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Hybrid Thermoelectric−Photovoltaic Generators under Negative Illumination Conditions

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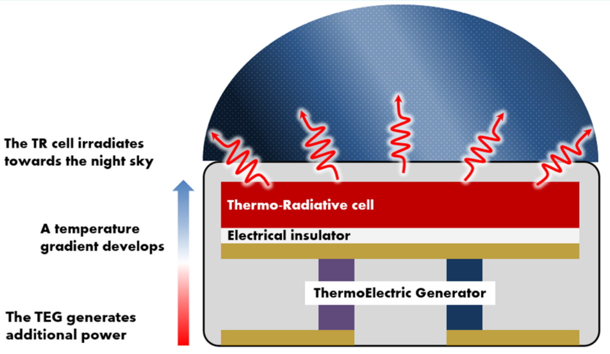

ABSTRACT: This paper analyses the working principles of hybrid thermoelectric photovoltaic generators under negative illumination (also referred to as thermoradiative configuration). These kinds of systems combine a thermoradiative photovoltaic cell (TR-PV cell) and a thermoelectric generator (TEG), placed in thermal contact with each other. In this configuration, the TR-PV part cools while irradiating toward the cold sky. For this reason, in addition to the generation of electrical output, the cell can set a difference of temperature (ΔT) across the TEG legs. A theoretical model describing the behavior of these kinds of hybrid devices is reported as a function of the emitter energy gap and temperature, the sky temperature, and the ΔT across the TEG. In analogy with the positive illumination case, the key parameter is found to be the cell temperature sensitivity, which sets the convenience of the hybrid approach. The results show that while the hybrid power density is in general smaller than the sole TR-PV case, a wide window of positive efficiency gains exists. This is possible because the outgoing power density varies with the cell temperature, in contrast with the positive illumination case where the incoming power density is fixed by the temperature of the Sun. This work sets the first theoretical attempt to understand the convenience of TR-hybrid thermoelectric−photovoltaic generators (TR-HTEPVG), quantitatively assessing the suitability of these novel kinds of devices.

KEYWORDS: *hybrid, photovoltaic, thermoelectric, negative illumination, thermoradiative*

I. INTRODUCTION

As renewables are becoming a big role player in satisfying the energy demand (at least in terms of electric energy), it is clear that their intrinsic intermittent nature is an issue that needs strong efforts to be overcome. Especially for solar, it is evident that photovoltaic (PV) panels are bound to provide energy only during the day as well as being tied up to meteorological conditions. These fluctuations naturally create the big problem of the asynchronism between the availability of solar power and energy demand.[1]

While nowadays major efforts are concentrated on energy storage, offering solutions as pumped hydroelectricity storage, batteries, and fuel cells,[2] some other options have been proposed recently. Among them, night-time generation employing so-called thermoradiative cells (TR cells) is one of the most interesting.

TR cells are essentially the opposite of standard PV cells. Instead of absorbing solar radiation and converting it into electricity, by means of electron−hole pair generation, they emit photons toward a colder object, by means of pair recombination. This process, often called negative illumination, to be efficient needs emitters with very small energy gaps, thus falling in the infrared (IR) spectral range.

In the literature, TR cells have been proposed theoretically as power generators that can convert thermal energy into electricity. In this case, the cell is maintained hot by a given source of heat and converts it into electricity when facing the environment.[3−7] Alternatively, very recently, Tervo et al. proposed a combination of a TR cell with a PV device to harness solar power in a more efficient way than PV cells alone.[8] Although the high efficiencies reported by these studies, the bottleneck of TR cells working at high temperature is the dominant Auger nonradiative recombination process that lowers the system performances.[9]

For this reason, other authors proposed TR cells as potential night-time devices, working at ambient temperature and harnessing energy directly from the coldness of the space.[10−13] In this case, the TR cell has to be spectrally matched with the atmospheric transparency window, between 8 and 13 μm,

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exploiting the principle of radiative cooling.[14] In this configuration, a TR cell can produce an ideal output power of 54 W/m^2,[15] which has been estimated to potentially add a ~12% contribution to what is produced by a solar cell during the day.[13]

