficiency, due to the temperature dependency of the PV [15]. In general, the conclusion is that with concentration a gain in performance is possible [16–20], but without concentration and using commercial TEG modules, no gain in performance is seen [21,22].

In this work, we determine the maximum performance for unconcentrated systems. We present the maximum theoretical performance of both combined and tandem PV and TEG systems for unconcentrated systems. We present an analytical approach that only relies on established material properties, such as the thermoelectric

---

* Corresponding author.
E-mail address: rabj@dtu.dk (R. Bjørk).

https://doi.org/10.1016/j.enconman.2017.11.009
Received 18 September 2017; Received in revised form 2 November 2017; Accepted 3 November 2017

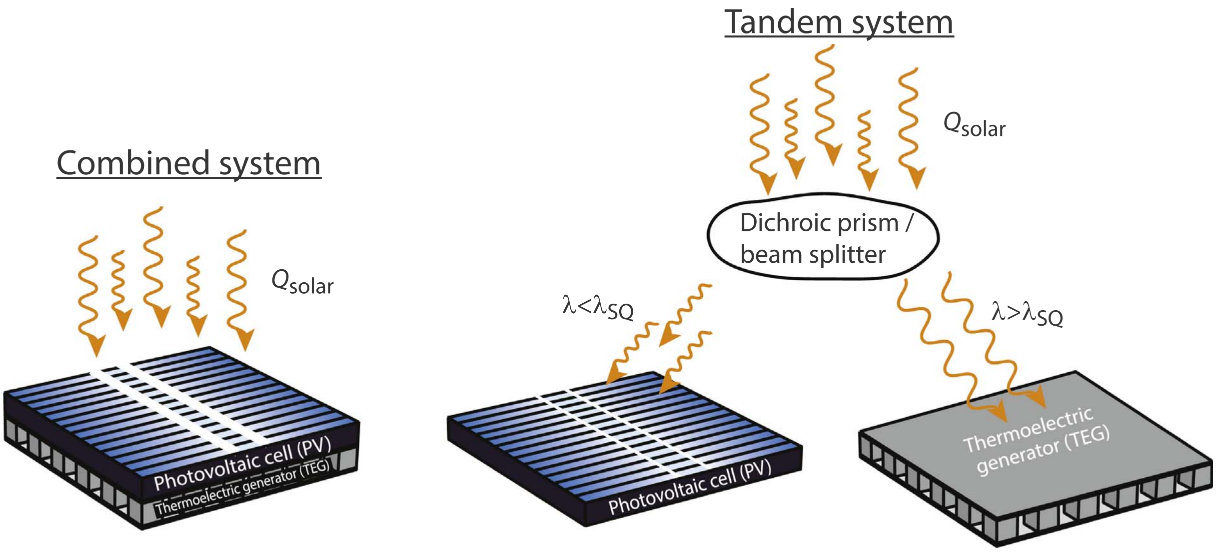

Fig. 1. An illustration of the two systems considered. In the tandem system, the incoming solar radiation, Q_{solar}, is split between the PV and TEG at a wavelength λ_{SQ}.

figure of merit, zT, and the PV Shockley-Queisser limit. The results are applicable to all current and future PV and TEG technologies and materials, as long as the system is not exposed to concentrated light. A somewhat similar approach was considered by Lorenzi et al. [22], except the performance was not given as a function of zT.

2. The studied systems

We consider two kinds of PV and TEG systems, namely a combined system and a tandem system. In a combined system, the TEG is mounted directly on the back of the PV. The hot side temperature of the TEG is thus equal to the temperature of the PV. In a tandem system, the incoming sunlight is split in wavelength by a dichroic beam splitter at a wavelength λ_{SQ}, such that the low energy (long wavelength) light is sent to the TEG, while the high energy (short wavelength) light is sent to the PV.

