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Solar Thermophotovoltaic Converters: Efficiency Potentialities

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Abstract. Solar thermophotovoltaic efficiency is theoretically estimated using the following optimisation parameters: sunlight concentration ratio, absorber/emitter temperature/efficiency, photon recirculation efficiency and TPV cell parameters. It has been found that emitter temperature exceeding 2000 K, absorber/emitter efficiency of 90% and TPV systems efficiency exceeding 30% can be obtained at sunlight concentration ratio exceeding $8 \cdot 10^3$ suns with using GaSb cells with back surface reflector and grey-body emitter in vacuum. Utilization of the selective emitter allows to increase the efficiency: calculated efficiency of TPV system with tungsten emitter increases from 30% to 36%.

INTRODUCTION

In solar thermophotovoltaic (STPV) system, the solar radiation is absorbed and reemitted as a thermal radiation before illumination of the solar cells. Absorption in a radiator and then re-radiating deteriorate the quality of the radiation by reducing its characteristic temperature. However, solar PV systems are strongly determined by the sunlight spectrum and by the fact that there is no back connection between a receiver and the Sun. In contrast to this, in STPV systems, the optimisation may imply a choice of the emitter spectrum and a possibility to return a useless part of radiation from the receiver back to the emitter surface supplying it by an "additional" power. TPV system allows to utilize selective filters/mirrors and sub-bandgap photon reflection to emitter, which ensures efficiency increase. The more so, as photons emitted by the PV cells by radiative recombination are utilized, since the emitter absorbs also these photons using their energy. Due to this effect, PV cells would be operated in the conditions, where the generated voltage is higher than in the case of solar PV without trapping the photons emitted due to radiative recombination.

Solar-powered or hybrid solar/fuel powered system have some additional advantages: - TPV fuel-fired part of the hybrid system would permit the use during the night; - hybrid system with PV conversion (or lighting) for visible part and TPV for infrared part of the solar spectrum can be created as well; - high-temperature (>2000K) emitter in a vacuum bulb can be used with a good enough "quality" of radiation in STPV systems; - like a concentrator photovoltaics, thermophotovoltaic conversion of concentrated sunlight have the perspectives to decrease the solar electricity cost in comparison with non-concentrated photovoltaics owing to reduction of PV cell area proportionally to an increase of the output electrical power density from PV cells, achieving the value of about 10 W/cm^2 in high concentrator STPV systems with high-temperature emitters.

Thus, there are three key problems arising at optimization of a STPV system: providing the high sunlight concentration; tailoring the emission spectrum of the photon emitter; filtering the radiation to organize photon recycling process and to reduce the thermal load on the photocells; cell design allowing the realization of the highest PV conversion efficiency of radiation with a matched spectrum. These problems may be interconnected. For instance, selective filter as a part of the system may be situated between a photon emitter and a photocell (it may be deposited directly on the photocell surface) reflecting long-wavelength radiation back to the emitter. But the role of such a filter may be played by a photocell itself, if there is a mirror on its back surface, which reflects the radiation, nonabsorbed in the photocell material.

Theoretical [1-5] and experimental studies [6-11] show an opportunity to achieve the high efficiency of STPV systems. For ideal system elements with no optical losses, maximal theoretical efficiency were found to be 85%, that is identical to the efficiency of large stack of tandem cells. Expected in practice efficiencies are 25-35%.

Possible solar TPV system design shown in Fig. 1,*a* consists of a sunlight concentrator (Fresnel lens and secondary lens) and a vacuum bulb with an emitter. To obtain a high concentration ratio exceeding $5 \cdot 10^3$ suns, spherical or parabolic dish mirrors are preferable (Fig. 1,*b*). It was shown [12] that efficiency of the systems with solar powered heat sources should be higher if two-stage concentrators is used: the first stage – dish mirror and the second stage-compound parabolic concentrator (CPC) or lens. The concentration ratio 8000-12000 suns was ensured by the developed [11] concentrator based on compound spherical mirror and CPC.

