Energy Conversion and Management 136 (2017) 152–160

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

An innovative thermodynamic model for performance evaluation of photovoltaic systems: Effect of wind speed and cell temperature

S.C. Kaushik, Rahul Rawat *, S. Manikandan

Centre for Energy Studies, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India

ARTICLE INFO

Article history:
Received 26 September 2016
Received in revised form 27 December 2016
Accepted 5 January 2017

Keywords:
Photovoltaic
Thermodynamics
Exergy
Modelling
Upper limit efficiency

ABSTRACT

The photovoltaic energy conversion is a thermodynamic system which converts the solar energy to the electrical and thermal energy. In this paper, a novel thermodynamic model of photovoltaic energy conversion system has been proposed on the basis of the first and second law of thermodynamics including entropy generation, optical, thermal, spectral and fill factor losses. Based on the irreversibilities, the proposed model has been classified into four cases i.e. reversible, endoreversible, exoreversible and irreversible systems, for which, the expressions of energetic and exergetic efficiencies have been derived. The upper limit efficiency of an ideal photovoltaic module placed in an irreversible environment, i.e. endoreversible system, is determined to be 82.8%. The effect of wind speed and module temperature on the energetic and exergetic efficiencies, thermodynamic losses and irreversibilities has also been presented.

1. Introduction

The first law of thermodynamics is based on the quantitative analysis of the conservation of energy in any energy conversion process, while the second law of thermodynamics includes qualitative analysis along with the quantitative analysis by taking account of irreversibilities associated with the energy conversion [1].

The photovoltaic energy conversion (PVEC) system is a thermodynamic system which converts low grade solar energy into high grade electrical energy [2]. It absorbs the solar radiation (photons having energy greater than or equals to the bandgap) in order to generate electrical energy with some amount of thermal energy losses to the environment [3]. The ideal solar cell is defined as a PV device which absorbs all the incident photon of the solar radiation without any losses and each photon generates an electron-hole pair which flows in the external circuit through the electrodes without any electrical losses. From ideal to practical PVEC system, it undergoes a number of losses at several stages which comprises of optical, thermal and spectral mismatch losses to the environment, entropy associated with the low grade solar radiation and electrical losses due to series and shunt resistance [4]. The losses in a practical PVEC system are as follows [5]:

- Optical losses (Reflection): Although, anti-reflective coating is being used in solar cells in order to reduce the reflection losses, the incoming solar radiation is partially reflected to the environment from the surface of the PV cell.
- Spectral mismatch losses: The PV cell is not an opaque device to entire solar spectrum, therefore only the radiation matching the spectral response of the PV technology is absorbed.
- Thermal losses: It includes radiative and convective heat transfer to the environment from the surface of the PV cell.
- Fill factor loss: The non-linear I-V characteristics of PV cell due to series and shunt resistance contribute to the fill factor losses.
- Irreversibilities due to entropy generation during the PVEC process.

There are several thermodynamic models proposed by researchers based on energy, exergy and entropy balance in order to predict the thermodynamic losses and the upper limit efficiency of the PVEC system however, the models are based on idealistic situations which have not considered the electrical modelling and actual losses [6]. The Shockley-Queisser (1961) has proposed the theoretical upper limit efficiency of solar cell of 1.1 eV band gap to be 30% based on the radiation balance theory assuming the sun and solar cell to be black body [7]. They assumed that all the photons having energy equal to or more than the band gap energy are absorbed in order to generate electron hole pair having infinite mobility, and only radiative recombination takes place in the cell. The analogy of PVEC system with the endoreversible thermody-

* Corresponding author.
E-mail address: rawatktp@gmail.com (R. Rawat).

http://dx.doi.org/10.1016/j.enconman.2017.01.011
0196-8904/

Nomenclature

B	exergy
Cp	heat capacity
Eout	energy output
FF	fill factor
h	convective heat transfer coefficient
I	current
I_{01}, I_{02}	leakage current
Irr	irreversibility
K	Boltzmann constant
M	mass
Pout	power output
Q	heat
Q	electron charge
R_S	series resistance
R_{SH}	shunt resistance
S	entropy generation
SF	spectral factor
SR	spectral response
T	temperature
V	voltage

