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Dense-array concentrator photovoltaic prototype using non-imaging dish concentrator and an array of cross compound parabolic concentrators

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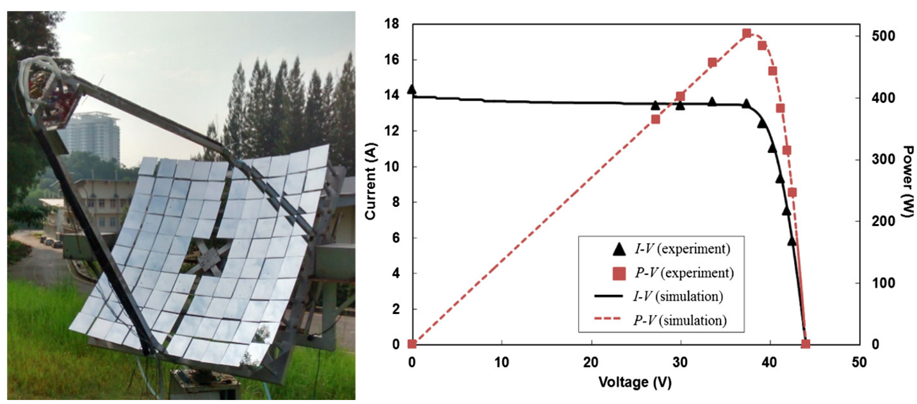
HIGHLIGHTS

- Cell efficiencies were measured onsite in the range from 35.0% to 36.1%.
- DACPV system efficiency was measured in the range from 16.1% to 17.4%.
- Maximum power of the prototype has been measured as 503 W at DNI of 789 W/m^2.
- $CR_{measured}$ of CCPC lens is only 4.07 or 67.9% of geometrical concentration ratio 5.998.
- The cost per watt of electricity produced by the proposed prototype is USD 5.8/W.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, we would like to report on a prototype of dense array concentrator photovoltaic (DACPV) system including the practical implementation and economic assessment. The newly proposed system consists of primary concentrator in the form of non-imaging dish concentrator and secondary concentrator as an array of dielectric filled crossed compound parabolic concentrators coupled to multi-junction solar cells. Optical and electrical simulations have been carried out to analyze the overall performance of the prototype for difference rim angles and tracking accuracies. A special method has been developed to plot the *I-V* and *P-V* curves of the prototype on-site without using commercial *I-V* tracer. The average cell efficiencies for all basic modules in the DACPV receiver were measured onsite in the range from 35.0% to 36.1%, which is very close to the laboratory test result conducted by Spectrolab at 38.5%. On the other hand, the system efficiency of our prototype system was measured only in the range between 16.1% and 17.4% at DNI ranging from 740 to 801 W/m^2. For economic analysis, the cost per watt of current prototype has been determined as USD 5.8/W based on the price of only building one unit. The techno-economic of DACPV system can be further improved in the future by increasing solar concentrator ratio more than 1600 suns and reducing the optical losses incurred by the secondary concentrator.

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Nomenclature

2-D	2-dimensional
3-D	3-dimensional
θ	rim angle
θ_i	angular half acceptance angle
θ_i'	half acceptance angle
a	half entrance aperture size
a'	half exit aperture size
ADC	Analog-to-Digital Converter
BiPV	building integrated photovoltaic
CCPC	crossed compound parabolic concentrator
CPC	compound parabolic concentrator
CPV	concentrator photovoltaic
$CR_{measured}$	measured solar concentration ratio
D	largest distance of central points between two flat facets located at opposite corners
DACPV	dense array concentrator photovoltaic
DBC	Direct Bond Copper
DNI	direct normal irradiance
f	focal distance of NIDC
FF	Fill Factor
GSI	global solar irradiance
HCPV	High Concentration Photovoltaic
I-V	Current-Voltage
I_{sc}	Short Circuit Current
I_{sc}^{CCPC}	short-circuit current of CPV + CCPC assembly set exposing to DNI only
I_{sc}^{DNI}	short-circuit current of CPV module contributed by DNI only
$I_{sc}^{DNI\text{-}1sun}$	short-circuit current of CPV module exposing to DNI only under one sun condition
$I_{sc}^{measured}$	measured short-circuit current of CPV module exposing to GSI
$I_{sc\text{-module}}$	short-circuit current of basic module
L	length of CCPC lens
MJ	multi-junction
n	refractive index
NIDC	non-imaging dish concentrator
NIPC	non-imaging planar concentrator
P-V	power-voltage
PAR	Peak-to-Average Ratio
PV	photovoltaic
PCE	power conversion efficiency
SCR	solar concentration ratio
SCR_{module}	total solar concentration ratio of basic module
SOE	secondary optical element
V_{oc}	open-circuit voltage
$V_{oc\text{-module}}$	open-circuit voltage of basic module

