SPECTRUM EXERGY ANALYSIS OF A SOLAR PHOTOVOLTAIC CONVERSION PROCESS

Chu S.X.*
*Author for correspondence
School of Mechanical Engineering and Automation,
Shenzhen Graduate School, Harbin Institute of Technology,
Shenzhen, 518055,
China,
E-mail: s_x_chu@163.com

ABSTRACT

Solar photovoltaic conversion is an approach for the direct conversion of solar radiation to electric power. The spectrum exergy of thermal radiation is derived on the basis of the definition of spectral radiation exergy intensity. By taking the model of a photovoltaic conversion process as an example, the present paper studied the conversion of solar photovoltaic from the view point of exergy analysis, and analyzed the distribution of spectrum exergy efficiency of solar photovoltaic conversion segments in photovoltaic conversion process. All in- and outgoing fluxes in the thermodynamic balance equations for spectrum energy and exergy must be known to evaluate the spectrum efficiency of this energy conversion process. The calculation procedure to obtain the spectral energy, and exergy fluxes is described. The energy flow diagram and the exergy flow diagram at given wavelength are described respectively. The results show that the spectral utilization for solar photovoltaic conversion is with promising.

INTRODUCTION

Traditionally, the analysis of utilization of solar energy is from the viewpoint of energy analysis [1-4]. Exergy analysis is a very effective method to analyze the process heat transfer and it provides a new insight that cannot be obtained from energy analysis. The solar photovoltaic conversion is one of the main approaches to utilize solar energy, and is also one of the spectral selective processes. Photons with energy less than the bandgap energy or photons with wavelengths longer than the cutoff wavelength are not used by photovoltaic devices [5, 6].

Many researchers have investigated the exergy efficiency of photovoltaic conversion process. Joshi et al [7] investigated the performance of photovoltaic and hybrid photovoltaic-thermal system by energy and exergy efficiency, regarded the solar radiation as the black body radiation, and calculated the incident solar radiation exergy by adopting the blackbody radiation exergy formulae. Sarhaddi et al [8] investigated the exergy efficiency of the solar cell array. As the same with Joshi et al [7], Sarhaddi et al [8] regarded the solar radiation as th blackbody radiation.

NOMENCLATURE

A	[m^2]	Area
c	[m/s]	Light velocity in vacuum
E	[W/m^2]	Energy flux
I	[W/(m^2 sr)]	Radiation intensity
L	[W/(m^2 sr)]	Radiation entropy intensity
P	[W]	Electrical power
Q	[W/m^2]	Heat flux
S	[W/(m^2 K)]	Entropy
T	[K]	Temperature
Special characters		
ε	[-]	Emissivity
β	[-]	Energy quality factor
λ	[μm]	Wavelength
η	[-]	Efficiency or percentage
θ	[-]	The angle between radiation beam and normal direction of the surface
ρ	[-]	Reflectivity
ψ	[W/(m^2 sr)]	Radiation exergy intensity
Ω	[sr]	Solid angle
Ψ	[W/m^2]	Exergy flux
Subscripts/Superscript		
0		Environment
b		Blackbody
bg		Bandgap
cf		Cut-off
dir		Direct terrestrial solar radiation
el		Electrical
em		Emission
in		Inlet
loss		Loss
out		Output
ph		Photon
re		Reflected

However, the references mentioned above regarded the solar radiation as blackbody radiation. In fact, the solar radiation is not the black body radiation for the terrestrial solar radiation utilization. The solar radiation is attenuated by the aerosol and gas, which cannot be regarded as the blackbody radiation. Moreover, the solar cell only absorbs part of the solar radiation. Therefore, the effect of the spectrum must be considered in the analysis the solar photovoltaic process.

ENERGY TRANSFER MODEL OF SOLAR CELL

The common solar cell consists of the semiconductor material at its backside and a glass layer on the front side. The glass serves as a protective coating against degradation due to mechanical and chemical attacks and as the substrate for the comparatively thin semiconductor layer. The energy flow diagram for a simple solar cell under a steady-state condition is shown in Fig.1. A is the photovoltaic active area of the solar cell. The incident solar radiation energy is AE_{in}. The reflected radiation energy reflected by the surface of solar cell is AE_{re}. The incident solar radiation energy except AE_{re} enters into the glass and semiconductor interior, and some of which converts to the electrical energy P_{el}, others converts to inner energy within the solar cell. The inner energy within the solar cell has to be conveyed to the environment by emission of infrared radiation of the glass layer AE_{em} or by heat convection on both sides of the solar cell Q.