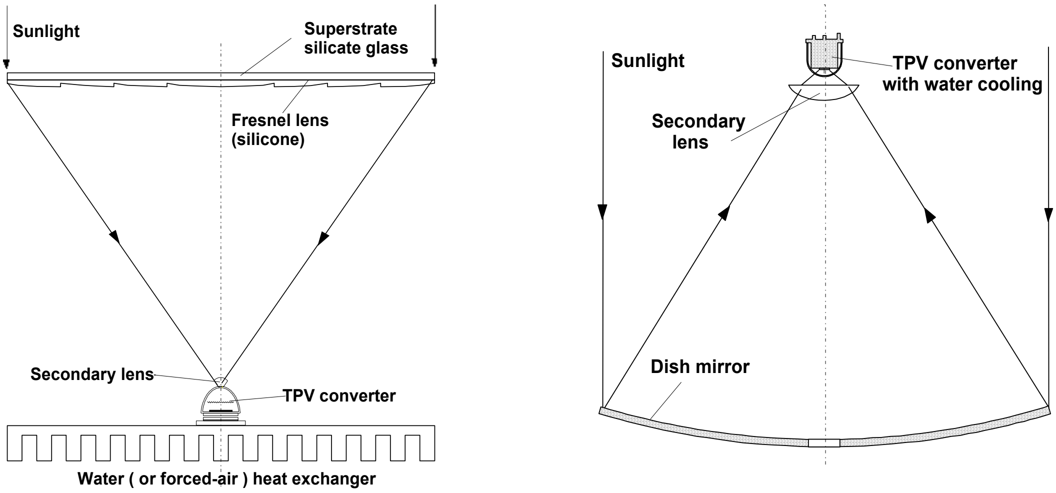
a) *b)*

FIGURE 1. Concepts of solar TPV systems: *a)* with Fresnel lens as a primary concentrator; *b)* with dish mirror.

IDEAL CONCENTRATOR-ABSORBER-EMITTER SYSTEM

Solar energy is concentrated in the absorber through an inlet hole, but a part of power is lost due to radiation through the same hole (Fig. 2). The inlet aperture size and correspondingly back radiation losses cannot be chosen small because the concentration ratio K_S for sunlight is limited. The back thermal radiation increases drastically and absorber/emitter efficiency (η_E) decreases as the emitter temperature T_E rises.

For the case of absence of the convective heat losses (case of an emitter in vacuum bulb), the absorber/emitter efficiency (η_E) is given as [12]:

$$\eta_E = 1 - \frac{K_{max}}{K_S}\left(\frac{T_E}{T_S}\right)^4 \qquad (1)$$

where $K_{\max} = 46146$ – is the theoretical maximum concentration ratio on the Earth orbit,
$T_S = 5780$ K – is the effective Sun surface temperature.

Both the concentrator efficiency and emitter absorption ability of 100% as well as no recirculations of photons radiated by emitter were assumed in this ideal approach.

Figures 3, 4 show the dependences calculated for concentrator-emitter systems with these ideal parameters in correspondence with the equation (1). It is seen, that for receiving the emitter temperatures exceeding 2000 K at emitter efficiency of 90%, the concentration ratio should be larger than 8000 suns.

Some additional approaches should improve the concentrator-emitter system performance. For example, a selective filter can be inserted on the input absorber side.

