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Performance analysis of a novel concentrating photovoltaic combined system

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ABSTRACT

In the present study, a novel Concentrating Photovoltaic Combined System (CPVCS) based on the spectral decomposing approach is introduced, modeled, tested experimentally and evaluated thermodynamically and economically. In this study, energy and exergy analyses of the system have been evaluated, economical analysis has been performed and the experimental results have been compared to data obtained by the control system. As a result, energy efficiencies of concentrator, vacuum tube and overall CPVCS have been determined to be 15.35%; 49.86%; and 7.3% respectively. Similarly the second law (exergy) efficiencies of concentrator, vacuum tube and overall CPVCS are 12.06%; 2.0%; and 1.16% respectively. The cost of energy production has been stated as 6.37 $/W and it is predicted that this value could be decreased by improving the system performance.

1. Introduction

The conversion efficiency of photovoltaic cells is relatively low, usually in the range of 10–20% for commercially available silicon cells and up to 39% for more sophisticated multi-junction cells. More than half of the solar radiation, collected with considerable effort and investment, is converted to thermal energy and then emitted to the environment. A well known way to achieve a better overall efficiency is cogeneration: capturing the waste heat as well and using it as an additional energy product. This can be achieved with photovoltaic/thermal (PV/T) collectors that contain a heat exchanger behind the PV cells to collect the heat rejected from the cells [1]. During the 1970s, the research on PV/T started, with the focus on PV/T collectors, with the main aim of increasing the overall energy efficiency [2]. The conventional single semiconductor solar cells only convert photons of energy close to the semiconductor band gap effectively. Photons with less energy are not absorbed and their energy is totally wasted [3]. A solar cell has its threshold photon energy corresponding to the particular energy band gap below which electricity conversion does not take place. Photons of longer wavelength do not generate electron–hole pairs but only dissipate their energy as heat in the cell. Common PV modules convert 4–17% of the incoming solar radiation into electricity, depending on the type of solar cells in use and the working conditions. In other words, more than 50% of the incident solar energy is converted to heat, not electrical energy. This may lead to extreme cell working temperature as much as 50 °C above the ambient environment. There can be two undesirable consequences: (i) a drop in cell efficiency (typically 0.4% per °C rise for c-Si cells) and (ii) a permanent structural damage of the module if the thermal stress remains for prolonged period [4]. In PV/T system applications the production of electricity is the main priority, therefore it is necessary to operate the PV modules at low temperature in order to keep PV cell electrical efficiency at a sufficient level. This requirement limits the effective operation range of the PV/T unit for low temperatures [5]. The co-generated heat is available at the relatively low temperature that can be achieved by flat plate collectors, usually about 40–60 °C. Keeping the temperature low is considered an advantage since the conversion efficiency of PV cells decreases with temperature. However, the collected thermal energy is suitable for domestic water heating or space heating, but it is inadequate for applications that require higher temperatures, such as absorption cooling. This limits the range of applications for PV/T systems. It also limits the practical system size, because the required collector area for water or space heating is usually much lower than the area requirement for electricity [6].

Even today the conventional solar cell applications, compared with conventional electric power generation high cost is the biggest obstacle to solar cell applications becoming widespread. The combination of solar concentrators with PV modules is up to now the most viable method to reduce system cost, replacing the expensive cells with a cheaper solar radiation concentrating system. By concentrating, a large part of the expensive PV area is replaced by cheap mirror area, which is a way to reduce the payback time. This argument is the driving force behind CPV systems. CPVs present higher efficiency than the typical ones, but this can be achieved only when PV module temperature is maintained as low as possible [7,8]. PVT and CPV systems have been investigated and discussed by many researchers for the last decade in

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Nomenclature

A	area (m^2)
C	specific heat (J/kg K)
C_{max}	concentration ratio
D	diameter (m)
d	image diameter (m)
$\dot{Ex}$	exergy rate (W)
f	focal length (m)
G	solar irradiance (W/m^2)
I	current (A)
$\dot{IP}$	exergetic improvement potential (W)
$\dot{m}$	mass flow rate (kg/s))
$\dot{Q}$	energy rate
S	absorbed solar irradiance (W/m^2)
T	temperature (K)
U	heat loss coefficient (W/m K)
V	potential difference (V)