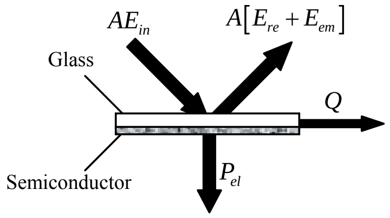

Figure 1 Sketch map of a simple solar cell model

The direct terrestrial solar radiation is attenuated on its path through atmosphere and a part of the scattered energy reaches the surface as diffuse terrestrial solar radiation. The polarization only affects the diffuse terrestrial solar radiation and the value of entropy flux for the isotropic diffuse radiation calculated under polarized radiation is only <2% lower than that under unpolarized radiation [9]. Therefore, the incident terrestrial solar radiation is considered to be unpolarized in the following analysis.

The solid angle of the sun's disc for present study is $\Delta\Omega = 6.7905244\times10^{-5}$ sr , and which was also recommended by Darula et al. [10] to calculate the luminance and illuminance. The incident direct terrestrial solar radiation is confined to a small solid angle $\Delta\Omega$ at normal orientation to the solar cell's surface.

Losses of incident solar radiation energy may occur because of the following three mechanisms, (1) the reflection of incident solar radiation at the air-glass interface, (2) the absorption in the glass material, and (3) the absorption of photons with $E_{\mathrm{ph}} = h\nu > E_{\mathrm{bg}} = hc/\lambda_{cf}$ and subsequent conversion to electrical energy. The cut-off wavelength λ_{cf} of the selected solar cell is 0.95μm in the paper.

RADIATION EXERGY

For unpolarized radiation, the spectral radiative intensity of blackbody at temperature T is determined by Planck's law [11] as

$$I_{b,\lambda} = \frac{2hc^2\lambda^{-5}}{\exp\left[hc/(k_b\lambda T)\right]-1} \tag{1}$$

And the spectral radiation temperature corresponding to any spectral radiative intensity I_λ is defined as

$$T_\lambda = \frac{hc}{k\lambda}\frac{1}{\ln\left[2hc^2\lambda^{-5}/I_\lambda + 1\right]} \tag{2}$$

The spectral radiative entropy intensity carried by a radiation beam with spectral radiative intensity I_λ defined by Planck [11] is as follows:

$$L_\lambda = 2k_bc\lambda^{-4}\left\{\left(\frac{I_\lambda}{2hc^2\lambda^{-5}}+1\right)\ln\left(\frac{I_\lambda}{2hc^2\lambda^{-5}}+1\right) - \left(\frac{I_\lambda}{2hc^2\lambda^{-5}}\right)\ln\left(\frac{I_\lambda}{2hc^2\lambda^{-5}}\right)\right\} \tag{3}$$

where λ is wavelength, c is speed of light in vacuum, h is Planck's constant and k_b is Boltzmann's constant, respectively.

Based on Planck's definition of radiative entropy intensity, Candau [12] defined the spectral radiative exergy intensity as

$$\psi_\lambda = I_\lambda - I_{0,\lambda} - T_0\left\{L_\lambda(I_\lambda) - L_{0,\lambda}\left[I_{0,\lambda}(T_0)\right]\right\} \tag{4}$$

where $I_{0,\lambda}$ and $L_{0,\lambda}$ are the spectral radiative intensity and spectral radiative entropy intensity of the blackbody at T_0, respectively. By integrating Eq. (4) over solid angle, the spectral radiative exergy flux is written as

$$\begin{aligned}\Psi_\lambda &= \int_\Omega \psi_\lambda \cos\theta \mathrm{d}\Omega \\ &= \int_\Omega \Big\{I_\lambda - I_{0,\lambda} \\ &\quad -T_0\left\{L_\lambda(I_\lambda) - L_{0,\lambda}\left[I_{0,\lambda}(T_0)\right]\right\}\Big\}\cos\theta \mathrm{d}\Omega\end{aligned} \tag{5}$$

