Heliosk: A bio-inspired, efficiency-improving design for organic photovoltaics (OPVs).

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Single sentence abstract

In this paper we present an innovative design to improve the vertical stacking efficiency of organic photovoltaic (OPV), inspired by the light focussing strategies of flower petals, and by light harvesting enhancement and quantum coherence effects in natural photosynthesis.

Abstract

OPV has great potential for contributing to a more sustainable future, provided that their efficiency will be significantly improved. In this paper we propose an innovative design to enhance OPV power output. The main efficiency-improving feature of the Heliosk design is inspired on shapes of flower petals, which optimize the specular reflection of sunlight. Furthermore, inspiration was drawn from thylakoid membrane stacking, which enhances light harvesting under low light conditions in plants. Moreover, quantum coherence effects in natural photosynthesis were studied in order to find an efficient OPV material.

Introduction

Carbon-based OPV has many advantages over the currently dominating silicon-based photovoltaics (PV) technology. Firstly, the power conversion of OPV is more efficient than that of silicon-based PV (Beliatis et al., 2013). Secondly, OPV panels are extremely thin (0.2µm, which is 100x thinner than a human hair). Therefore, OPV is much more material-efficient and therefore far less resource-costly than traditional PV. Moreover, the thinness makes OPV panels lightweight, which affords portability and benefits safety. Furthermore, OPV panels are flexible, which affords abundant design possibilities. As heavy metals are used in PV production but not in OPV, OPV panels are also less harmful in terms of environmental pollution. Last but not least, OPV panels are cheap and easy to manufacture, as they are printable by roll-to-roll processing techniques (Krebs et al., 2010).

However promising, current OPV technology has two important drawbacks. Firstly, due to wear-sensitivity, the current lifetime of a OPV panel is limited to approximately 7 months. Secondly, the current efficiency of a OPV panel can go up to 15% (Scharber & Sariciftci, 2013), which entails that a typical building of the TU Delft would require half a football field of OPV panels to generate sufficient energy. For this project, we developed a bio-inspired OPV design which increases the power output per surface area. With the proposed design, we aim to resolve the efficiency issue of OPV panels.

In-depth biology

The inspiration for the main efficiency-improving feature of the proposed design comes from the petals of flowering plants. Most diurnal (daytime) flowering plants have parabolic flower petals, whereas most nocturnal (nighttime) flowering plants have hyperbolic petals. Maximizing the amount of sunlight captured in the flower's reproductive organs is of major importance for flower growth. Thus, the petal shapes are adapted to optimize the specular (mirror-like) reflection of sunlight. Since the angle of reflection equals the angle of sunlight incidence, a parabolic petal shape works best for diurnal flowers, which open up during daytime (Fig. 1). Nocturnal flowers on the other hand adapted a hyperbolic petal shape to ensure maximization of the amount of sunlight captured when the sunlight incidence has a more inclined angle. In flowering plants, petal movement is caused by either changes in turgor (osmotic pressure) or by a elongation difference of the inner and the outer side of the petals. The opening of the petals can be triggered by a number of factors and results in active water transport into the petals or active ion transport to decrease its water potential, while closure reverses that process by active transport (van Doorn & Kamdee, 2014). Similarly, configurational change of the petal-like structures could be managed by manipulating pressure within separate compartments of the petal-like structures.

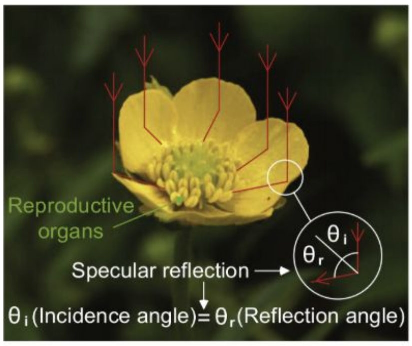

Fig. 1. The specular reflection of sunlight around noon (vertical incidence) in a diurnal flower with parabolic petals. Reprinted from Momeni & Ni (2018).

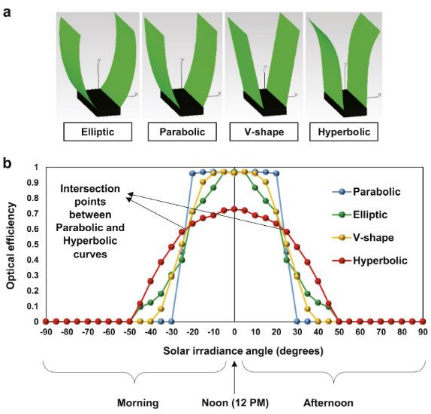

Fig. 2. (a) The concentrator models that were analysed with ray tracing software. (b) The optical efficiency of the concentrator models as a function of various irradiation angles. Reprinted from Momeni & Ni (2018).

