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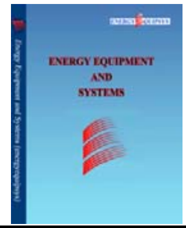

Thermodynamic and economic comparison of photovoltaic electricity generation with and without self-cleaning photovoltaic panels

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ABSTRACT

In this study, thermodynamic and economic analysis of a photovoltaic electricity generation system (PVEGS) with and without self-cleaning panels is reported. In the first part, thermodynamic analyses are used to characterize the performance of the system. In the second part, the economic comparison of photovoltaic electricity generation with and without self-cleaning panels is carried out for all climate zones of Iran. A computer simulation program using EES software is developed to model the solar photovoltaic electricity generation system in four different climates of Iran. The solar photovoltaic system provides electricity during the year. Our goal is to point out the potential of electricity production using conventional panels compared to self-cleaning panels under the same condition. The analysis involves the specification of the effects of varying solar radiation intensity (SRI) on the electricity generation rate of the photovoltaic electricity generation system. The average output power values for the solar photovoltaic system with self-cleaning panels and the solar photovoltaic system without self-cleaning panels are found to be 50767 and 48120 kWh/year, respectively, which means that the solar photovoltaic system with self-cleaning panels has the higher performance than the solar photovoltaic system without self-cleaning panels in all climate zones of Iran.

Keywords: Thermodynamic and Economic Analysis, Photovoltaic Electricity Generation System, Self-Cleaning.

1. Introduction

The soiling of PV systems result in the shadowing of the PV cells and thus considerably reduces the efficiency of the installed PV systems to be well below their expected capacity rating [1]. Cleaning dusty PV panels with several detergents can be time-consuming, expensive, and perilous to the environment or even corrode the solar panel frame. Because of that, scientists are trying to develop self-cleaning PV systems [2]. Recently, self-cleaning coatings on the cover glass are proposed as one of the feasible solutions to retain the PV cell efficiency against dust cumulation [3]. Since solar energy is one of the most widely-used energy sources, many researchers have contributed to different researches. Arabatzis et al. [4] Monitored the outdoor performance of coated and uncoated PV systems for several months at different climate conditions in order the extra energy produced due to coating to be measured.

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They showed that, under real outdoor conditions, the coated PV systems showed an average gain of 5–6% for the monitored time. Fouad et al. [5] reviewed the factors affecting the performance of PV panels. They conducted that, researchers can build on their study by researching new ways to decrease the effect of certain factors which can further enhance the performance of PV systems. Rawat et al. [6] conducted thermodynamic study of a solar PV system. They used thermodynamic basis to carry out performance assessments and feasibility studies on PV systems in order to improve the design and efficiency of them. They also carried out Energetic and exergetic performance analysis of CdS/CdTe based PV technology in real operating conditions [7]. Cuce et al. [8] carried out an accurate model for PV modules to determine electrical characteristics and thermodynamic performance parameters. Özalp et al. [9] conducted a comparative thermodynamic analysis of different exergetic efficiency methods for a PV system. They showed the exergetic efficiency of the PV module are functions of environmental, operational and design parameters. Iran's unique geographical position means 90% of the country has enough sun to generate solar power 300 days a year. Figure 1 indicates the map of solar irradiation in Iran [10].

As can be seen in Fig. 1, Iran has been zoned into four solar irradiation zones as listed below:

- ✓ Zone 1: With annual-mean daily irradiation of 5.2 to 5.4 kWh/m^2/day
- ✓ Zone 2: With annual-mean daily irradiation of 4.5 to 5.2 kWh/m^2/day
- ✓ Zone 3: With annual-mean daily irradiation of 3.8 to 4.5 kWh/m^2/day
- ✓ Zone 4: With annual-mean daily irradiation of 2.8 to 3.8 kWh/m^2/day