Here θ is the angle between radiation beam and normal direction of the surface. By integrating Eq.(5) over wavelength, the radiative exergy flux is written as

$$\begin{aligned}\Psi &= \int_\lambda \Psi_\lambda \mathrm{d}\lambda \\ &= \int_\Omega\int_\lambda \Big\{I_\lambda - I_{0,\lambda} \\ &\quad -T_0\left\{L_\lambda(I_\lambda) - L_{0,\lambda}\left[I_{0,\lambda}(T_0)\right]\right\}\Big\}\cos\theta \mathrm{d}\lambda \mathrm{d}\Omega\end{aligned} \tag{6}$$

SPECTRUM EXERGY FLOW OF SOLAR CELL

As the diffuse terrestrial solar radiation energy is low quality energy, only the direct terrestrial solar radiation energy is to be taken into consideration, and the incident spectral radiative intensity is

$$I_{in,\lambda} = \frac{E_{in,\lambda}}{\cos\theta\Delta\Omega} = \frac{E_{in,\lambda}^{dir}}{\cos\theta\Delta\Omega} \quad (7)$$

and the spectral radiation entropy flux is

$$S_{in,\lambda} = \int_{\Delta\Omega} L_{in,\lambda}(I_{in,\lambda})\cos\theta \mathrm{d}\Omega \quad (8)$$

The reflected spectral radiation energy flux and spectral radiation entropy flux are

$$E_{re,\lambda} = \int_{\Omega} I_{re,\lambda}\cos\theta \mathrm{d}\Omega = \int_{\Omega} \rho_\lambda I_{in,\lambda}\cos\theta \mathrm{d}\Omega \quad (9)$$

$$\begin{aligned} S_{re,\lambda} &= \int_{\Delta\Omega} L_{re,\lambda}(I_{re,\lambda})\cos\theta \mathrm{d}\Omega \\ &= \int_{\Delta\Omega} L_{re,\lambda}(\rho_\lambda I_{in,\lambda})\cos\theta \mathrm{d}\Omega \end{aligned} \quad (10)$$

where ρ_λ is the spectral reflectivity of the glass-air surface.

The emission of the glass layer is the diffuse radiation, and the radiation energy mainly focuses in infrared region around $10\mu\mathrm{m}$. The emitted spectral radiation energy flux and spectral radiation entropy flux are

$$E_{em,\lambda} = \varepsilon_\lambda I_{b,\lambda}(T_A) = \varepsilon_\lambda \frac{2hc_0^2\lambda^{-5}}{\exp\left[hc_0/(k\lambda T_A)\right]-1} \quad (11)$$

$$S_{em,\lambda} = \int_{\Omega} L_{em,\lambda}\left(\varepsilon_\lambda I_{b,\lambda}(T_A)\right)\cos\theta \mathrm{d}\Omega \quad (12)$$

where ε_λ is the spectral emissivity of the glass layer, and T_A is temperature of the solar cell.

The maximum useful work per unit area of the solar cell at wavelength λ, i.e., the spectral incident direct terrestrial solar radiation exergy flux is

$$\Psi_{in,\lambda} = E_{in,\lambda} - E_{0,\lambda} - T_0(S_{in,\lambda} - S_{0,\lambda}) \quad (13)$$

The spectral energy quality factor of the incident direct terrestrial solar radiation energy is

$$\beta_{in,\lambda} = \frac{\Psi_{in,\lambda}}{E_{in,\lambda}} \times 100\% \quad (14)$$

The incident solar radiation is mirror reflected by the surface of solar cell. The reflected spectral radiation exergy flux per unit area of the solar cell is

$$\Psi_{re,\lambda} = E_{re,\lambda} - E_{0,\lambda} - T_0(S_{re,\lambda} - S_{0,\lambda}) \quad (15)$$

The emitted spectral radiation exergy flux per unit area of the solar cell is

$$\Psi_{em,\lambda} = E_{em,\lambda} - E_{0,\lambda} - T_0(S_{em,\lambda} - S_{0,\lambda}) \quad (16)$$