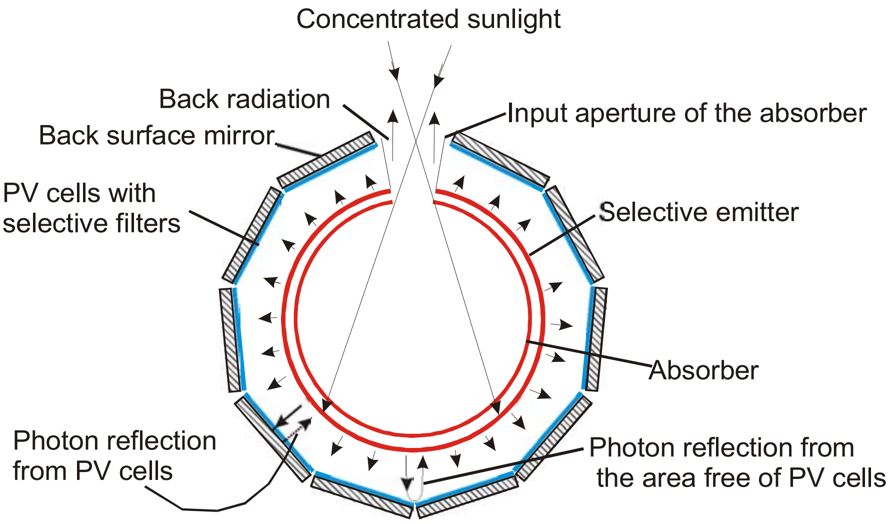

FIGURE 2. Schematic of a solar TPV converter

This filter should be selectively transmitive for most (visible and near IR) of the solar spectrum but should be reflective in the long wave length range, where the intensity of IR radiation from the absorber exceeds that of the absorbered incoming solar radiation. It allows minimizing the backradiation losses. Recirculation of photons reflected from the front and back surfaces of TPV cells should increase the both emitter efficiency and temperature. Even the photons emitted by PV cells by radiative recombination can improve the concentrator-emitter system performance.

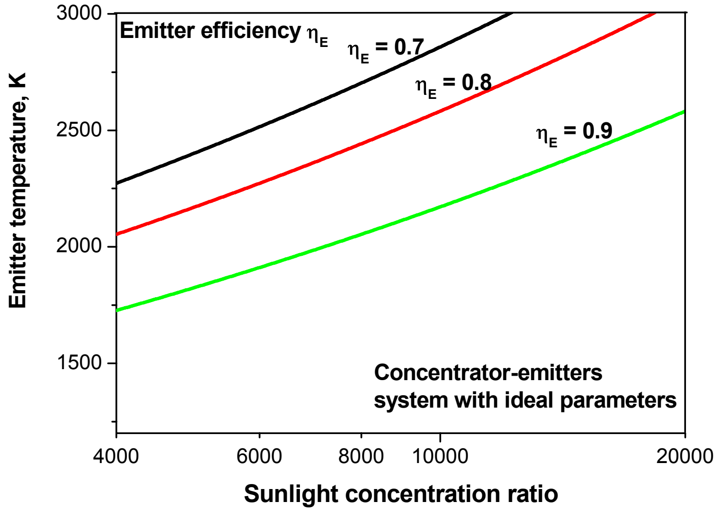

FIGURE 3. Emitter temperature vs. sunlight concentration ratio for the different emitter efficiencies

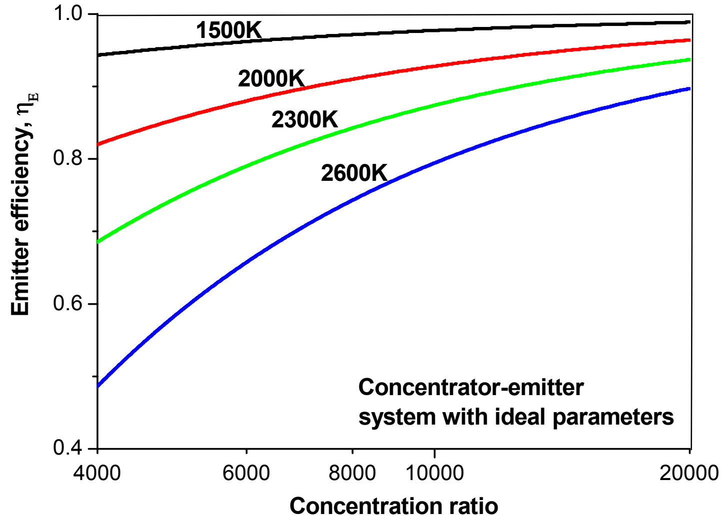

FIGURE 4. Emitter efficiency vs. sunlight concentration ratio at different emitter temperatures

“REAL” SOLAR TPV CONVERTERS

Figure 2 shows the principal geometry of a solar TPV module used in the efficiency calculations.