Another solution for night generation proposed in the literature consists in the use of the radiative cooling principles applied to thermoelectrics.[16−20] In this case, an optimized emitter is placed in thermal contact with the cold side of a thermoelectric generator (TEG), while the other side is kept at room temperature. In this configuration, a TEG made with materials exhibiting the best thermoelectric performances up to date could generate ~2 W/m^2 of output power.[18]

Contrary to the case of standard solar cells, very few efforts have been already dedicated to investigating hybridization of the two systems reported above, namely the combination of TR cells with TR-TEGs. Actually for the positive illumination case, many theoretical and experimental studies have been published showing the convenience of hybridization of solar cells with thermoelectrics.[21−23] In analogy with the standard case, in thermoradiative hybrid thermoelectric−photovoltaic generators (TR-HTEPVG), a TEG is placed in thermal contact with a TR cell. Irradiating photons toward the sky, the cell can build up a difference of temperature at the TEG plates, thus inducing the generation of an additional electrical output. In the literature, only Zhao et al. have studied very recently a hybrid configuration in which a commercial TEG is attached to a silicon-based solar cell.[24] The system generates ~9 mV of open circuit voltage (V_{oc}) during the night (when the V_{oc} should be zero), demonstrating that this approach can be effectively used to generate power during the night-time. Nevertheless, silicon solar cells are very inefficient thermoradiative systems, since their energy gap is too wide. Furthermore, no systematic theoretical study has been dedicated to investigating the potential of generic TR-HTEPVG devices.

The intent of this paper is to cover this gap through a theoretical model able to predict the convenience of thermoelectric hybridization of TR cells, as the function of parameters such as the working temperature and the energy gap of the material constituting the TR cell, the sky temperature, and the nonradiative processes happening in the cell. This approach sets guidelines for the engineering of effective TR-HTEPVG systems, in terms of suitable materials, sensitivity to temperature, and working scenarios. Moreover, it defines the suitability and the upper bounds of their energetic convenience. For these reasons, this work is a substantial advance in the understanding and the development of effective thermoradiative energy harvesters.

II. WORKING PRINCIPLES

In this work, we consider a unit cell of a generic thermoradiative hybrid thermoelectric−photovoltaic generator (TR-HTEPVG) as shown in Figure 1. In this system, a small-gap photovoltaic (PV) cell is placed in thermal contact but electrically isolated from a couple of p- and n-type thermoelectric materials. For the sake of simplicity, here, we will consider the case of a thermoelectric generator (TEG) composed only by a couple of materials. The unit cell is encapsulated within an evacuated environment, reducing convective heat exchange with the exterior.

We also want to clarify that the term PV cell is used here to highlight that a TR cell is nothing else than a p−n junction converting a photon flux into electricity. Nevertheless, in this paper, the TR cell is not conceived to be also implemented during the daytime, since it has to be optimized for night-time operation.

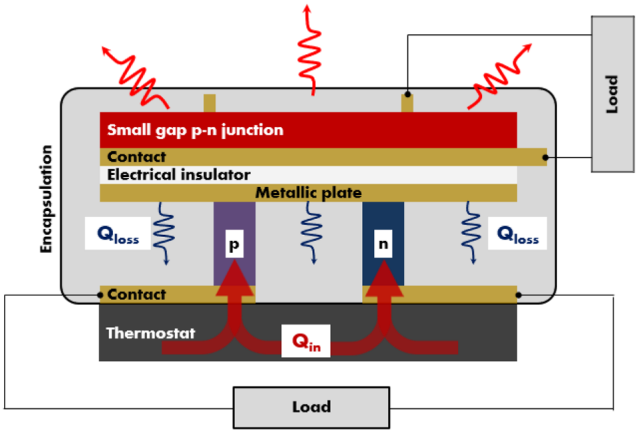

Figure 1. Assemble of a generic TR-HTEPVG system where the PV cell is placed in thermal contact with the TEG but electrically separate from it. Red arrows indicate the heat flux ($\dot Q_{in}$) flowing through the thermoelectric legs and then irradiated toward the sky. Blue arrows indicate radiative heat exchange (Q_{loss}) between the hot and cold sides.