Greek letters

δ	dispersion angle
ε	exergy efficiency
η	energy efficiency
τ	transmission coefficient
ρ	reflectivity

Subscripts

a	ambient
ap	aperture
b	beam
c	control
con	convective
$dish$	dish
$elect$	electrical
ev	vacuum tube
f	focal
hm	hot mirror
in	inlet
max	maximum
min	minimum
o	optimum
out	outlet
pv	solar cell
rad	radiative
rim	rim
T	total
u	useful

the literature [9–30]. There are also many studies which employ Fresnel lenses for CPV systems in the literature [31–36]. Besides, some studies on the integration PVs and heat pumps were performed [37,38].

There are very limited studies on concentrating photovoltaic thermal systems (CPVTs). Kribus et al. [39] presented and analyzed a novel miniature concentrating PV (MCPV) system. The system tested with a reflector of 0.95 m^2 aperture area, under normal beam insolation of 900 W/m^2. Most of thermal energy was removed by the coolant flow, but some is lost to the environment through the front and back surfaces. A miniature concentrator PV/thermal system producing about 140–180 W of electricity and an additional 400–500 W of heat was developed. Kribus et al. [6] also proposed simultaneous production of electrical and high grade thermal energy with a concentrating photovoltaic/thermal (CPVT) system operating at elevated temperature. CPVT collectors may operate at temperatures above 100 °C, and the thermal energy can drive processes such as refrigeration, desalination, and steam production. In this study, the performance and cost of a CPVT system with single effect absorption cooling was investigated in detail. The results showed that under a wide range of economic conditions, the combined solar cooling and power generation plant can be comparable to and sometimes even significantly better than, the conventional alternative. Again Kribus et al. [40] proposed a coupled system, comprised of a concentrating photovoltaic/thermal collector field and a multi-effect evaporation desalination plant. The combined system produces solar electricity and simultaneously exploits the waste heat of the photovoltaic cells to desalinate water. In this study, a detailed simulation was performed to compute the annual production of electricity and water. They indicated that the results indicate that the proposed coupled plant can have a significant advantage relative to other solar desalination approaches.

There is a very crucial issue for the basis of PV, PVT and CPVT systems: Spectral effect. Today, the spectral effect in the use of solar cells is a parameter that is not considered in the vast majority of solar energy technologies. However, this feature is the basis of electricity generation with solar cells. Solar irradiance at shorter wavelengths is absorbed by solar cells. At long wavelengths, the radiation cannot be convert electricity and causes the excessive heat load on the cell material. This situation is related to spectral response range of the semiconductor material of the solar cell. Most of the solar radiation falling on cannot be converted into electrical energy due to spectral characteristics of solar cells. More than 80% remaining after conversion to solar energy to electrical energy transformed into heat is wasted to the environment [41]. This excessive heat loss means energy loss for the conversion system. There is a very promising approach to prevent energy loss and to improve energy efficiency for concentrated solar energy technologies: Spectral decomposition. If solar radiation spectrum on the solar cell can be filtered to its operating range, almost all solar radiation will be converted into electrical energy and it will be possible to benefit from the full solar spectrum most effectively. The basic logic in PVT and CPVT systems is to use thermal energy due to solar radiation falling onto the cell via various systems and try to protect the cell from the negative effects of high temperature. However, if not all of the solar radiation but the section of on the spectral response range can be fallen on the cell, close to all of this energy can be converted to electrical energy. In other words, the part of the solar radiation can be utilized by solar cells most effectively is the part that spectrally separated before falling on the cell, in this case excessive heating on the solar cell is not in question. In the CPVT system which integrated with concentrators and filtered according to the spectral response range, almost of the solar radiation falling on the cell be converted to electrical energy as well as high-temperature radiation will be able utilized with high efficiency in thermal applications. In reviewing the literature on the subject, there is no existing system in which solar radiation is separated, extracted or evaluated spectrally before falling on the solar cells. In all systems studied all solar radiation is fallen on the solar cell the load of heat occurred in cell tried to be assessed by taking. This spectral decomposition approach which has been introduced and performed in the present study could also be applied to many different solar power generation systems.

In this study, a novel Concentrating Photovoltaic Combined System (CPVCS), which has not been found open literature, is