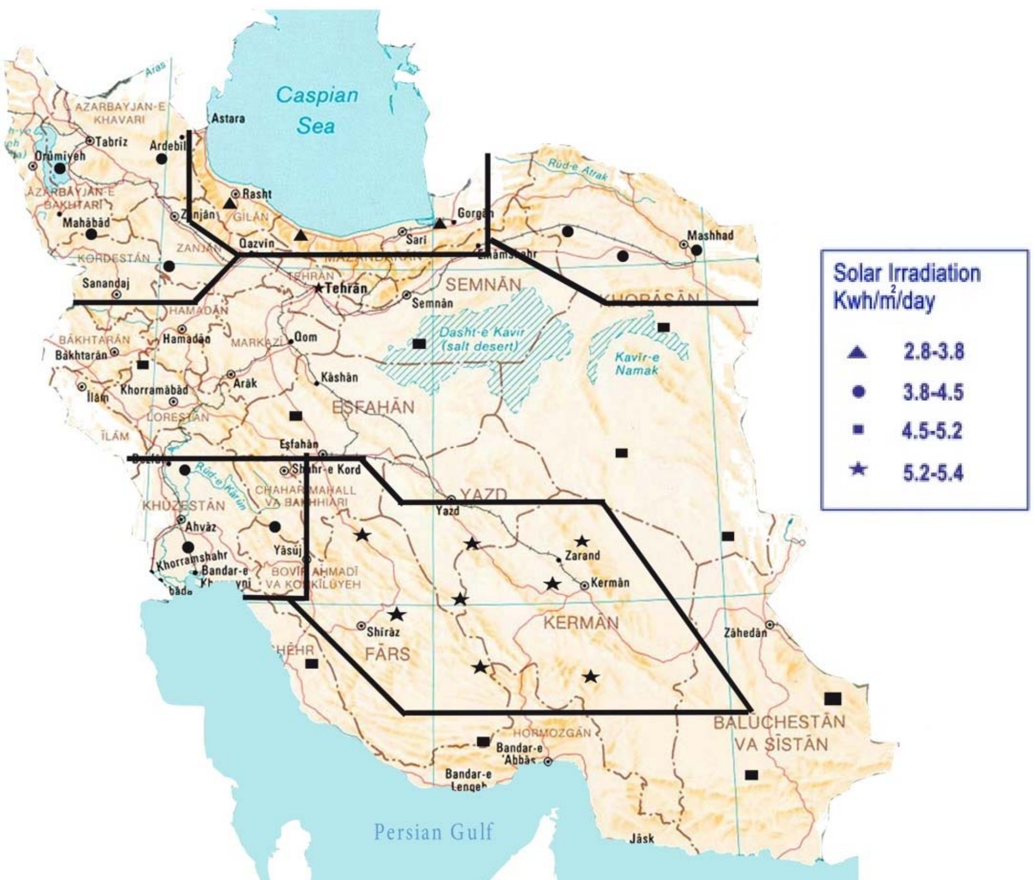

Fig. 1. The map of solar irradiation in Iran

The lowest zone with an annual average daily irradiation of 3.3 kWh/m^2/day is the low lands of the Caspian Sea, and the highest zone with an average irradiation of 5.3 kWh/m^2/day is the very high lands in the southern central zones of Iran.

In this study, a PVEGS consist of a solar PV, a DC/AC inverter and a fusebox is thermodynamically modeled and assessed with thermodynamic and economic analyses. The primary objectives are to improve understanding of this PVEGS with using self-cleaning coatings and promotion using self-cleaning solar PV systems instead of conventional solar PV panels. The following specific works are carried out:

- Model and simulate (using EES software) the PVEGS.
- Validate the model.
- Perform thermodynamic analyses of the PVEGS.
- Energetic and exergetic performance comparison of the PVEGS with conventional and self-cleaning solar panels.
- Economic comparison of the PVEGS with conventional and self-cleaning PV panels.

The system description and assumptions are presented next. Then, system modeling, results and discussion and conclusions are presented, respectively.

Nomenclature

amb	Ambient
A_{PV}	The solar PV surface (m^2)
CV	Control volume
E	Energy
$\dot{E}$	Exergy rate, kW
e	Exit
G_b	Solar radiation intensity, kW/m^2
h	Specific enthalpy (kJ/kg)
i or in	Inlet
$\dot{I}$	Exergy destruction rate (kW)
kW	kiloWatt
kWh	KiloWatt-hour
$\dot{m}$	Mass flow rate (kg/s)
MIRR	Million Rials
PVEGS	Photovoltaic electricity generation system
P	Pressure (kPa)
PV	Photovoltaic
$\dot{Q}$	Heat rate, kW
s	Specific entropy (kJ/kg-K)
S	Sun
SATBA	Iran Renewable Energy and Energy Efficiency Organization
SRI	Solar radiation intensity (kW/m^2)
T_S	Sun temperature (K)
T	Temperature ^0C or K
t	Time
V	Volume
$\dot{W}$	Work rate, kW
$\dot{W}_{net,SC}$	Work rate with using self-cleaning panels, kW
$\dot{W}_{net}$	Work rate without using self-cleaning panels, kW
0	Dead state