Within a PV cell working under negative illumination, the output current is produced by the radiative photon emission toward the cold sky. This photon emission drives electron−hole recombination and, thus, a positive current flow and negative output voltage as depicted in the schemes of Figure 2. Following Strandberg,[3] the current density delivered by a TR cell can be defined as

$$I_{tr}^{out} = q[\dot N(T_s, 0) - \dot N(T_c, \Delta\mu_c)] \tag{1}$$

with q being the electron charge, T_s and T_c, respectively, being the sky and the cell temperatures, and $\Delta\mu_c$ being the potential difference between the quasi-Fermi levels of electrons and holes in the cell. $\dot N(T_s, 0)$ and $\dot N(T_c, \Delta\mu_c)$ are respectively the flux of photons absorbed by the cell from the sky and those emitted by the cell to the sky. The photon flux can be made explicit as follows

$$\dot N(T, \Delta\mu) = \frac{2\pi}{h^3c^2}\int_{E_g}^{\infty}\frac{\varepsilon^2}{\exp[(\varepsilon - \Delta\mu)/kT] - 1}\mathrm{d}\varepsilon \tag{2}$$

with h being the Planck's constant, c being the speed of light, k being Boltzmann's constant, and ε being the photon energy.

Considering that the voltage across the cell electrodes is $V = \Delta\mu_c/q$, it is possible to write the TR cell output power as

$$P_{tr}^{out}(T_c) = IV = \Delta\mu_c[\dot N(T_s, 0) - \dot N(T_c, \Delta\mu_c)] \tag{3}$$

From eq 3, it is clear that the number of photons emitted has to be higher than those absorbed, to have $P_{TR}^{out} > 0$. As the TR cell radiates photons toward the sky, its temperature drops accordingly. This is the principle of radiative cooling, which has been the objective of intense research in recent years.[14,25] Defining $\dot Q_{in}$, the heat flux required to keep the cell at a constant temperature, the efficiency of the TR cell can be computed as

$$\eta_{tr}(T_c) = \frac{P_{tr}^{out}}{\dot Q_{in}} \tag{4}$$

with

$$\dot Q_{in} = P_{tr}^{out} + \dot E_{ph}(T_c, \Delta\mu_c) - \dot E_{ph}(T_s, 0) \tag{5}$$

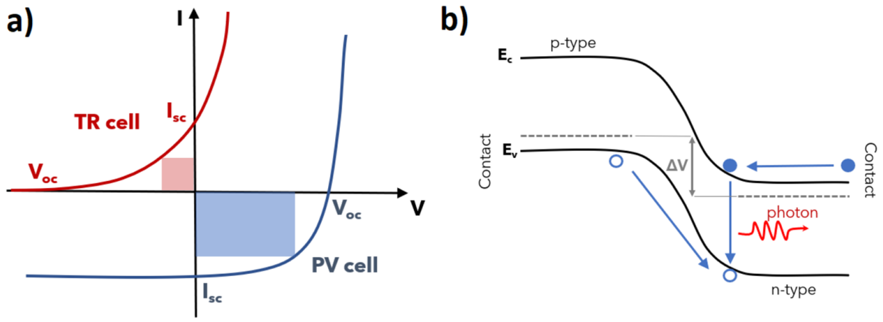

Figure 2. (a) The current−voltage characteristic of a TR cell compared to that of a normal solar cell. (b) Band diagram of a TR cell showing the electron−hole recombination process causing the photon emission.

where $\dot{E}_{ph}(T_s, 0)$ and $\dot{E}_{ph}(T_c, \Delta\mu_c)$ are respectively the energy flux absorbed by the cell from the sky and that emitted by the cell to the ambient environment. The energy flux can be made explicit as follows

$$\dot{E}_{ph}(T, \Delta\mu) = \frac{2\pi}{h^3c^2}\int_{E_g}^{\infty}\frac{\varepsilon^3}{\exp[(\varepsilon - \Delta\mu)/kT] - 1}d\varepsilon \qquad (6)$$

Further details on the theory of TR cells are available in the refs 3, 13, and 15.