2.1. TEG properties

We consider a general TEG, for which the efficiency is given according to the figure of merit, zT, of the device. The efficiency as a function of zT is given by [23]

$$\eta_{\mathrm{TEG}} = \frac{T_{\mathrm{H}}-T_{\mathrm{C}}}{T_{\mathrm{H}}}\frac{\sqrt{1+zT}}{\sqrt{1+zT}+\frac{T_{\mathrm{C}}}{T_{\mathrm{H}}}} \tag{1}$$

where T_{H} and T_{C} are the hot and cold side temperatures, respectively, and the figure of merit is

$$zT = \frac{\sigma S^2 T}{\kappa} \tag{2}$$

where σ is the electrical conductivity, S is the Seebeck coefficient, T is the temperature and κ is the thermal conductivity. Here we take zT to be a material parameter, as is traditionally done in the field of thermoelectrics. For current thermoelectric materials zT varies between 0.5 and 1.5, and increases significantly with temperature [24,25]. It is noted that a TEG operates between a hot, T_{H}, and a cold, T_{C}, temperature and that zT is a function of temperature. Thus zT in Eq. (1) can be considered as the average value over the temperature range T_{C} to T_{H}. A TEG can be designed with an arbitrary thickness or area, and thus its thermal resistance can be completely controlled without affecting its zT value.

We also consider the maximum theoretical efficiency possible when operating a heat engine between two thermal reservoirs, namely a Carnot engine. For this the efficiency is given as

$$\eta_{\mathrm{Carnot}} = 1-\frac{T_{\mathrm{C}}}{T_{\mathrm{H}}}. \tag{3}$$

This corresponds to a TEG with $zT \to \infty$.

2.2. PV properties

We consider a single p-n junction PV that performs at the maximum theoretical efficiency, known as the Shockley-Queisser (SQ) limit [26]. In this limit losses occurring due to impedance matching, recombination, blackbody radiation and spectrum losses are all accounted for. The efficiency of the SQ PV depends on the band gap of the p-n junction, or correspondingly on the wavelength, here termed λ_{SQ}. The efficiency has been tabulated as a function of λ_{SQ} for a PV cell operating at 25 °C irradiated by the AM 1.5G spectral irradiance (ASTM G173-03) and considering radiative emission only from the front side due to a perfect reflector at the rear side [27]. These tabulated values are used throughout this work.

For the case of the combined PV and TEG, the PV will increase in temperature. The degradation in PV efficiency with temperature is given by

$$\eta_{\mathrm{PV}} = \eta_{T_{\mathrm{ref}}}(1+\beta(T_{\mathrm{ref}}-T)) \tag{4}$$

where $\eta_{T_{\mathrm{ref}}}$ is the efficiency of the PV at the reference temperature T_{ref}, taken to be 25 °C, and β is the temperature coefficient [28]. Here $\eta_{T_{\mathrm{ref}}}$ is given by the Shockley-Queisser (SQ) limit [27]. For reference, the values for the temperature coefficient for typical commercial PVs are 0.392, 0.110, 0.353 and 0.205% K^{-1} for crystalline Si (c-Si) [28], amorphous Si (a-Si) [28], copper indium gallium (di) selenide (CIGS) [29–31] and cadmium telluride (CdTe) [32] PVs, respectively.

3. The physical models

We assume an incoming solar flux of 1000.37 W m^{-2} and the full AM 1.5G spectral irradiance (ASTM G173-03), with an intensity denoted by $I_{\mathrm{AM1.5}}$ as a function of frequency. First, we consider the combined PV and TEG system. Here the incoming solar flux will either be converted to electricity by the PV or to heat, raising the temperature of the PV and the hot side of the TEG. The efficiency of the PV is given by the SQ limit as a function of wavelength as described above.

The amount of heat available to the TEG depends on the efficiency of the PV through $Q_{\mathrm{hot}} = Q_{\mathrm{sun}}(1-\eta_{\mathrm{PV}})$ plus an additional heat Q_{amb}, which is the radiation from the ambient. This accounts for the fact that