Greek symbols

η_{ex}	Exergy efficiency
ψ	Specific exergy, kJ/kg
η_{en}	Energy efficiency

2. Material and Methods

In this section, the characteristics of the PVEGS and its components are explained.

2.1 System description

Figure 2 shows a schematic of the PVEGS consist of a solar PV array, a DC/AC inverter and a fusebox.

This solar system uses the solar energy to electricity generation through the PV panels during the year in different climatic zones of Iran (four solar irradiation zones, according to SATBA reports). This PVEGS allows families to power their home. Furthermore, this system is connected to the electric grid, and any excess electricity is sold into the grid. This PVEGS could be an excellent way to poverty alleviation in poor families of Iran because they can reap profit by selling surplus electricity to the grid.

To carry out the thermodynamic analysis and economic analysis of the PVEGS with and without self-cleaning PV panels, these assumptions are used:

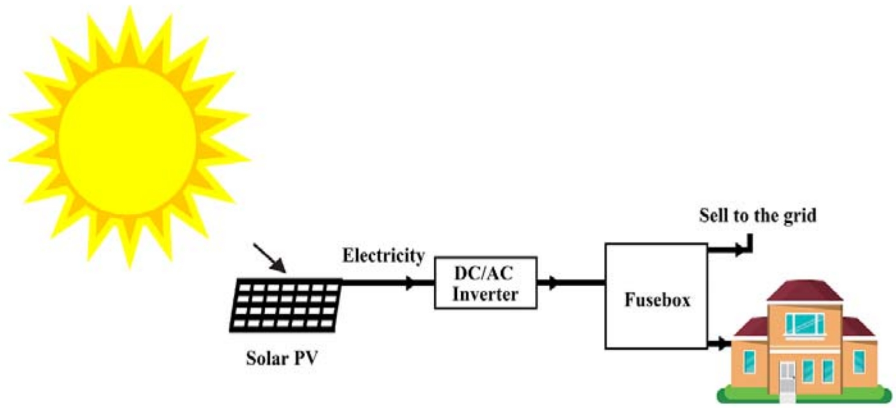

Fig. 2. Schematic of the PVEGS.

- The dead state pressure is 101kPa.
- For modeling the PVEGS, accurate annual climatic data is used in order to predict specific outputs of the PVEGS in different geographical locations of Iran.
- All the processes are considered to be operating at steady state.
- Exergy destructions in invertor and fusebox were neglected.
- The average/annual load of a typical residential house in Iran is used.
- The dead state temperature is 298.15 K.
- The ambient temperature is 298.15 K.
- The average solar radiation during the system operation period was (220.8 W/m^2 in zone 1, 202.1 W/m^2 in zone 2, 172.9 W/m^2 in zone 3 and 137.5 W/m^2 in zone 4.)
- Chemical exergy of components and the kinetic, potential energy and exergy are neglected.

3. Analysis

For thermodynamic modeling of the PVEGS, the equations developed are programmed using Engineering Equation Solver software. The input data used in this model are given in Table 1.

Energy and exergy balances for any control volume at steady-state operation with negligible potential and kinetic energy changes can be expressed, respectively, by

$$\frac{dE_{CV}}{dt} = \sum \dot{Q}_{CV} - \dot{W}_{CV} + \sum_i \dot{m}_i h_i - \sum_e \dot{m}_e h_e \tag{1}$$

$$\frac{d\psi_{CV}}{dt} = \sum_i \dot{m}_i \psi_i - \sum_e \dot{m}_e \psi_e + \sum_j (1 - \frac{T_0}{T_J}) \dot{Q}_j - (\dot{W}_{CV} - P_0 \frac{dV_{CV}}{dt}) - \dot{I}_{CV} \tag{2}$$

The specific exergy is given by

$$\psi = (h - h_0) - T_0 (s - s_0) \tag{3}$$

Then the total exergy rate associated with a fluid stream becomes

$$\dot{E} = \dot{m}\,\psi \tag{4}$$

The thermodynamic analysis of the PVEGS is presented in this subsection. To model the PVEGS, we consider the method used by S. Joshi et al. [12]. The governing equations for the PVEGS are shown in Table 2.