Contrary to the positive illumination case, for which the efficiency of the device decreases as the temperature increases, for TR cells, the efficiency decreases as the system temperature decreases (we will focus on this point in the next section). For this reason, as shown in eqs 4 and 5, a certain amount of thermal power has to be spent to keep the TR cell at room temperature, to preserve its room-temperature efficiency.

Within a TR-HTEPVG instead, the temperature of the PV part is left free to decrease, to build a difference of temperature across the TEG. This temperature difference builds additional electrical power, which contributes to the system output power.

The present model, describing the behavior of this TR-HTEPVG device, takes the following assumptions:

1. The PV cell is at uniform temperature T_c equal to that of the TEG cold side T_{cold} in thermal contact with it.
2. The hot side of the TEG is kept a room temperature T_a.
3. The system is perfectly insulated from the environment, and the only source of heat losses is the radiative heat exchange.
4. The thermoelectric properties of the TEG are independent of temperature.
5. Electrical and thermal contact resistances are negligible.

With these assumptions, the TEG output power can be described as the product between the heat flowing through the system $\dot{Q}_{in}$, the thermoelectric efficiency η_{teg}, and the so-called thermo-optical efficiency η_{to}

$$P_{teg}^{out}(T_c) = \dot{Q}_{in}\eta_{to}\eta_{teg} \qquad (7)$$

where η_{to} is the efficiency with which the system converts heat into emitted photons. The name thermo-optical efficiency comes as a natural conversion from what was used in the case of solar thermoelectric systems (daytime operation). Actually, in those cases, the efficiency with which the device converts photons into thermal power is called optothermal efficiency.[26] In this work, since the process is the opposite (conversion of thermal power into emitted photons) we use the term thermo-optical efficiency. This efficiency takes into account heat losses P_{loss} and is equal to

$$\eta_{to} = \frac{Q_{loss}}{\dot{Q}_{in}} \qquad (8)$$

Since we assume a perfectly insulated system, Q_{loss} is exclusively composed by radiative heat exchange between the hot and cold TEG plates. Thus, it can be written as

$$Q_{loss} = \varepsilon_{tot}\sigma(T_{hot}^4 - T_{cold}^4) \qquad (9)$$

where we have neglected the presumably small area occupied by the TEG legs, and where T_{hot} and T_{cold} are the temperatures of the hot and cold TEG plates. In eq 9, ε_{tot} is the total emittance due to the exchange between the TEG plates, and it can be calculated using the results of radiation heat transfer between two parallel surfaces[27]

$$\varepsilon_{tot} = \frac{1}{1/\varepsilon_h + 1/\varepsilon_c - 1} \qquad (10)$$

where ε_h and ε_c are respectively the TEG hot and cold side emittances and where we have neglected the contribution to the radiation exchange coming from the side walls of the TEG legs.[26,28] The TEG plates are normally made of copper. Since the emissivity of copper ranges between 0.02 and 0.05, $\varepsilon_{tot} = 0.015$.

Returning to eq 7, the thermoelectric efficiency can be calculated as

$$\eta_{teg} = \frac{T_{hot} - T_{cold}}{T_h}\frac{\sqrt{1 + Z_{pn}T_m} - 1}{\sqrt{1 + Z_{pn}T_m} + \frac{T_{cold}}{T_{hot}}} \qquad (11)$$

where Z_{pn} is the thermoelectric figure of merit given by

$$Z_{pn} = \frac{(\alpha_p - \alpha_n)^2}{(\sqrt{\kappa_p\rho_p} + \sqrt{\kappa_n\rho_n})^2} \qquad (12)$$

with α, ρ, and κ respectively being the Seebeck coefficient, the electrical resistivity, and the thermal conductivity of the p and n thermoelectric materials composing the TEG and T_m being the average temperature between the TEG hot and cold sides

$$T_m = \frac{T_{hot} + T_{cold}}{2} \qquad (13)$$

Note that for assumptions 1 and 2, we have that $T_{hot} = T_a$ and $T_{cold} = T_c$; thus, T_m becomes

$$T_m = \frac{T_a + T_c}{2} \qquad (14)$$

In addition, assumption number 4 implies that Z_{pn} is temperature-independent. In this work, therefore, $Z_{pn}T_m$ is assumed to be fixed and equal to 1. This is a plausible assumption with current technology considering a not-large ΔT near room temperature.