The following non-idealities have been introduced in order to approach efficiency limits for TPV systems with real parameters:

- Direct sunlight (850 W/m^2) is focused by means of a “spherical mirror-CPC” concentrator system with overall efficiency of 90%.
- The absorber inlet aperture area S_{apert} depends on the sunlight concentration ratio (K_S is in the range from 4000x to 16000x) and, correspondingly, on the initial mirror area.
- The dimensionless parameter of the relative emitter size (emitter efficiency) $\eta_{emitter} = S_{emitter} /(S_{emitter} + S_{apert})$ was used, due to which the area of the initial mirror plays no role, and the emitter area ($S_{emitter}$) becomes automatically associated with sunlight concentration ratio.
- In real TPV device, absorber area (S_{abs}) and emitter area S_{emitt} are different. In these calculations, we assume that $S_{abs} = S_{emitt}$.
- The temperatures of the absorber and emitter surfaces are assumed to be equal. This condition can be realized at a perfect thermal conduction between these two surfaces.
- Emitter is a gray-body with emittance equal to 0.28 and with the spectrum corresponding to that of the absorber black-body.
- A part of the absorbed radiation leaves the absorber through the inlet aperture with efficiency of an absolutely black-body.
- The emitter radiation scattered by elements of the inner construction (these losses are accepted equal to 10%) falls on photocells, which occupy 90% of the whole irradiated surface (view factor is 90%).
- Radiation, which do not get PV cells, returns back to the emitter, reflecting from a mirror surface with reflectance of 90%.
- Radiation with photon energies $h\nu < Eg$ returns from PV cells to the emitter with the return efficiency RE = 50-90%.
- Photons emitted by the TPV cells by radiative recombination is not taken into account in this calculations.
- Heat conductive loss is taken into account as heat transfer along 2 portions of the ceramic pivots 1 mm in diameter and 10 mm long. No convection losses were assumed taking into account that absorber/emitter is placed into a vacuum bulb.

The emitter temperature was found in solving the equation:

$$E_{solar} + E_{return} = E_{emit} + E_{cond}\,, \tag{2}$$

where E_{solar} is concentrated solar radiation,

E_{return} is radiation returned to emitter after reflection from TPV cells and other parts of PV receiver,

E_{emit} is radiation from the emitter,

E_{cond} is heat conductive losses.

Figure 5 shows the emitter temperature dependences on the emitter efficiency (relative emitter size) for different concentration ratios. These results are similar to the dependences (Figures 3 and 4) obtained for the concentrator-emitter system with ideal parameters. It means that non-idealities introduced into real system, partly compensate each other. For example, the temperature decrease due to lower concentrated sunlight intensity in the real system is compensated partly by photon recirculation processes discussed above.

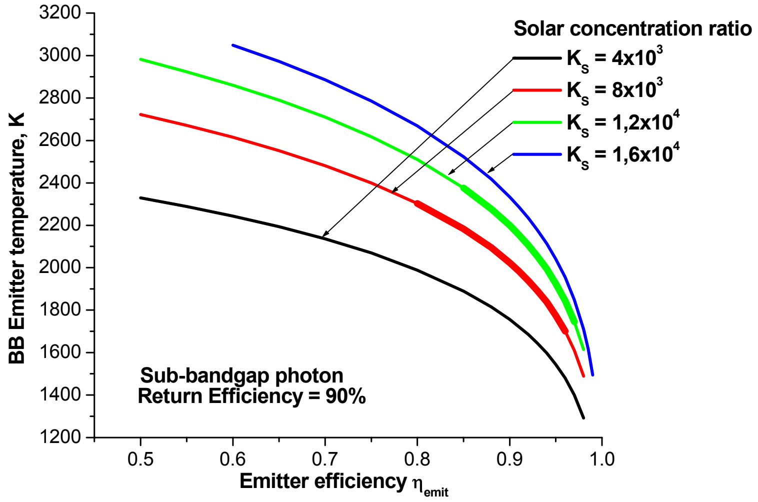

FIGURE 5. Calculated dependences of emitter temperature on emitter efficiency for various solar concentration ratios. Input aperture of absorber/emitter is determined by solar concentration ratio.

