Applied Energy 226 (2018) 772–783

Contents lists available at ScienceDirect

Applied Energy

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

Design and characterization of hybrid III–V concentrator photovoltaic–thermoelectric receivers under primary and secondary optical elements

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HIGHLIGHTS

- Novel integration of III:V concentrator photovoltaic cells-thermoelectric modules.
- Optimized thermoelectric module geometry for cell temperature sensing and cooling.
- New III:V triple-junction cell six-parameter one-diode equivalent model developed.
- The model fitted experimental current–voltage data with a low 4.44% mean error.
- High combined primary & secondary optical intensity gain coefficient 0.92 obtained.

ARTICLE INFO

Keywords:
Concentrator photovoltaic
III:V triple-junction solar cell
Thermoelectric
Cell temperature
Secondary optical element
Optimization

ABSTRACT

Lattice-matched monolithic triple-junction Concentrator Photovoltaic cells ($InGa_{(0.495)}P/GaIn_{(0.012)}As/Ge$) were electrically and thermally interfaced to two Thermoelectric Peltier module designs. An electrical and thermal model of the hybrid receivers was modelled in COMSOL Multiphysics software v5.3 to optimize cell cooling whilst increasing photon energy conversion efficiency. The receivers were measured for current–voltage characteristics with the cell only (with sylguard encapsulant), under single secondary optical element at x2.5 optical concentration, and under Fresnel lens primary optical element concentration between x313 and x480. Measurements were taken in solar simulators at Cardiff and Jaén Universities, and on-sun with dual-axis tracking at Jaén University. The hybrid receivers were electrically, thermally and theoretically investigated. The electrical performance data for the cells under variable irradiance and cell temperature conditions were measured using the integrated thermoelectric module as both a temperature sensor and as a solid-state heat pump. The performance of six hybrid devices were evaluated within two 3-receiver strings under primary optical concentration with measured acceptance angles of 1.00° and 0.89°, similar to commercially sourced Concentrator Photovoltaic modules. A six-parameter one-diode equivalent electrical model was developed for the multi-junction cells under both primary and secondary optical concentration. This was applied to extract six model parameters with the experimental current–voltage curves of type A receiver at 1, 3 and 500 concentration ratios. Standard test conditions (1000 W/m^2, 25 °C and Air Mass 1.5 Global spectrum) were assumed based on trust-region-reflective least squares algorithm in MATLAB. The model fitted the experimental current–voltage curves satisfactorily with a mean error of 4.44%. The combined primary and secondary optical intensity gain coefficient is as high as 0.92, in comparison with 0.50–0.86 for crossed compound parabolic concentrators. The determined values of diode reverse saturation current, combined series resistance and shunt resistance were similar to those

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https://doi.org/10.1016/j.apenergy.2018.06.018
Received 27 December 2017; Received in revised form 16 May 2018; Accepted 2 June 2018

of monocrystalline PV cell/modules in our previous publications. The model may be applicable to performance prediction of multi-junction CPV cells in the future.

1. Introduction

Concentrator photovoltaic (CPV) technology utilizes low cost glass/polymer optics to significantly increase direct normal irradiance (DNI) photon flux onto a small [typically 5.5 mm × 5.5 mm] CPV cell. The optics concentrate sunlight and homogenise photon spectral distribution, significantly increasing cell efficiency. To maximize optical concentration two lenses are typically applied to CPV cells, a primary optical element (POE) and a secondary optical element (SOE). Modular CPV systems typically include dual-axis tracking systems to follow the sun's trajectory and maximize energy generation throughout the day.

CPV is a viable renewable energy technology for commercial-scale generation of solar electricity, with typically between x300 and x1000 optical concentration. The cumulative global installation capacity of CPV is currently greater than 370 MWp (December 2016) [1] with several power plants of ≥30 MWp capacity. These plants have been built in Golmud China, [Suncore, 60 MWp (2012) and 80 MWp (2013)], Touwsrivier, South Africa [Soitec, 44 MWp (2014)] and Alamosa, Colorado [Amonix, 30 MWp (2012)], with demonstrated reliability for over 7 years. For technical and economic viability annual DNI needs to exceed 2000 kWh/m^2, found in approximately 50% of global locations. A global map which represents the long-term average of daily/yearly global DNI is shown in Fig. 1 [2].

Compound semiconductor multi-junction CPV cells hold the highest world record cell efficiency at 46.0% [3], held by Fraunhofer ISE, Soitec and CEA-LETI [4]. CPV cells are structurally designed to minimize thermalisation and transmission losses. Multiple direct bandgap materials are epitaxially grown via metal organic vapour phase epitaxy (MOVPE) or molecular beam epitaxy (MBE). High purity III:V layers, with typical total epitaxial thickness of < 10 µm, have almost perfect crystallinity leading to low non-radiative losses in the CPV device. High extinction coefficients and anti-reflective coating of the cell enables effective absorption of incident solar photons in the wavelength range, 250–2500 nm. High charge carrier mobility and separation enables full-spectrum energy harvesting. World III–V cell efficiency records have typically increased ~1% per year over the past decade. Advanced modelling indicates realistic cell efficiency targets of greater than 50% (1000x concentration) by 2020 [5]. High-volume production cell efficiencies generally closely follow research trends. Recent techno-economic evaluation states that to compete with crystalline Silicon system, CPV system efficiency needs to reach 40% with cell efficiencies of 50% and module efficiencies of 44% [6].