From eqs 4, 7, and 15, the TR-HTEPVG output power can be calculated simply as

$$P_{h}^{out}(T_c) = P_{tr}^{out} + P_{teg}^{out} \tag{15}$$

and the hybrid efficiency results

$$\eta_h(T_c) = \frac{P_{tr}^{out} + P_{teg}^{out}}{\dot{Q}_{in}} \tag{16}$$

Note that at first glance, η_h (T_c) appears to be always higher than η_{tr} (T_c) (eq 4), since it has additional power at the numerator. However, the additional power is greater than zero only if the cell temperature is smaller than T_a. This implies a TR cell efficiency smaller than its room-temperature value. Therefore, as in the positive illumination case, the convenience of thermoelectric hybridization depends on the trade-off between the TR cell efficiency decrease versus temperature and the increase due to the TEG addition.

In these terms, we can define an efficiency gain, also called the energetic convenience index ($EnCI$), as the difference between the hybrid efficiency and the TR cell efficiency at room temperature T_a

$$EnCI(T_c) = \eta_h(T_c) - \eta_{tr}(T_a) \tag{17}$$

A positive $EnCI$ indicates a gain compared to the TR cell alone, while a negative value indicates a loss of efficiency. In the following section, we will analyze the condition to obtain positive efficiency gains.

Finally, to understand the working principle of a TR-HTEPVG, we need to discuss the thermodynamics of the PV effect.

In general terms, the PV effect is a two-body process requiring a hot object emitting photons and a cold object absorbing them. In the case of positive illumination, the hot radiative object is the Sun, while the cold absorbing object is the solar cell. In this case, the incoming radiation is normally taken as fixed. Actually, the temperature of the hot object is stable, and it is not influenced by the cell temperature. For this reason, the incoming power is constant, and the maximum efficiency corresponds to the efficiency at maximum output power, often called the maximum power point (MPP). This is a general result applicable to engines working in a constant flux regime[29,30] and thus keeps valid for hybrid devices for which the TEG efficiency at MPP corresponds to its maximum efficiency.[31]

In the case of TR cells instead, the hot radiative object is the cell itself, while the cold absorbing object is the sky. It follows that the outgoing flux varies with the cell temperature through eq 2. This implies that the maximum efficiency differs from efficiency at MPP. Strandberg has clearly shown this behavior by plotting the theoretical maximum efficiency of TR cells and comparing it with their efficiency at MPP.[3]

III. RESULTS AND DISCUSSION

In this paper, we consider TR cells working at room temperature facing the cold sky. In our case, the discrepancy between the maximum efficiency and MPP mentioned earlier is even more remarkable than what was reported by Strandberg.[3] Actually, in his paper, Strandberg mostly considers TR cells working at temperatures higher than the ambient temperature, irradiating toward the environment at 300 K. Considering instead an ideal TR cell having an energy gap (E_g) of 0.1 eV working at room temperature (300 K) facing the cold temperature of the universe (3 K), it would have an efficiency of 98.6% but with a practically zero power output. Conversely, at its MPP, the cell would have a power output of 13.45 W/m^2 with a corresponding efficiency of 15.7%. In these terms, the case of maximum efficiency is of very poor practical interest. In fact, the very small magnitude of $\dot{Q}_{in}$ implies an almost zero output power (eq 7). Therefore, in this paper, we will focus our attention merely on the MPP and efficiency at MPP.

Regarding hybrid devices, since the constant flux regime is not applicable for TR cells, it follows that also for TR-HTEPVG the efficiency at maximum power does not correspond to its maximum efficiency. In general, this fact determines the different behaviors of hybrid devices under positive and negative illumination conditions. Table 1 reports the values of the main parameters used in this work.

Table 1. Main Parameters Used in This Work

parameter	value	description
$Z_{pn}T_m$	1	thermoelectric figure of merit
ε_{tot}	0.015	effective emissivity of TEG electrodes
T_a	300 K	ambient temperature

A. TR Cell Efficiency versus Temperature.

As explained in the previous section, in this paper, we will focus our attention merely on the MPP and the efficiency at the MPP of TR cells and their hybrids with thermoelectrics. First of all, let us analyze the sensitivity of TR cells to temperature. In Figure 3, the efficiency at the MPP of an ideal TR cell working at temperature T_c and facing the cold sky at 3 K is reported. The graph shows the case of TR cells with different values of E_g, ranging from 0 to 0.3 eV.