1. Introduction

Solar energy is the most abundant, renewable and clean energy source available on the earth, which is important to support rapid economy growth in a sustainable manner. Scientists have estimated that the maximum solar energy derivable over land on the earth is 16,300 terawatts, which is about 1000 times of the current energy usage of the whole world [1]. Many methods have been developed to tap the solar energy and convert it into useful type of energy such as electrical and thermal energies. Flat photovoltaic (PV) panel is widely deployed device in building integrated photovoltaic (BiPV) system and solar power plant to convert the solar energy into electrical energy due to the advantages of low maintenance and easy installation. Even though Flat PV panel is highly popular accredited to its competitive production cost comparing to the conventional way of burning fossil fuel, the power conversion efficiency (PCE) has been saturated at 25% and it has caused inefficient used of land area. As an alternative solution, concentrator photovoltaic (CPV) system has been explored as a better option to convert solar energy at higher efficiency. Table 1 shows the detailed comparison of various PV technologies in the current scenario in terms of their benefits and drawbacks. Flat PV module prices have fallen rapidly since the end of 2009, to between USD 0.52/W and USD 0.72/W in 2015. According to International Renewable Energy Report in 2016, we found that on-grid commissioned and planned utility-scale flat PV projects between 2014 and 2018 range from USD 1.2/W to USD 4.9/W in Africa, which agrees with the estimated worldwide weighted average for utility-scale projects of USD 1.8/W in 2015 [2]. Over the period 2010–2017, the average total installed cost of these flat PV projects relies on the capacity and scale with a range from USD 7/W for a 2.5 MW project to around USD 1.2/W to USD 1.4/W at the lower end for both small (<40 MW) and large projects (80–100 MW). Conclusively, the price of PV technologies are very much dependent on the both production and installation scale in which flat PV has achieved maturity of commercial scale as compared to CPV technology. Nevertheless, CPV is an emerging technology and the future potential cannot be ignored even the current price in USD/W is still higher as compared flat PV. Another obvious benefit of CPV over flat PV is that the CPV system always equipped with sun tracking mechanism to enable the solar cells operating at maximum solar irradiance throughout the day.

Recently, the achievement of multi-junction solar cell with PCE as high as 46% have given huge boosts to the development of concentrator photovoltaic (CPV) system [20]. The idea of replacing the solar cell material with cost-effective solar concentrator to focus sunlight up to thousand folds on multi-junction solar cell can reduce the cost per watt of electricity. Many different designs of solar concentrator system have been developed in past 30–40 years towards this direction, but there is still more improvement needed to be done for the existing system with a better outcome.

The most popular design is Fresnel lens type of CPV system where each primary concentrator of Fresnel lens is coupled to a single solar cell via a secondary optical element to improve the optical alignment and to increase acceptance angle [21–25]. The disadvantages of Fresnel lens include chromatic aberration and the requirement of highly accurate manufacturing process for the teeth of the Fresnel lens. Furthermore, the vast majority of Fresnel systems are constructed as a single module with an optical device per cell and thus waste heat recycling process is not possible. On the other hand, the point focus type of imaging system utilizing large parabolic dish has been proposed to focus sunlight on the dense array of multi-junction solar cells with water-cooled system. Despite the advantage of waste heat recollection, parabolic dish encounters fundamental optical limitation by producing non-uniform Gaussian flux distribution not favorable to dense-array concentrator photovoltaic (DACPV) receiver because the non-uniform illumination can cause current mismatch problem for solar cells connected in series.