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Thermodynamic study of solar photovoltaic energy conversion: An overview

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ABSTRACT

The thermodynamic basis of energy conversion systems is being utilized to carry out performance assessments and feasibility studies on photovoltaic (PV) systems in order to improve the design and efficiency of the system. The thermodynamic process of converting solar radiation directly into electrical energy, i.e. solar PV energy conversion, has been established, which includes electrical power generation, optical/thermal losses and electrical losses. In this paper, the thermodynamic modeling based on energy, endoreversible, entropy and exergy models of solar PV energy conversion system has been presented using the first and second law of thermodynamic, with an updated literature survey. The energetic and exergetic efficiencies of PV system have been evaluated and the reported theoretical upper limit efficiency of PV system using different thermodynamic models have been presented.

1. Introduction

The theory of solar PV energy conversion can be classified broadly on the basis of dual nature of solar radiation, i.e. particle and wave nature. While assuming the solar radiation to be particle nature, the photons of energy greater than and equal to the energy band gap of the solar PV cell are responsible for the electric energy generation, and the energy difference between the band gap and higher energy photons are contributing to the heat energy through the thermalization process [1]. On the other hand, while assuming it to be wave nature, the wavelength of absorbed solar radiation matching with the spectral response of the solar cell, i.e. nearly visible range, is mainly responsible for electrical energy generation and the remaining absorbed radiation of mostly infrared range contributes to the generation of heat energy. The quantitative study of the solar energy conversion is being carried out on the basis of the first law of thermodynamic, which deals with energy balance, while the qualitative analysis of solar energy conversion is being carried out on the basis of both first and second laws of thermodynamic which includes energy, entropy and exergy balance [2]. The exergy or available energy or availability is the measure of maximum useful work that can be achieved from a system during the interaction with environment irrespective of the entropy generation or exergy destruction or irreversibility or lost available work [3]. It is an effective tool which can be utilized for the design, optimization, and performance analysis of energy systems in order to facilitate the policy making and sustainable development, and also to study the economic and environmental impact of the system [4–8].

The solar radiation can be converted into thermal, electric and chemical energy for utilization by photothermal, photovoltaic, photochemical processes respectively [9]. However, the solar PV conversion is one of the most widely used application of solar radiation for up to kW scale household appliances as well as MW scale grid connected electricity production [10]. The solar PV energy conversion is a complex hybrid system which generates dual output i.e. electric and heat, from a single input i.e. solar radiation. The solar PV cell is a p-n junction semiconductor device which converts solar radiation into electric energy as well as some low grade heat energy which can be utilized for the back surface of the cell. The solar radiation is absorbed by the semiconductor material which leads to the generation and separation of charge carrier. The excited charge carriers from valence to conduction band due to the photon absorption gives rise to the electric power generation. The detailed characteristic parameters of the solar PV cell are given in Fig. 1.

In this paper, an attempt has been made to critically review the various thermodynamic models, efficiencies and upper limit of the efficiencies of solar PV energy conversion system as reported in the literature. The main objective of the paper is to study the various thermodynamic models of the PV system for their utilization in the performance analysis so as to identify the possible locations of improvement in the PV system. The paper accrues the different thermodynamic models of solar PV energy conversion system in order to clarify the ambiguity of the subject. The assessment of practical and theoretical upper limits of thermodynamic efficiencies has been carried out.

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Nomenclature

A	Area of PV module (m^2)
B	Exergy
C_1, C_2	Proportionality Coefficients
E	Output electrical energy (W)
G	Incident solar irradiance (W/m^2)
h	Connective heat transfer coefficient (W/cm^2-K)
H	Incident solar radiation over the given time (Wh/m^2)
I	Current
N	Photon particle flux
Q	Energy
P	Power output
S	Entropy
T	Temperature (K)
v	Wind velocity (m/s)
W	Work

Subscripts

0	Ambient/Environment
C	Convective
exp	Isothermal expansion of etendue
gen	Generation
ic	Irreversible cooling
I	Instantaneous
kin	Kinetic
m	Module
M	Maximum power point
PV	Photovoltaic
PVT	Photovoltaic-Thermal
R	Reflected solar radiation
RD	Radiative heat transfer
S	Solar Radiation/Sun
sky	Sky
T	Transmitted through cell
TH	Thermalization
U	Useful/Recoverable