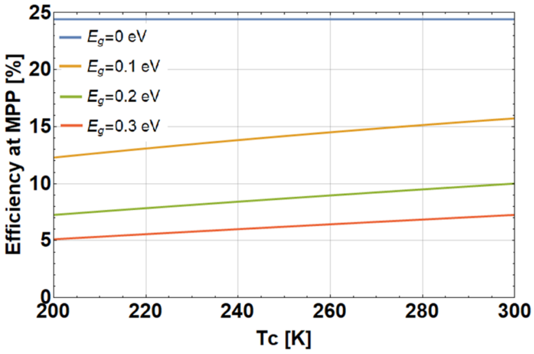

Figure 3. TR cell efficiency at MPP versus temperature for different energy gaps.

First of all, let us notice that as expected the efficiency decreases increasing the E_g value, as carriers recombination becomes less probable. Also, the efficiency decreases decreasing the working temperature T_c.

In analogy with the positive illumination case, we found a linear dependency of the efficiency as a function of temperature. Therefore, it is possible to define a coefficient β as the slope versus temperature of η_{tr}, normalized at its value at 300 K. This coefficient, which has the unity of $[1/K]$, quantifies the sensitivity of the TR cell efficiency with temperature. Namely, the higher the value of β, the higher the sensitivity of the cell.

As shown in Figure 4, the sensitivity depends on the energy gap of the material constituting the cell. Contrary to the positive illumination case, the smaller the energy gap, the smaller the efficiency sensitivity. Note also that for the extreme case of $E_g = 0$, the efficiency is not dependent on temperature. This means that in this case, referring to eq 4, the decrease of the electrical power due to a smaller rate of electron−hole recombination is exactly compensated by the decrease of $\dot{Q}_{in}$.

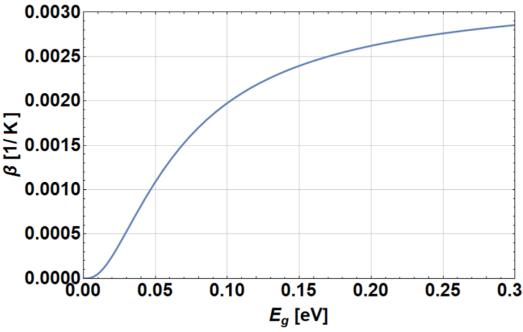

Figure 4. Slope of the normalized TR cell efficiency dependence with temperature versus energy gap.

Since the convenience of thermoelectric hybridization depends directly on the sensitivity of TR cell versus temperature, it is clear from Figure 4 that hybridization is more favorable for small energy gaps.

B. Thermodynamic Limit. In this section, we want to investigate the hybridization convenience in the case of ideal conditions. These conditions represent the thermodynamic limit and imply that (1) the recombination processes in the TR cell are purely radiative and that (2) there is a perfect spectral match between the TR cell and the sky (namely, the TR cell absorptivity is equal to 1 within the transparency window of the atmosphere and 0 outside of it), which implies $T_s \approx 3$ K.

In the thermodynamic limit, a TR cell with $E_g = 0$ generates 54 W/m^2, reduced to 0.038 W/m^2 for a cell with $E_g = 0.3$ eV.[13]

In Figure 5, we report instead the dependency of the maximum output power of a TR cell with $E_g = 0$, as a function of temperature. In the same graph, we also show the maximum output power of a TEG with a figure of merit equal to 1, working between T_c and room temperature. It is easy to see that the TEG contribution is not enough to overcome the decrease of the TR cell power as the cell temperature decreases. This is valid also in the case of higher energy gaps. Thus, the best solution to maintain a high level of output power from a TR cell is to keep the TR cell as hot as possible.