Previous literature on first-generation Silicon PV cell technologies list the positive benefits of hybrid photovoltaic-thermoelectric performance, increasing the annual electricity yield of the lone PV module by 11–14.7% at 25 °C [7]. There are only three research papers on III:V CPV cells integrated with thermoelectric (TE) technology. Two theoretical papers describe a GaAs/Ge PV-TE system providing a further 8% electrical efficiency relative to the lone PV technology [8]. Four PV technologies (compound Silicon, Copper Indium Gallium diselanide, Gallium Arsenide and a triple junction Gallium Indium Phosphide/Indium Gallium Arsenide/Germanium) were also theoretically modelled as part of a hybrid system [9]. For triple junction cell performance under 1-sun and higher concentrations, the hybrid device showed a larger system efficiency. One experimental reference paper detailed a hybrid III:V CPV-TE high system investigated under high optical concentration (approx. x200) [10]. The hybrid produced more power than the PV alone at concentrations larger than x100, using the thermoelectric module as a generator in Seebeck mode.

The original work in this paper investigates the functionality and performance of novel hybrid CPV-TE receivers. The thermoelectric module is used as both an accurate cell temperature sensor (via V_{oc}) and a heat pump in Peltier mode (upon application of current) for cell temperature control.

Domed-shaped single optical (SILO) lenses were used as the SOE for the receiver [11]. These optics also effectively encapsulate both the CPV cell and top electrical (n-type) contacts for protection against environmental conditions. The inevitable consequences of high irradiance

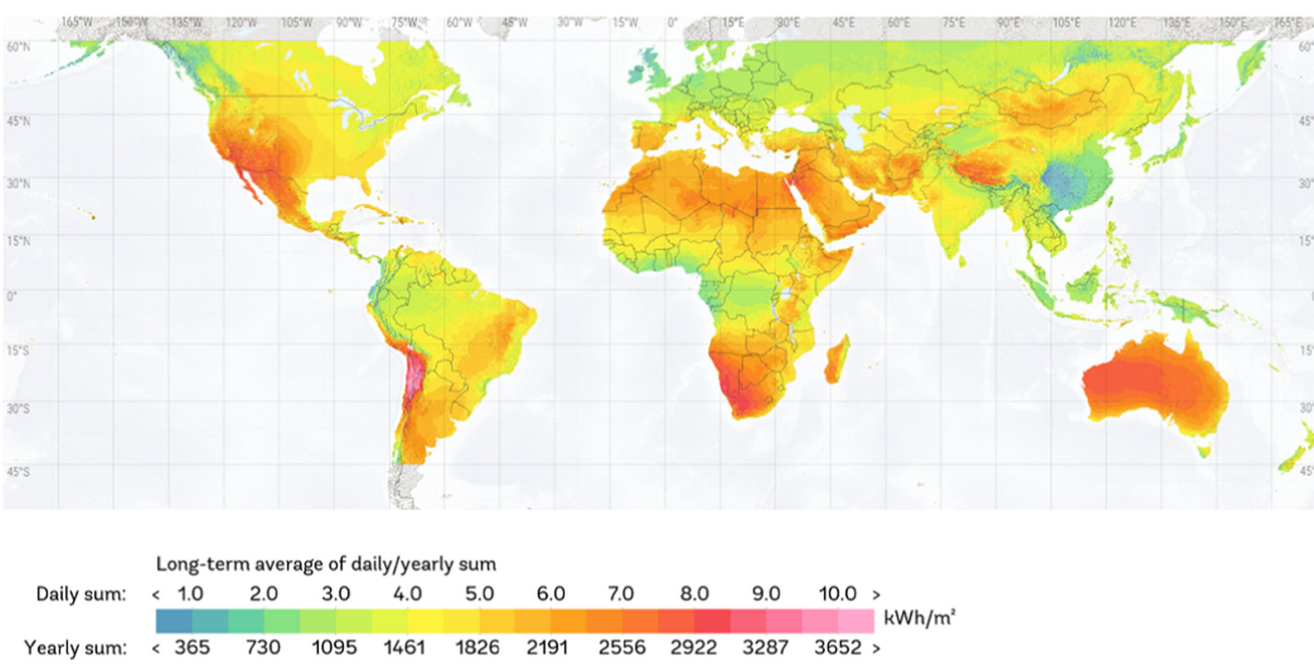

Fig. 1. Global resource map of direct normal irradiation. The solar resource is calculated by the Solargis model from atmospheric and satellite data with 10, 15 or 30-min time-steps. The effect of terrain are represented at a nominal spatial resolution of 250 m.