Greek Letters

∂B	Exergy destruction
ρ	Reflection coefficient
μ	Chemical potential
ψ	Exergetic efficiency
ξ_{in}	Etendue of incident radiation
ε	Emissivity
η_s	Exergy of solar radiation
η	Energetic efficiency
ξ_{out}	Etendue of emitted radiation

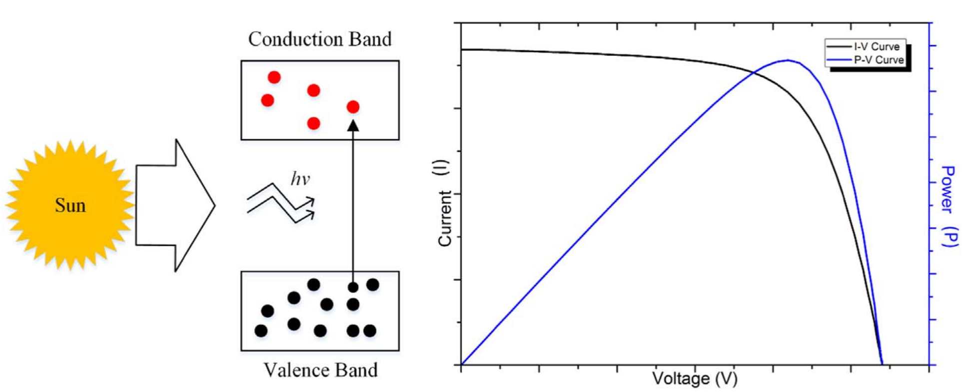
2. Thermodynamics of solar photovoltaic energy conversion

Park et al. [11] reviews the methodology for energy and exergy analysis of different solar energy conversion systems. The upper limit of utilization or conversion of solar radiation for a given environmental condition is known as the exergy of solar radiation [12,13]. Bejan [14] has studied the Petela, Jetter and Spanner theory of exergy of radiation and considered all of them to be correct as per their assumption while Badescu [15] has recommended Petela and Jetter theory for solar radiation utilization. The expression for calculating exergy of solar radiation is given by several researchers (Table 1).

The thermodynamics of solar PV energy conversion are being explored using first and second law of thermodynamic by several researchers for performance evaluation and efficiency improvement [25–27]. Baruch et al. [28] uses the thermodynamic approach in order to understand the operation and investigate the effect of energy band gap on the performance of solar PV cell. Rusirawan [29] has carried out an exergetic assessment of a PV system by thermodynamic as well as photonic energy method. Koroneos and Stylos [30] has carried out an exergetic life cycle assessment (LCA) of polycrystalline silicon grid connected PV plant and recommended the utilization of exergetic sustainability for environmental decision making. Gong and Wall [31] have also recommended the utilization of the exergy concept for LCA of solar PV systems. Sundaram and Raju [32] have carried out performance analysis of 5MW$_P$ grid connected PV plant installed in south India on the basis of energy as well exergy efficiency. Gaur and Tiwari [33] has carried out exergoeconomic analysis of semitransparent and opaque crystalline silicon and thin film PV technology modules. Bicer et al. [34] have presented the photo-thermo-electrical processes of the solar PV system and assessed irreversibilities associated with the processes. The thermodynamic studies of PV system, available in the literature, has been classified into the following models:

2.1. Energy model

The energy model of solar PV cell is based on the first law of thermodynamic, which shows that the solar radiation (Q_S) received over the PV surface is partly reflected back from the top glass (Q_R) and partly absorbed by the PV module. The absorbed solar radiation energy is distributed in the following components: (i) energy loss to the



(a) (b)

Fig. 1. Characteristics of Solar PV cell (a) absorption of incident photon of solar radiation and charge excitation from valence to conduction band (b) current-voltage (I-V) and power-voltage (P-V) curve of solar PV generation.

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