The spectral electrical energy generated in solar cell, i.e. the actual spectral exergy flux available is

$$\Psi_{out,\lambda} = P_{el,\lambda}/A \quad (17)$$

The spectral exergy efficiency is

$$\eta_{\Psi,\lambda} = \frac{\Psi_{out,\lambda}}{\Psi_{in,\lambda}} \times 100\% \quad (18)$$

The percentage of the reflected spectral radiation exergy flux, and that of the emitted spectral radiation exergy flux per unit area of the solar cell are

$$\eta_{\Psi,\lambda}^{re} = \frac{\Psi_{re,\lambda}}{\Psi_{in,\lambda}} \times 100\% \quad (19)$$

$$\eta_{\Psi,\lambda}^{em} = \frac{\Psi_{em,\lambda}}{\Psi_{in,\lambda}} \times 100\% \quad (20)$$

The percentage of the exergy loss generated in solar cell inner and that in the convective heat transfer between solar cell and environment is

$$\eta_{\Psi,\lambda}^{loss} = \frac{\Psi_{em,\lambda}}{\Psi_{in,\lambda}} \times 100\% \quad (21)$$

RESULTS AND DISCUSSIONS

The spectral energy quality factor of the direct terrestrial solar radiation is shown in Figure 2. It can be seen that the spectral energy quality factor is larger than 0.9 in the near ultraviolet, the visible light region and infrared region (0.762–0.931μm, 0.958–1.112μm, 1.155–1.327μm and 1.505–1.76μm). As the cut-off wavelength of the selected solar cell is 0.95μm, the terrestrial solar radiation with wavelength larger than λ_{cf} cannot be absorbed by the solar cell, thus cannot be utilized. Therefore, the incident direct terrestrial solar radiation in the near ultraviolet, the visible light region and infrared region (0.762–0.931μm) can be best utilized.

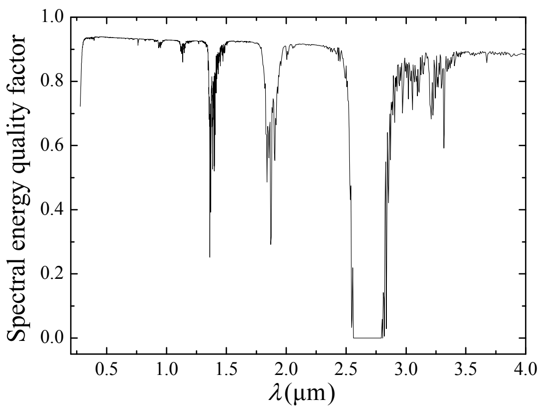

Figure 2 Spectral energy quality factor of the incident spectral direct terrestrial solar radiation

As shown in Figure 3, the spectral exergy efficiency of the solar cell is almost linearly distributed in visible region and infrared region under consideration. However, the spectral exergy efficiency of the solar cell firstly decreases and then increases in ultraviolet region. The percentage of the exergy loss firstly increases and then decreases. And the exergy loss generated in the ultraviolet is larger than that in the visible region and infrared region under consideration. The percentage of the spectral reflected radiation exergy flux increases first and then decreases with the increase of wavelength, and the maximum of which is 3.935% at $\lambda = 0.285\mu\text{m}$. The magnitude of the percentage of the spectral emitted radiation exergy flux is quite small, and the maximum of which is only in the order of 10^{-16}. Therefore the percentage of the spectral emitted radiation exergy flux is not given in Figure 3. Overall, the effect of the reflected and the emitted part on the spectral exergy efficiency of the solar cell is quite small.

It can be clearly seen that the spectral exergy efficiency and the percentage of the exergy loss intersects with each other at around $\lambda = 0.92\mu\text{m}$, and the spectral exergy efficiency is larger than the percentage of the exergy loss when $\lambda > 0.92\mu\text{m}$. The incident direct terrestrial solar radiation in the near ultraviolet, the visible light region and infrared region (0.762–0.931μm) is high quality energy (see Figure 2). Therefore, the terrestrial solar radiation energy in infrared region (0.92–0.931μm) can be best utilized for the selected solar cell.