4. Results and Discussion

In this section, the results of thermodynamic and economic modeling of the PVEGS are presented.

4.1. Validation of the solar PV system

The analysis of the PVEGS is validated with Khan et al. study [13], as shown in Table 3.

The PVEGS was analyzed using the above equations. The thermodynamic and economic analysis results are summarized in Table 4 and Table 5 and Table 6.

Table. 1. Input data for the PVEGS

The solar cell efficiency	(equal to 0.38 [11]) η_c
The packing factor of solar cell	(equal to 0.83 [11]) β_c
The transitivity of the solar cell glass	(equal to 0.95 [11]) τ_g
The solar panels surface, m^2	(equal to 100 m^2) A_{PV}
The sun temperature	(equal to 4500 K) T_S
Power purchase rate by the Iranian Ministry of Energy (Rials/kWh)	8000
Annual electrical energy consumption per household in Iran	2740 kWh [12]

Table. 2. The governing equations for the PVEGS

Input energy to the PV panels	$\dot{Q}_{in} = G_b A_{PV}$
The power produced by the PV panels	$\dot{W}_{PV} = \eta_c G_b \beta_c \tau_g A_{PV}$
The energy efficiency of the PVEGS	$\eta_{en} = 100 \times \frac{\dot{W}_{PV}}{G_b A_{PV}}$
The exergy efficiency of the PVEGS	$\eta_{ex} = 100 \times \frac{\dot{W}_{PV}}{\dot{E}_S}$
The total inlet exergy to the PVEGS.	$\dot{E}_S = G_b A_{PV}(1 + \frac{1}{3}(\frac{T_{amb}}{T_S})^4 - \frac{4}{3}(\frac{T_{amb}}{T_S}))$
The exergy destruction rate of the PVEGS	$\dot{I}_{PV} = \dot{E}_S - \dot{W}_{PV}$
Average power gain due to the self-cleaning coatings	5.5% [4]

Table. 3. Validation of the PVEGS

Khan et al. study [13]	Present study
PV cycles efficiency: 12.2 to 40 %	PV cycle efficiency: 29.96 to 31.61%

Table. 4. The results of thermodynamic and economic analysis of the PVEGS with self-cleaning coatings

Parameters	Zone 1	Zone 2	Zone 3	Zone 4
Energy efficiency (%)	31.61	31.61	31.61	31.61
Exergy efficiency (%)	34.67	34.67	34.67	34.67
Power rate (kW)	6.98	6.39	5.47	4.35
Input energy (kW)	22.08	20.21	17.29	13.75
Exergy destruction rate (kW)	13.15	12.04	10.3	8.189
Annual electrical energy generation (kWh)	61150	55964	47878	38075
Annual electrical energy consumption (kWh)	2740 [12]	2740 [12]	2740 [12]	2740 [12]
Annual electrical energy sell to the grid (kWh)	58410	53224	45138	35335
Annual electrical energy generation (MIRR)	489.2	447.7	383	304.6
Annual electrical energy sell to the grid (MIRR)	467.28	425.79	361.1	282.68

Table. 5. The results of thermodynamic and economic analysis of the PVEGS without self-cleaning coatings

Parameters	Zone 1	Zone 2	Zone 3	Zone 4
Energy efficiency (%)	29.96	29.96	29.96	29.96
Exergy efficiency (%)	32.87	32.87	32.87	32.87
Power rate (kW)	6.617	6.056	5.181	4.12
Input energy (kW)	22.08	20.21	17.29	13.75
Exergy destruction rate (kW)	13.52	12.37	10.58	8.415
Annual electrical energy generation (kWh)	57963	53046	45382	36090
Annual electrical energy consumption (kWh)	2740 [12]	2740 [12]	2740 [12]	2740 [12]
Annual electrical energy sell to the grid (kWh)	55223	50306	42642	33350
Annual electrical energy generation (MIRR)	463.7	424.4	363.1	288.7
Annual electrical energy sell to the grid (MIRR)	441.78	402.45	341.14	266.8

