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Optics for concentrating photovoltaics: Trends, limits and opportunities for materials and design

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ABSTRACT

Concentrating photovoltaic (CPV) systems are a key step in expanding the use of solar energy. Solar cells can operate at increased efficiencies under higher solar concentration and replacing solar cells with optical devices to capture light is an effective method of decreasing the cost of a system without compromising the amount of solar energy absorbed. However, CPV systems are still in a stage of development where new designs, methods and materials are still being created in order to reach a low levelled cost of energy comparable to standard silicon based PV systems. This article outlines the different types of concentration photovoltaic systems, their various design advantages and limitations, and noticeable trends. This will include comparisons on materials used, optical efficiency and optical tolerance (acceptance angle). As well as reviewing the recent development in the most commonly used and most established designs such as the Fresnel lens and parabolic trough/dish, novel optics and materials are also suggested. The aim of this review is to provide the reader with an understanding of the many types of solar concentrators and their reported advantages and disadvantages. This review should aid the development of solar concentrator optics by highlighting the successful trends and emphasising the importance of novel designs and materials in need of further research. There is a vast opportunity for solar concentrator designs to expand into other scientific fields and take advantage of these developed resources. Solar concentrator technologies have many layers and factors to be considered when designing. This review attempts to simplify and categorise these layers and stresses the significance of comparing as many of the applicable factors as possible when choosing the right design for an application.

From this review, it has been ascertained that higher concentration levels are being achieved and will likely continue to increase as high performance high concentration designs are developed. Fresnel lenses have been identified as having a greater optical tolerance than reflective parabolic concentrators but more complex homogenisers are being developed for both system types which improve multiple performance factors. Trends towards higher performance solar concentrator designs include the use of micro-patterned structures and attention to detailed design such as tailoring secondary optics to primary optics and vice-versa. There is still a vast potential for what materials and surface structures could be utilised for solar concentrator designs especially if inspiration is taken from biological structures already proven to manipulate light in nature.

Contents

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1. Introduction

1.1. *The benefits of concentrator photovoltaics and review objectives*

The sun delivers 120 petajoules of energy per second to the Earth. In 1 h the sun delivers more energy to Earth than humanity consumes over the course of a year. The ability to harvest this solar energy efficiently and cost effectively however is challenging. For this reason, there is a growing interest in concentrating photovoltaic (CPV) technologies which are systems made up of optical devices that focus light towards decreased areas of photovoltaic (PV) material. In this way the expensive PV material is replaced by more affordable mirrors and/or lenses, reducing the overall cost of the system but maintaining the area of energy captured and the efficiency at which it is converted. Not only can CPV systems be the answer to reducing the cost of solar power but they are more environmentally friendly than regular flat plate PV panels. This is due to two reasons; CPV technology uses less semiconductor components which are made from heavily mined and relatively rare metals, and CPV technology has a smaller impact on the albedo change in an area than flat plate PV panels [1,2]. Burg et al. [1] and Akbari et al. [2] explain this further. Aside from this, the two main advantages of concentrating photovoltaics (CPV) are their ability to reduce system costs and to increase the efficiency limits of solar cells [3].

However, at present it is difficult to produce cost competitive CPV systems in comparison to those of flat plate photovoltaic (PV) [4–6]. More reliable optics of higher concentration levels and lower dependencies on expensive tracking and cooling systems need to be designed. This requires novel structures and materials to be investigated. Secondary optics in particular hold a vast potential for improving the acceptance angle and optical tolerance of a CPV system and there are many more designs and materials yet to be tested.

This literature review aims to identify new routes to developing high performance and reliable optics for solar concentrator applications. To do this, the subject of solar concentrators must first be explained as it stands, and then broadened to justify novel design opportunities. One objective of this review is to give a basis of the most established methods of solar photovoltaic concentrating and group them where possible. By categorising designs effectively, development trends can be seen more clearly and routes for improved devices substantiated. This also requires presenting the advantages and disadvantages of each group of devices which can become very complicated as a solar concentrator's performance depends on multiple factors (Fig. 1). We also aim to outline the design considerations and in particular emphasis the importance of surface structure and material on a concentrator optics performance as shown in Fig. 1. This area of research hence requires us to branch into the materials science where inspiration can often be taken by structures found in nature. Overall, this results in a rather extensive review but one which is necessary to fully appreciate the potential for solar concentrator designs and guide them towards a more comprehensive capacity.

1.2. *Concentrator design categorisation*

Concentrating photovoltaic systems can be categorised in a variety of ways as shown in Fig. 2. We will provide a simple grouping of these different designs in order to aid the comparison of different research areas and literature. The concentration of a system or optic can be classed as low (<10 suns), medium (10–100 suns), high (100–2000 suns) and ultrahigh (>2000 suns) due to the different solar tracking requirements outlined by Chemisana et al. [7]. The main methods of concentration are; reflective, refractive, luminescent, and total internal reflection (TIR) although the latter is included within the refractive and luminescent types. This paper focuses on reflective and refractive photovoltaic systems. Each type of concentrating photovoltaic system has advantages and disadvantages and it is important to know the application and location to choose the most appropriate design. A concentrator characterisation table is given in Table 1 to help visualise the different basic systems and the many combinations possible.

2. Primary optics

The most common and widely adopted primary design concepts are the Fresnel lens and parabolic mirror (Table 1). These two concentrators differ in a number of ways, allowing them to suit different applications. One important characteristic is their range of concentration. Under normal incidence the maximum concentration ratio achievable on earth is 46,000 $\times$ [8]. Languy et al. [9] investigated the concentration limits of Fresnel lenses and found the concentration limit to be around 1000 $\times$ due to

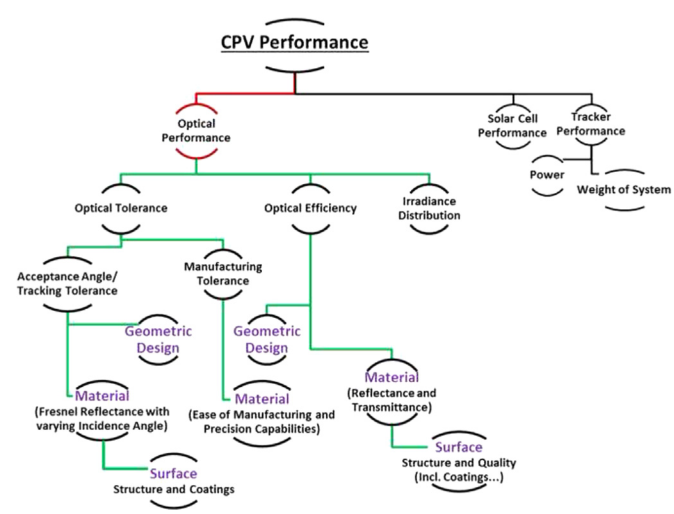

Fig. 1. Factors affecting CPV performance.