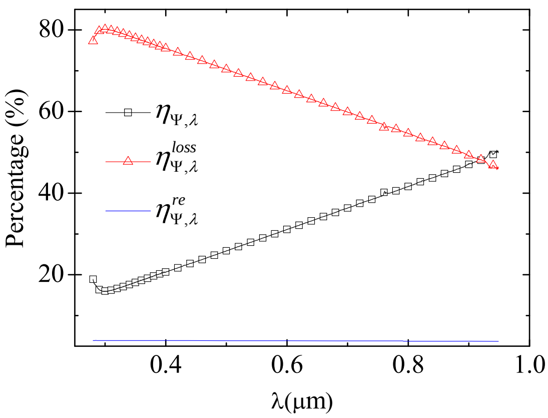

Figure 3 Percentage of the spectral radiation exergy flux

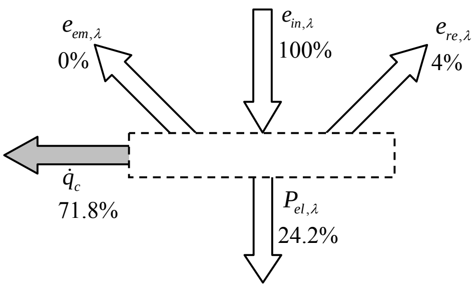

Figure 4 Energy flow diagram of solar cell at $\lambda = 0.5\mu\text{m}$

The energy flow and exergy flow diagram at $\lambda = 0.5\mu\text{m}$ and $\lambda = 0.93\mu\text{m}$ are given in Figure 4, 5, 6 and 7, respectively. The wavelength selected by 0.5μm is random, and wavelength 0.93μm is chosen as the best utilized for the selected solar cell.

It can be clearly seen that the spectral exergy efficiency is larger than the spectral energy efficiency. The energy loss generated in the solar cell is 71.8% (at $\lambda = 0.5\mu\text{m}$) and 50.98% (at $\lambda = 0.93\mu\text{m}$), respectively; however the exergy loss is 70.29% and 47.26%. The energy efficiency of the solar cell is 24.2% (at $\lambda = 0.5\mu\text{m}$) and 45.02% (at $\lambda = 0.93\mu\text{m}$), respectively; however the exergy efficiency is 25.85% and 49.01%.

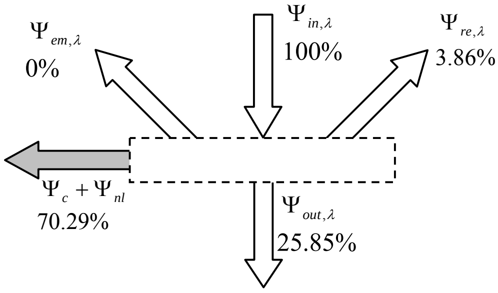

Figure 5 Exergy flow diagram of solar cell at $\lambda = 0.5\mu\text{m}$

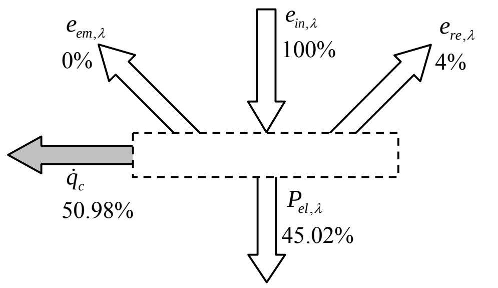

Figure 6 Energy flow diagram of solar cell at $\lambda = 0.93\mu\text{m}$

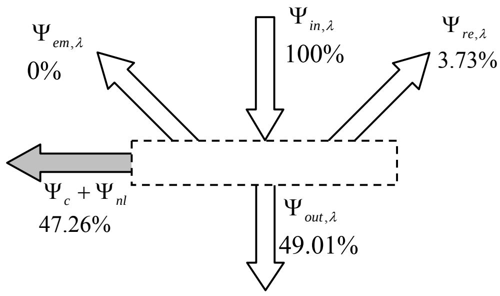

Figure 7 Exergy flow diagram of solar cell at $\lambda = 0.93\mu\text{m}$

As mentioned above, the losses of the incident solar radiation energy may occur because of the absorption of the photons with $E_{\text{ph}} = hv > E_{\text{bg}}$ and subsequent conversion to electrical energy, and which has to be conveyed to the environment by heat convection on both sides of the solar cell. Actually, the exergy loss generated in the convective heat transfer for whole spectrum is far less than 70.29% or 50.98%, which has to be given in Ref [13]. And the energy efficiency published is less than 30% for silicon solar cell. In another word, the spectral utilization for solar photovoltaic conversion is with promising. However, the spectral utilization for solar photovoltaic conversion is rather sophisticated and not easy to achieve.