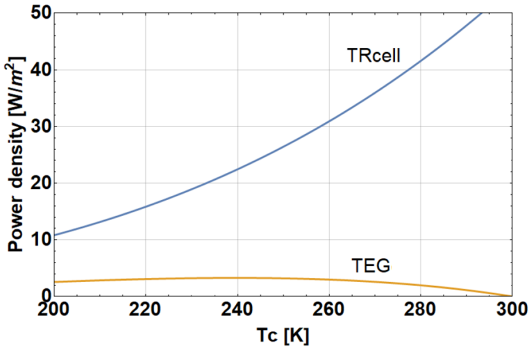

Figure 5. Ideal TR cell with $E_g = 0$, and TEG maximum output powers as a function of temperature.

However, this conclusion does not apply to the efficiency. Actually, to keep the TR cells hot, some thermal power has to be spent. Therefore, in terms of efficiency, the evaluation of TR-HTEPV systems changes dramatically. In fact, from Figure 3, one can understand that for at least the extreme case of $E_g = 0$ (for which the TR efficiency is temperature-independent), any additional contribution from the TEG will increase the overall efficiency.

Also for higher E_g values, in some cases, hybridization is convenient in terms of overall efficiency as shown by Figure 6. As expected, the efficiency gain due to thermoelectric hybridization increases as the cell temperature decreases, until it reaches a maximum at a certain optimal temperature T_{opt} (for $E_g = 0$, $T_{opt} \approx 170$ K). At a working temperature smaller than T_{opt}, the thermal-optical efficiency η_{to} drops, leading to a decrease of P_{teg}^{out} (eq 7) and consequently also a decrease of η_h and *EnCI* (eqs 16 and 17). The drop of η_{to} is due to the increase of Q_{loss} and the simultaneous decrease of $\dot{Q}_{in}$. For energy gaps higher than zero, the drop of η_{to} is stronger, and that is the reason efficiency gains and values of T_{opt} are smaller in these cases.

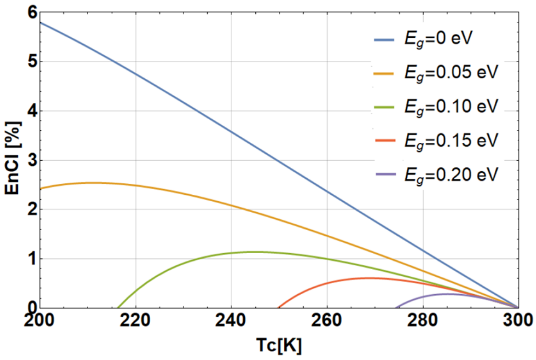

Figure 6. Efficiency gains for different values of the TR cell energy gap, in the thermodynamic limit.

From Figure 6, it is evident that, as pointed out by Deppe and Munday,[13] TR cells and consequently the TR-HTEPV device need materials with $E_g < 0.1$ to be suitable for implementation. With these kinds of emitters, efficiency gains can be expected to be between 1 to 6%.

In the next section, we will analyze the behavior of TR-HTEPV systems in a not-ideal scenario.

C. Nonideal Case. Let us now consider the convenience of thermoelectric hybridization of TR cells below the thermodynamic limit. In order to do that, we need to relax the two conditions describing the ideal case. Thus, we will take into account nonradiative recombination processes and an imperfect spectral match between the TR cell and the sky.

Regarding the first condition, it is known from the theory of the photovoltaic effect that electron−hole recombination is not always radiative.[32] Nonradiative recombination can involve other carriers (Auger recombination) or traps and impurity levels (Shockley−Read−Hall recombination). To account for these processes, we only need to modify eq 3, increasing the flux of photons absorbed by the cell from the sky. To do that we have to multiply $\dot{N}(T_s, 0)$ for a factor γ defined as

$$\gamma = \frac{\dot{N}_{rad} + \dot{N}_{nr}}{\dot{N}_{rad}} \tag{18}$$

namely the inverse of the fraction of the radiative recombination over the total recombination events. In this way, if the recombination is totally radiative, it follows that $\gamma = 1$, while if radiative recombination accounts for only 10% of total recombination, then $\gamma = 10$.