Table 6: The PVEGS with self-cleaning coatings, thermodynamic and economic advantages over the conventional PVEGS

Parameters	Zone 1	Zone 2	Zone 3	Zone 4
Energy efficiency improvement (%)	1.65	1.65	1.65	1.65
Exergy efficiency improvement (%)	1.8	1.8	1.8	1.8
Power rate increment (kW)	0.363	0.334	0.289	0.23
Exergy destruction rate decrement (kW)	0.37	0.33	0.28	0.226
Annual electrical energy generation increment (kWh)	3188	2918	2496	1985
Annual electrical energy generation increment (MIRR)	25.5	23.34	19.97	15.88

4.2. Effect of varying solar radiation intensity on PVEGS work rate with and without using self-cleaning panels

The SRI falling on the PV panels varies depending on the location of the panel and the time intervals in a day. Therefore, SRI has a direct effect on the panel power. Figure 3 shows the variation with SRI of the PVEGS work rate with and without using self-cleaning panels. As shown in this figure, increasing SRI, increases the work rate of the PVEGS with and without using self-cleaning panels, this observation is imputable to the fact that the PVEGS work rate is a linear function of SRI.

The family rooftop PVEGS can increase the average annual household income by at least 304.6 million Rials with using self-cleaning solar panels and 288.7 million Rials without using self-cleaning solar panels, thus, the family rooftop PVEGS for poverty alleviation for poor families is remarkable to help families in poor zones increase their income.

5. Conclusions

In this study, the steady-state thermodynamic and economic analysis of a PVEGS is conducted under Iran annual climate conditions. The primary aims of this study are to improve understanding of this PVEGS with using self-cleaning coatings and promotion using self-cleaning PVEGS instead of conventional PVEGS in Iran. The results of thermodynamic and economic analysis showed that the PVEGS with self-cleaning coatings has many advantages over

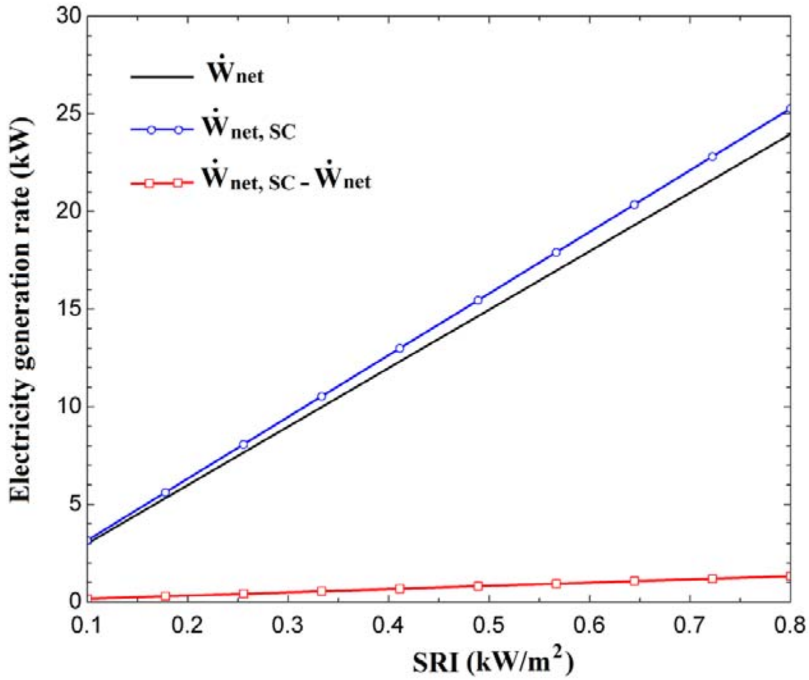

Fig. 3. Effect of varying SRI on PVEGS work rate with and without using self-cleaning panels

the conventional PVEGS. Additional conclusions follow:

- The results from the economic analysis show that using the PVEGS increases the poor family's income in Iran.
- Cleaning dirty PV panels can be time-consuming, expensive, and dangerous to the environment, using self-cleaning PVEGS, can solve this problem.
- An increase in SRI increases PVEGS work rate.

The self-cleaning solar panels, stop dust, pollen and pollution from sticking to PV panels, keeping them clean, maintaining their efficiency, ensuring the maximum amount of electricity is produced.

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