CONCLUSION

On the basis of the definition of spectral radiation exergy intensity, the present paper deduced the spectrum exergy flux and spectrum exergy efficiency. The energy flow diagram and the exergy flow diagram at given wavelength are described respectively. The utilization of available energy in solar energy is illuminated more effectively by exergy analysis than that by energy analysis. The results show that the exergy efficiency of the solar cell in visible region and infrared region (0.762-0.931μm) is larger than that in ultraviolet region. The terrestrial solar radiation energy in infrared region (0.92–0.931μm) can be best utilized for the selected solar cell.

The spectral exergy efficiency is quite larger than the efficiency of silicon solar cell published. The spectral utilization for solar photovoltaic conversion is recommended, however, which is rather sophisticated and not easy to achieve. The present paper is an attempt to adopt the spectrum exergy analysis for solar photovoltaic process.

ACKNOWLEDGEMENTS

The supports for this work by the National Science Foundation for the Strategic Emerging Industry Development Special Foundation of Shenzhen (No. JCYJ20130329160901934), Post-doctoral Scientists of China (No. 2013M531038), and the National Natural Science Foundation of China (No. 51206111), are gratefully acknowledged.

REFERENCES

[1] P. Baruch, A. De Vos, P. T. Landsberg, J. E. Parrott. On Some Thermodynamic Aspects of Photovoltaic Solar Energy Conversion. Solar Energy Materials and Solar Cells, 1995, 36(2): 201-222

[2] V. Badescu, P. T. Landsberg. Statistical Thermodynamic Foundation for Photovoltaic and Photothermal Conversion. Ⅱ. Application to Photovoltaic Conversion. Journal of Applied Physics, 1995, 78(4): 2793-2802

[3] D. Labuhn, S. Kabelac. The Spectral Directional Emissivity of Photovoltaic Surfaces. International Journal of Thermophysics, 2001, 22(5): 1577-1592

[4] T. Markvart, P. T. Landsberg. Thermodynamics and Reciprocity of Solar Energy Conversion. Physica E, 2002, 14(1-2): 71-77

[5] A. De Vos, S. M. Peter. Comments in a Thermodynamic Paradox Presented by P. Wufrel. Journal of Physics C: Solid State Physics, 1983, 16: 6897-6909

[6] T. J. Coutts. A Review of Progress in Thermophotovoltaic Generation of Electricity. Renewable and Sustainable Energy Reviews, 1999, 3(2-3): 77-184

[7] A.S.Joshi, I. Dincer, B. V. Reddy. Performance analysis of photovoltaic systems: A Review. Renewable and Sustainable Energy Reviews, 2009, 13(8): 1884-1897

[8] F. Sarhaddi, S. Farahat, H. Ajam, et al. Exergetic Performance Evaluation of a solar Photovoltaic (PV) Array. Australian Journal of Basic and Applied Sciences, 2010, 4(3): 502-519

[9] C. A. Gueymard. Prediction and Validation of Cloudless Shortwave Solar Spectra Incident on Horizontal, Tilted, or Tracking Surfaces. Solar Energy, 2008, 82(3): 260-271

[10] S. Darula, R. Kittler, C. A. Gueymard. Reference Luminous Solar Constant and Solar Luminance for Illuminance Calculations. Solar Energy, 2005, 79(5): 559-565

[11] M. Planck. The Theory of Heat Radiation. New York: Dover Publications, 1959

[12] Y. Candau. On the exergy of radiation. Solar Energy, 2003, 75(3): 241-247

[13] Chu Shuangxia, Liu Linhua. Thermodynamic analysis of photovoltaic conversion process in solar cell. Acta Energiae Solaris Sinica. 2008,29(12):1494-1498