Similarly, the optical efficiency of OPV panels can be increased by adding petal-like structures to the outer edges, which take on hyperbolic shapes in the morning and the afternoon, and parabolic shapes around noon. Momeni & Ni (2018) have shown that in this way, the incident light energy per ground area of OPVs can be increased by 25% over the day. As illustrated in Fig. 2, they analysed petal-like structures had either an elliptic, parabolic, hyperbolic, or V-shape (Fig. 2a), which affected their optical efficiency under various solar irradiance angles (Fig. 2b). To achieve deformation in an automatic manner, Momeni and Ni made the petal-like structures out of a thermo-sensitive material. Utilizing heat to manage the configuration of the petal-like structures is a method to automate the deformation process. However, the solution may not be robust since OPV panels will be situated in different climates and additionally experience seasonal fluctuations. Moreover, the thin thermo-sensitive material is rather prone to damage.

In order to catch even more light, the design is loosely inspired by thylakoid membrane stacking, a strategy used by green plants to enhance light harvesting under low light conditions. Thylakoid membranes are the site of the light-dependent reactions of photosynthesis in green plants and cyanobacteria. When light conditions are low, light harvesting is enhanced by increasing the number of thylakoid membrane layers in the grana stacks (Fig. 3). This stacking of thylakoid membranes enhances light harvesting through the formation of large arrays of PSII-LHCII supercomplexes (Trissl & Wilhelm, 1993). Since OPV panels are flexible, the design is able to achieve a considerable enlargement of active layer surface without demanding a substantially larger ground area.

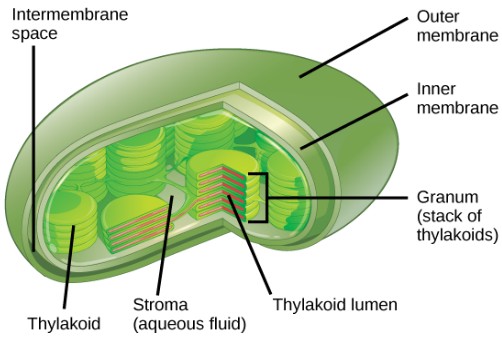

Fig. 3. A plant chloroplast organelle, containing stacks of thylakoid membranes.

Novelty and benefit

OPV's have great potential for contributing to a more sustainable future, provided that their efficiency will be significantly improved. Challenged by this prerequisite, the Heliosk is designed to improve commercial OPV power output for an area of ground. The proposed design is shown in Fig. 4. This design increases the power output per area by combining the light guiding features of flower petals with a cylindrical light trapping design and the use of nature-inspired OPV design. The configuration of the petal-like structures is based on the light focussing strategies of diurnal and nocturnal flowering plants, which can increase the incoming solar power input by 25% over the day (Momeni & Ni, 2018). Any light that is not directly absorbed by the panels will be reflected within the tube, thereby having multiple chances of being absorbed.

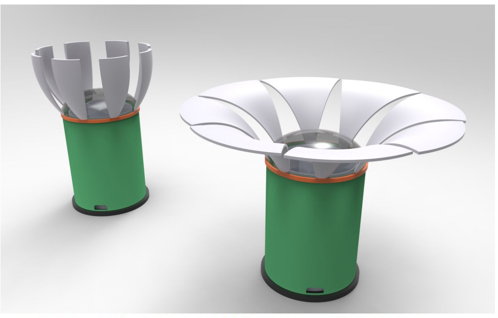

Fig. 4. The proposed efficiency-improving Heliosk design featuring deformable petal-like structures and a surface enlarging inner tube

Existing approaches for solar concentrators heavily make use of lenses or mirrors, which are material costly. By using 3D-printable petal-like structures, power output per ground area can be increased while saving on material costs for the concentrators. The cylindrical design reduces the amount of light hitting the cylindrical solar panel compared to a flat solar panel. This results in a lower panel temperature, which will increase its efficiency and lifespan. Cylindrical designs have been seen in a paper by Song, Lihui & Uddin (2012), where they explore the ability for a cylindrical OPV design to trap light and increase efficiency. In it, simulations show that this design has the ability up to double its efficiency when compared to a flat surface organic solar panel of the same ground area. This means the design could be able to increase the power output per area up to 50%. Moreover, encapsulating the OPV in the device decreases the wear on the panels, increasing their lifespan.

Outlook

Though promising in terms of power gain, the design has some challenges as well. A major challenge is the lifespan of the inner panels. OPV panels are susceptible to degradation caused by sunlight. As such, the lifespan of unencapsulated OPVs is approximately 7 months. Though the OPVs in our design are situated rather enclosed within the light tube structure and will therefore degrade somewhat less rapidly, finding a solution for improving the life span remains an essential topic. The limited life span leads to a second challenge, concerning the ease of changing the OPVs when they become degraded. The changing mechanism needs to be uncomplicated, so that the user is able to get the job done by himself in an effortless way.

Potential materials and mechanisms for the petal-like structures have yet to be studied in more detail. Furthermore, to achieve an optimal efficiency of the Heliosk, prototypes need to be generated, tested and iterated upon in order to find the optimal form, dimensions and curvation for the inner light tube. Also, the actual efficiency gain needs yet to be quantified. Moreover, concept ideas have to be conceived for achieving ease of changing the OPVs when they become degraded.

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