Even if nonradiative recombination has a great effect on $P_{\rm tr}^{\rm out}$, it does not influence $\dot{Q}_{\rm in}$ and therefore *EnCI*. Actually, it can be seen from eq 7 that the TEG contribution depends only on $\dot{Q}_{\rm in}$ and on the working temperatures $T_{\rm c}$ and $T_{\rm a}$ (through $\eta_{\rm to}$ and $\eta_{\rm teg}$). Therefore, in general, nonradiative recombination, although detrimental for TR cells, is irrelevant on the hybridization convenience with thermoelectrics.

For what concerns instead the spectral matching between the sky and the hybrid device, in real-case scenarios, some thermal radiation from the atmosphere could be absorbed by the TR cell. This moves the recombination−absorption equilibrium of eq 1 toward the absorption and thus lowering the cell output power. This behavior is due to the fact that common diodes absorb also outside the atmospheric window of transparency,[12] thus also absorbing most of the photons coming from the atmosphere.

The effect of the atmosphere can be modeled by modifying the sky temperature (assumed to be equal to 3 K in the thermodynamic limit) with an effective sky temperature $T_{\rm s}'$. Figure 7 shows the influence of an increasing $T_{\rm s}'$ on *EnCI* for the case of the hybrid device with TR cells having $E_{\rm g} = 0$, 0.05, and 0.1 eV. As can be seen, although this influence is strong in the case of $E_{\rm g} = 0$ eV, it becomes smaller when increasing the TR cell energy gap. Actually, for the case of $E_{\rm g} = 0$ eV, *EnCI* starts to drop for an effective temperature as small as ∼40 K, while it is insensitive until a temperature of ∼80 K for $E_{\rm g} = 0.05$ eV and ∼120 K for $E_{\rm g} = 0.1$ eV.

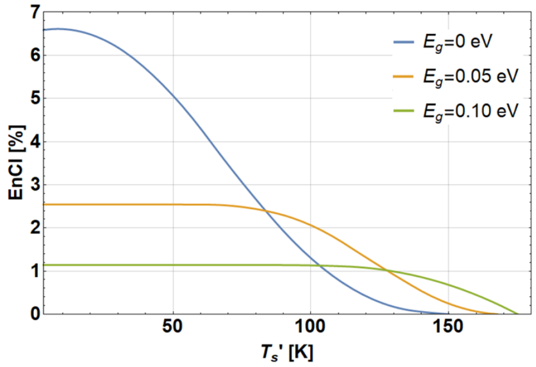

Figure 7. Efficiency gains as a function of the effective sky temperature $T_{\rm s}'$ for different values of the TR cell energy gap.

This behavior is due to the fact that, as shown recently by Deppe and Munday,[13] TR cell output power (and thus $\dot{Q}_{\rm in}$) is less sensitive to $T_{\rm s}'$ for higher TR cell energy gaps. It is clear however that preserving the convenience of hybridization with thermoelectric spectral matching seems fundamental. In this perspective, the development of materials and systems able to guarantee very high absorptivity only in the range of the atmospheric window of transparency is critical.[12]

IV. CONCLUSION

In this work, a model describing the behavior of a hybrid generator composed of a TR cell and a TEG is presented. The main parameters of the model are the temperature and the energy gap of the TR emitter and the sky temperature. The results are expressed as efficiency gain due to the thermoelectric hybridization *EnCI* (namely, the difference between the efficiency of the hybrid system and that of the TR cell alone working at room temperature).

We showed that in terms of output power, the TEG cannot give a contribution able to overcome the TR cell decrease due to the temperature sensitivity. In contrast, efficiency gains are significant for $E_{\rm g} < 0.1$ eV and show values between 1 and 6%. However, we also noted a very strong influence of the sky temperature on *EnCI*, highlighting the importance of a proper spectral matching between the device and the sky (namely, an emitter absorptivity equal to 1 within the transparency window of the atmosphere and 0 outside of it).

Finally, we also studied the effect of nonradiative recombination, and although it is known to be detrimental for TR cell output powers, it was found to be influential on hybridization convenience with thermoelectrics.

In conclusion, we found that thermoelectric hybridization of TR cells is for sure an interesting area of research that can give a considerable contribution to the competitiveness of these devices. However, further studies are needed to optimize emitters' spectral properties to reach the best performances obtainable.

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Notes

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