The developed by us concentrator-emitter system [11] ensures the concentration ratio exceeding 8000x. Emitter temperature T_E > 2000 K at η_E = 90% is expected in this system (see Fig. 3).

For calculations of the overall TPV system efficiency, the following PV cell parameters and conditions were assumed.

The whole radiation with $hv > Eg$ is absorbed in the semiconductor and generates electron-hole pairs. Recombination losses have the lowest value limited by radiative recombination. No ohmic losses are assumed. The cell bandgap is taken equal to 0.72 eV (GaSb). The cell operating temperature is equal to 50° C. Proceeding from the obtained current density, the load characteristics were calculated and the optimum load points were found. The TPV converter efficiency was determined as a ratio of output electric power to inlet solar energy flux incident on the absorber aperture.

Figure 6 shows the TPV converter operation efficiency in dependence on the emitter temperature (here and further the emitter is a gray-body), which varies only due to variation of the emitter size. The return efficiency (*RE*) of radiation with $hv < Eg$ is varied in the range of 50-90%. The drop in the efficiency with lowering down temperature is explained by the decrease of the conversion efficiency of the GaSb PV cell, whereas the drop at high temperatures is associated mainly with rise of losses at back radiation through the absorber aperture. For this reason with increasing sunlight concentration ratio an efficiency increase and a temperature increase take place, when maximum efficiency is achieved.

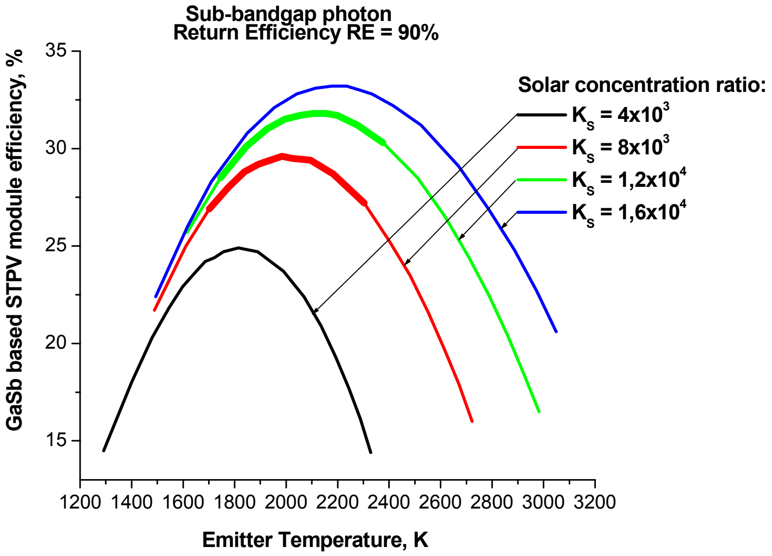

FIGURE 6. Dependences of GaSb based STPV efficiency versus emitter temperature for various solar concentration ratios.

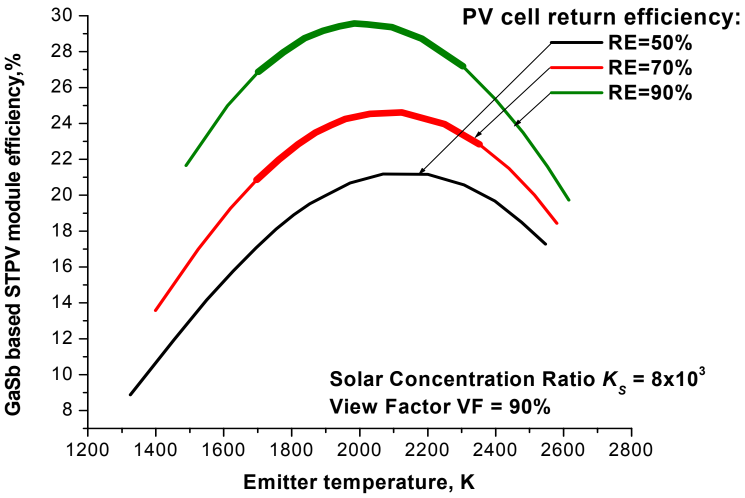

FIGURE 7. Calculated dependences of GaSb based STPV converter efficiency versus emitter temperature for various PV cell return efficiencies at concentration ratio of 8000x.

