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A holistic approach to thermodynamic analysis of photo-thermo-electrical processes in a photovoltaic cell

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ABSTRACT

In this study, a novel approach for energy and exergy analyses of a photovoltaic (PV) cell is presented, and the exergy destructions within the relevant optical, thermal and electrical processes are quantified. The present study uses a holistic approach to cover all processes and their interactions inside a PV cell; such as photonic: photons transmission, reflection and spectral absorption, background (blackbody) radiation emission at cell temperature; electrical: electron excitation to create a photocurrent, electron-hole recombination, electrical power transmission to an external load; and thermal: internal heat generation by shunt and series resistances, and heat dissipation by conduction-convection. A physical model which considers the highly complex interaction and interdependence among these processes is introduced based on energy and exergy balances completed by writing various constitutive equations, including correlations for the convective heat transfer coefficient and the photocurrent dependence of the spectral distribution of the quantum efficiency. The irreversibilities caused by the processes are assessed in terms of their relative magnitudes of the exergy destructions. The largest exergy destruction occurs in PV generator-photo current generation process followed by wafer-light absorption process. The overall energy and exergy efficiencies are then determined based on the novel model for seven different atmospheric and ecological conditions. The lowest and highest exergy efficiencies of the PV cell are calculated as 9.3% and 14% for two sample locations as Oshawa in Canada and Emirdag in Turkey, respectively. Furthermore, the effects of varying ambient conditions, light spectrum, wind velocity and solar intensity on the PV cell performance are investigated for comparative evaluations.

1. Introduction

Solar energy is the most abundant source of energy on the earth. The majority of physical and chemical reactions encountered on earth, including photosynthesis and water and air circulation in the atmosphere, is a direct or indirect result of solar radiation. In order to effectively utilize solar energy, the first issue encountered is the low density of solar radiation per unit of earth surface [1]. Hypothetically, the solar spectrum is more effectively utilized if instead of converting the concentrated radiation in high temperature heat, one produces hydrogen via high energy spectrum, one produces electricity with photovoltaic modules using middle spectrum photons and one converts only the high temperature heat associated with long wave photons to electricity using a suitable thermodynamic power cycle [2]. The spectral splitters can easily be developed by employing an appropriate combination of optical filters. Various dielectric coatings can be deposited in thin films to generate selective filters or selective reflective surfaces. There are, in this regard, various studies presented in the literature to investigate the PV and PV/T system performances with/without those surfaces.

Rawat et al. [3] presented a study for energy and exergy performances of PV systems to define the long-term performance in actual operational conditions. The degradation rate of 3.2 kWP CdTe PV system is found to be 0.18% per year after 23 months of operation in composite climate which is lower than the reported degradation rate of earlier CdTe technology. Nagae et al. [4] demonstrated that the FOF (field output factor) of a-Si PV panels meaningfully depends on the change of the incident solar spectrum. In their research, for stacked a-Si PV modules, little influence of both APE (average photon energy) and module temperature on FOF was observed. Bicer et al. [5,6] assessed the performance of a PV cell under various spectral irradiance by conducting experimental studies using different type of optic filters and measurement

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Nomenclature

A_c	PV cell surface area (m^2)
A_λ	spectral absorbance
c	photonic constant (mK)
c	speed of light (3×10^8 m/s)
CPV	concentrated photovoltaic
e	charge of an electron ($1.60217657 \times 10^{19}$ C)
$\dot{E}$	energy rate (W)
$\dot{E}x$	exergy rate (W)
ex	specific exergy (J/kg)
h	Planck's constant ($6.62606957 \times 10^{-34}$ m^2 kg/s)
h_c	heat transfer coefficient (W/m^2 K)
I	irradiance (W/m^2)
J	current density (A/m^2)
k	Boltzmann constant (1.3806488×10^{23} J/K)
k	extinction coefficient
k_t	thermal conductivity (W/mK)
n	refraction index
P	pressure (kPa)
PV	photovoltaic
$\dot{Q}$	heat transfer rate (W)
R	reflectance
R_s	internal series resistance of PV cell
SF	shape factor
S_{T_o}	total amount of normal radiation (W/m^2)
S_T	global solar radiation (W/m^2)
$\dot{S}$	entropy rate (W/K)
s	specific entropy (J/kg K)
$\mathcal{T}$	transmittance
T	temperature (K)
U	overall heat transfer coefficient (W/m^2 K)
v	wind speed (m/s)
V	voltage (V)
$\dot{W}$	work rate (W)