Greek letters

Ε	emissivity
Η	energetic efficiency
η_{d1}, η_{d2}	ideality factor of diodes
Λ	wavelength
Ρ	reflectivity
Σ	Stefan-Boltzmann constant
Ψ	exergetic efficiency

Subscripts

C	convective
CD	heat sink (Cold)
E	environment
gen	generation
H	heat source (Hot)
I	internal
M	PV module
MP	maximum power point
S	sun
SC	short circuit
SKY	sky
SM	spectral mismatch
R	reflective
RD	radiative

namic engine has been explored by Vos and Pauwels [8]. Based on the endoreversible model, the upper limit efficiency of single junction solar cell was estimated to be 40.8% by Vos [9] and multi-junction solar cell assuming infinite number of junction was estimated to be 86.8% by Grosjean and Vos [10]. The Landsberg limit for PVEC is found to be 93.3%, which is higher than the earlier models and have taken account of entropy generation. The thermodynamic analysis of the system have not included the entropy generation during absorption and emission in the Landsberg limit however, a theoretical basis has been proposed for further exploration [11]. Badescu and Landsberg [12] have modelled an optimally cooled silicon solar cell having improved radiative recombination efficiency and ideal optical properties in order to estimate the theoretical efficiency of solar cell to be 30%. They have also determined the theoretical efficiency of silicon solar cell without cooling and optical enhancement, having ideal absorption and typical radiative recombination efficiency to be 13%. Luque and Marti [13] have determined the theoretical limit for black body radiation based on entropy balance equation to be 93.1%. Sahin et al. [14] have investigated the thermodynamics of the solar PVEC system based on the exergy balance equation. Noel et al. [15] have introduced the free energy for charge transfer at the interface, which increases the recombination loss, and reduces the Shockley-Queisser limit for organic solar cell to 27%. Gruber et al. [16] have also applied the detailed energy balance principle for calculating the upper limit efficiency of inorganic solar cell, including charge transfer loss and found the upper limit efficiency to be 23.6%. Nozawa and Arakawa [17] have calculated the upper limit efficiency of intermediate band solar cell using detailed balance theory which comes out to be 74.6% for 4 intermediate bands in between the conduction and valence bands and it is found to be approaching 80% by increasing the intermediate bands. The detailed balance chemical kinetic model by Hanna and Nozik [18] have proposed the upper limit efficiency of single junction solar cell to be 33.7% of the cells with no carrier multiplication and 44.4% of the cells with carrier multiplication. The efficiency of the cells with carrier multiplication has been further revised to 45.9% by considering it as endothermic exciton solar cell [19]. The upper limit efficiency for multijunction cell with full concentration of radiation has been estimated to be 85% and 84.1% by Wurfell [20] and Wright et al. [21] respectively. Rajput et al. [22] have proposed a mathematical modelling of a crystalline silicon solar cell, including thermal and electrical modelling of hot spots. The proposed modelling is based on the energy balance and the second law of thermodynamics has not been considered. Zarei and Abdolzadeh [23] have carried out the optical-thermal modelling of tilted solar PV modules incorporating the effect of dust deposition over the top surface. Rawat et al. [24] have carried out performance evaluation of PV system using energy and exergy balance. Markvart [25] has investigated the potential for development of future generation of solar photovoltaic cells using thermodynamic models. Slimani et al. [26] have carried out a comparative performance analysis of different PV system configuration based on a detailed numerical model. Slimani et al. [27] have studied the photovoltaic thermal system for solar dryer on the basis of energy analysis.

Based on the literature survey, it can be concluded that the existing thermodynamic models of the solar PVEC systems have not incorporated the detailed electrical, thermal and thermodynamic losses in the analysis. The models are complex and have been intended for characteristics of solar cells. It has also been found that some of the exergy losses have not been accounted in the existing thermodynamic modelling and analysis of PV cell. The solar PV module is practically used for the power generation which is the combination interconnected solar cells, conductor for collecting generated charge, encapsulation and external connections enclosed in the glass. The response of PV module to environmental conditions and solar irradiance is different to that of a solar cell. In the present study, a novel thermodynamic modelling of the PVEC system has been proposed on the basis of the first and second law of thermodynamics, incorporating the electrical, thermal and thermodynamic losses. The proposed thermodynamic model is simple and has been assessed for four different thermodynamic cases. A detailed analysis has been carried out for the effect of environmental parameters.