Figure 7 shows TPV module efficiency in dependence on the emitter temperature for different return efficiencies of PV cells. It is seen that the rise in the return efficiency results in significant increase in the entire system efficiency from 20% at *RE* = 50% to 30% at *RE* = 90%.

The dependences in Fig. 5-7 were calculated for radiation of an emitter – gray-body with emittance equal to 0.28, and with the spectrum corresponding to that of the absolute black body. In utilization of a selective emitter (for example, made of tungsten), the efficiency increases owing to better matching in the radiation and PV cell photosensitivity spectra.

Efficiency was calculated also for the system being developed at the moment [11]: - 0.45 m^2 primary mirror; two stage (dish mirror + CPC) concentrator with concentration ratio of 8000x; - emitter is made from tungsten in the vacuum bulb. The comparison of a nonselective emitter (grey-body) and a selective emitter (tungsten) is was made. The calculated conversion efficiency in the system with return efficiency of 90% is about 30% for the grey-body and 36% for the tungsten emitter.

It is interesting to compare the calculated results with measured efficiencies in the TPV cells. For example, the efficiencies of 28-30% in GaSb TPV cells have been extracted [6,8,11,13] from the measured cell parameters using a band edge filter to reflect black-body radiation with energy below the GaSb bandgap (i.e. at $\lambda > 1800$ nm). Efficiency of these cells under whole blackbody spectrum increases with blackbody emitter temperature increase from ~ 10% at 1300 K to more than 20% at $T_{BB} > 1800$K [13]. It is evident, that there is a room for practical efficiency increase owing to development of tandem TPV cells, selective filters on the absorber side and between emitter and PV cells as well as utilizing the photons emitted by PV cell by radiative recombination. For example, efficiencies of 44-49% were received [9] in the developed GaSb cells under the monochromatic radiation wavelength of 1680 nm at photocurrent densities exceeding 10 A/cm^2.

Concerning the possibility to achieve large value of return efficiency for sub-bandgap photons. *RE* value exceeding 90% has been obtained in InGaAs/InP MIM TPV cells on the basis of semi-insulating InP substrates [14] as well as in Ge based TPV cells [10]. It means that accepted in calculation *RE* value of 90% is available for creation of high efficiency STPV systems.

CONCLUSION

The fulfilled analysis allows to make a conclusion that solar thermophotovoltaics has prospects for the efficiency increase to produce low cost solar electricity. It was shown that efficiency of STPV devices could be greater than 25% using the current technology and more than 35% using the advanced technologies. There are ways for efficiency increase owing to possible development of tandem TPV cells and perfect matching of the selective emitters and PV cells.

Utilization of the high-temperature ($T > 2000$ K) emitters in vacuum bulb and high-effective sub-bandgap photon recirculation allows to consider semiconductors with bandgap energy more than 1 eV (Si, GaAs) as promising materials for high-efficient STPV systems. For example, efficiencies of 54-56% were obtained in GaAs PV cells under monochromatic radiation with wavelength of 820 nm at photocurrent densities of 5-100 A/cm^2. In addition, an external quantum efficiency of radiative recombination as high as 70% was measured [15] in the AlGaAs/GaAs heterostructures with internal quantum efficiency of 95-97%. It means, that non-radiative recombination in the TPV cells based on these heterostructures could be lower than radiative recombination. In one's turn, radiative recombination can be utilized owing to photons returning to emitter. The high radiative recombination is expected also in the TPV cells based on the other III-V compounds (GaSb, InGaAs, InGaAsSb) with direct transitions between valence and conduction bands.

The losses associated with considered non-idealities are still lower than in the real STPV systems. The main difficulty is to achieve low optical and heat losses in the system operating at high concentration of about 10^4 suns and at high emitter temperature exceeding 2000 K.

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