Greek symbols

η_{en}	energy efficiency
η_{ex}	exergy efficiency
η_c	ideal conversion effectiveness of solar radiation
λ	wavelength
θ	incident angle
Φ	spectral quantum efficiency
π	Pi number

Subscripts

abs	absorbed
act	actual
b	blackbody
c	cell
cas	casing
d	destruction
D	diode
g	gap
in	input
m	maximum
max	maximum
min	minimum
oc	open circuit
ov	overall
pce	power conversion efficiency
POA	plane of array
ph	photon
rad	radiation
rev	reversible
s	serial
s	sun
sc	short circuit
sh	shunt
waf	wafer
tot	total
$\circ$	ambient condition

devices. It was concluded that separation of spectrum could be beneficial when whole spectrum is utilized properly. Saloux et al. [7] developed electrical and thermal models of PV/T system operating under different environmental conditions such as solar intensity and ambient temperature considering the irreversibilities. Ho et al. [8] analyzed the solar concentration limits for high concentrated photovoltaic cells by using a two-phase cooling design. The results from their analysis emphasized that the limits are close to 2000 suns for the six organic fluids investigated, but for water and ammonia, the practical concentration limit could rise until about 4000 and 6000 suns, respectively.

Current efficiency values of PV systems continue to improve as reported by many researchers. Peumans and Forrest [9] evaluated power conversion efficiency of an organic thin-film double-heterostructure photovoltaic cells using vacuum-deposited copper phthalocyanine/C60. In 2001, they found the efficiency as 3.6% and resulted that the efficiency of organic solar cells employing an EBL can be significantly higher than conventional cells, depending on materials and processing parameters. As reported by Green et al. [10] on regular basis, currently Si (multi-crystalline) PV cell confirmed efficiencies can rise up to 21.2% while thin film (GaAs) types can be more efficient reaching up to 28.8% for terrestrial cells. Furthermore, for a concentration of 508 suns, GaInAsP/GaInAs based multi-junction cell efficiency was measured as 46% for a really small cell with an area of 0.0520 cm^2.

There have been a couple of studies related to exergy analysis of PV or PV/T systems. Zamfirescu and Dincer [11] proposed thermodynamic model to study the exergetic content of incident solar radiation reaching on the Earth's surface which can be used to produce work through a dually cascaded thermodynamic cycle. The model shows that the whole Earth functions as a heat engine coupled to a brake such that the insolation and also the climate are predictable as a constructal design of the global flow system. Agrawal and Tiwari [12] compared the performances of various types of PVT collectors operated throughout the year. The unglazed PVT air collector in their study had the highest exergetic efficiency. They also emphasized the inverse relation between the cell temperature and electrical efficiency of the PVT by suggesting further life cycle cost assessment studies. Sudhakar and Srivastava [13] performed energy and exergy analysis of a PV array to determine exergy losses during the PV conversion process considering the operating and electrical parameters, PV module temperature, overall heat loss coefficient, open-circuit voltage, short-circuit current and fill factor as experimentally. They concluded that the exergy losses increased with increasing module temperature and the exergy efficiency can be improved if the heat can be removed from the PV module surface. Energy and exergy efficiencies for PV module were found to be 6.4% and 8.5%, respectively. Joshi and Tiwari [14] evaluated exergy analyses of a hybrid photovoltaic–thermal (PV/T) parallel plate air collector for cold climate circumstance of