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Non-uniform illumination in concentrating solar cells

Hasan Baig [a], Keith C. Heasman [b], Tapas K. Mallick [a,*]

[a] Mechanical Engineering Department, School of Engineering and Physical Sciences, Heriot Watt University, Edinburgh EH14 4AS, UK
[b] PV Technology Centre, Narec, Blyth, NE24 1LZ, UK

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ABSTRACT

After a gap of more than two decades, Concentrator Photovoltaics (CPV) technology is once again under spotlight for making use of the best available solar cell technologies and improving the overall performance. CPV finds its use in a number of applications ranging from building integration to huge power generation units. Although the principles of solar concentration are well understood, many practical design, operation, control issues require further understanding and research. A particular issue for CPV technology is the non-uniformity of the incident flux which tends to cause hot spots, current mismatch and reduce the overall efficiency of the system. Understanding of this effect requires further research, and shall help to employ the most successful means of using solar concentrators. This study reviews the causes and effects of the non-uniformity in the CPV systems. It highlights the importance of this issue in solar cell design and reviews the methods for the solar cell characterization under non-uniform flux conditions. Finally, it puts forward a few methods of improving the CPV performance by reducing the non-uniformity effect on the concentrator solar cells.

Contents

1. Introduction

Concentrating photovoltaics (CPV) seems to be the much needed breakthrough enabling the solar energy industry to be

* Corresponding author. Tel.: +44 131 451 4379; fax: +44 131 451 3129.
E-mail address: T.Mallick@hw.ac.uk (T.K. Mallick).

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competitive in the power generation [1,2] market. Although, discovered more than three decades ago, this technology did not gain the needed momentum due to several reasons [3]. Today, with increasing solar cells efficiencies and their associated high costs for manufacture, CPV technology is back into business to make the best use of the technology advancement and the solar cell materials. CPV technology promises not only to reduce the cost of the overall system, but also increases the amount of power produced. It reduces the intake of raw materials needed for manufacture, improves recycling and makes it economically feasible to be used for a number of applications. A recent paper highlights the benefits of using CPV [4] and its role in increasing overall system efficiency and reducing the use of semiconductor material. A typical CPV system consists of several elements essentially including an optical system which could be either reflective or refractive, Concentrator solar cells, a thermal dissipation system, a casing or support system and a tracking mechanism. The overall performance of the CPV system depends on how effectively each of these elements performs individually and collectively. Using the basic principle of focusing large amount of sunlight on a small solar cell by the help of an optical concentrator, which could be a Fresnel lens [5–7], parabolic troughs [8], dishes [9,10] or v-groove mirrors [11–13], refractive prism [14–17], luminescent glass [18–20], compound parabolic concentrator [21–26] or some other optical system [27,28], solar concentration is sought to be one of the most effective ways of reducing overall energy generation costs. The principles of optical concentration are well established [29–33] and explained for applications in both photovoltaics and solar thermal applications. The research and development of CPV technology effectively started at the National Sandia Laboratories in 1976 with Sandia-I and Sandia-II spurred by the oil crisis in 1973 [34]. A brief history on the concentrators is presented by highlighting the factors needed to push forward the large scale production of concentrators [35]. One of the most early and successful implementation of concentrator PV saw its dawn in Saudi Arabia [36], where a complete village was powered using Concentrating PV system comprising of 160 arrays with 4000 m^2 area and generating a power of 350 kW peak output. However with the end of oil crisis and absence of any significant breakthroughs the research and development in this area slowed down in the next few decades. In later times, the interest shifted towards applications for building integration; the CPV systems once again came back to picture with the development of several CPV systems for building applications like sky lighting, façade applications, wall curtains and few other applications still undergoing development. A recent review demonstrates latest developments and the scale of this industry [37]. With PV industry gaining impetus in power production recently a number of new companies are now coming forward to introduce CPV systems which can effectively produce electricity and readily compete with the conventional electricity costs [38].

The use of CPV systems in BIPV and power generation remains to be the most important. Recently a hybrid power and desalination plant able to produce 30,000 m^3 of pure water per day working on HCPV technology with a concentration ratio of 1500x was announced in the kingdom of Saudi Arabia [39]. Several other power plants working on CPV technology are also being announced [40]. With these figures growing higher and higher CPV technology seems very promising. Concentrating the sunlight by using concentrators reduces the area of expensive solar cells or modules, and, increases their efficiency. However, this technology has one shortcoming as it requires continuous tracking to keep it normal to the sun.

The amount of concentration produced by using a concentrator varies over a wide range of values. A geometrical parameter "Concentration Ratio" defined as the ratio of the areas of the concentrator and the solar cell is used for distinguishing the type of concentrator. Based on the illumination intensity it focuses on the solar cell, the concentrators may be classified as Low Concentration Photovoltaics (LCPV), Medium Concentration Photovoltaics (MCPV) and High Concentration Photovoltaics (HCPV) systems further details of which can be found under [41]. These systems utilize different type of solar cell technologies depending on the area of application and the economics of the system.

1.1. Concentrating solar cells

The Solar Cell is the key element of any CPV system, and its design plays an important role in enhancing the performance of the entire CPV system. In CPV systems special kinds of cells are required which can operate at high concentrations and elevated temperatures.

These concentrator cells differ significantly from one-sun cells in several ways, including the method of manufacture and the overall cell design and their performance, the concentrator solar cells generally include bus bars around the perimeter of the cell which can be accommodated without blocking any of the incoming light [42]. In addition to the bus bars, they have fingers which carry the current generated in the emitter towards the busbars. Depending on the concentration ratio, application and the type of concentrator different types of solar cells are utilized for having an optimum performance and reliability of the system. The type of solar cells to be used in the CPV system can be single junction silicon cells [1, 21, 23, 43–46], thin films [47] or multi-junction cells [4, 44, 48–50]. For applications demanding high concentrations like point focused systems, multi-junction solar cells are needed which can perform under high concentration and extreme temperatures and are durable for a large period of time. This demands not only special materials and chemical processing but also a very effective design [51] which further increases the cost of the solar cells in the CPV systems. These types of systems are mainly used in power generation where the high investment gets paid off [52]. For applications that are line focused there is a scope of utilizing cheaper materials or the usual Si solar cells with design improvements, and improved efficiencies. The LCPV and MCPV systems use some high quality single junction silicon solar cells, which are cost effective as their manufacturing is not much different from those used in conventional PV panels. These Si solar cells can be manufactured by making improvements in material quality having longer minority carrier lifetimes [46], proper grid design, light trapping and improved surface passivation. These solar cells usually have a single junction and are capable of absorbing limited regions of the solar spectrum. On the contrary multi-junction solar cells (III–V Cells) [4] utilize a broad portion of the visible spectrum but are expensive. Multi-junction solar cells are made of several layers of semiconductor material so that different layers of the cell can absorb different regions of the light spectrum making them capable to utilize more of the spectrum and reach higher efficiencies. Few MCPV and almost all HCPV systems use multi-junction solar cells [53]. The cells utilize materials having different band gaps and are bonded together to utilize maximum portion of the visible spectrum which tremendously increases its efficiency. Although, it has not been very long since these technologies came into existence and reliability studies have been carried out [54] under simulated conditions, these results show that these cells are expected to perform for at least 30 years.

In order to obtain high efficiency low cost cells, Laser Grooved Buried Contact (LGBC) [55] solar cell technology could be used to obtain efficiencies higher than 18% on mono-crystalline CZ wafer at lower cost. This process utilizes a laser to scribe grooves into