Biomimicry: White Butterflies as Solar Photovoltaic Concentrators

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What is Biomimicry?

Biomimicry is an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies. The goal is to create products, processes, and policies—new ways of living—that are well-adapted to life on earth over the long haul[1].

What are Photovoltaic Concentrators?

- Use mirrors and lenses to capture light and direct it towards smaller areas of photovoltaic material where solar energy is converted into electrical energy
- Decreases area of photovoltaic material required which is typically the most expensive part
- Results in very bulky systems
- Reduce solar energy costs and improve efficiency, but size and weight often limit their deployment

Figure 1. V-trough Concentrator image[2].

Reflective Surface Designs for Concentrators

- Polished metal surfaces
  - polished surfaces are very heavy and specific curved shapes are difficult and therefore expensive to manufacture
- Reflective film adhered to plastic mirrors
  - low reflectivity when applied to complex surfaces
- Polymer mirror films are a more recent third method to gain reflectance values of >90%
  - require specially designed structures to gain the appropriate shapes for a given application
- Vacuum metalizing is current best option
  - process is highly dependent on the material and surface quality it is bonded with in order to ensure a high quality mirror finish

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How could the White Butterfly help with reflective properties?

- White butterflies of the family Pieridae are especially effective at early take-off on cloudy days, and can therefore fly before other groups of butterflies in poor weather, reasoned that this ability is due to the V-shaped posture they adopt with their wings while 'thermal' basking. [3]

- V shaped posture gather and focus solar energy reflected by wings, onto the body

- Notice that the V-shaped design of the butterfly is strikingly similar to the V-trough solar concentrator

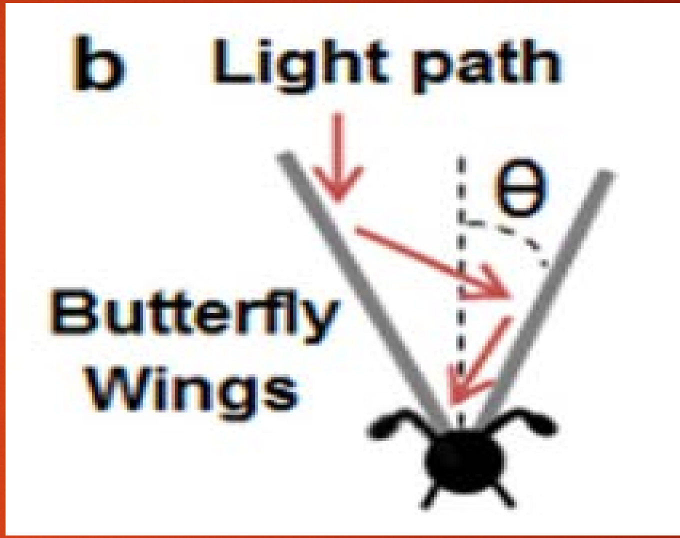

Figure 2. Light path showing reflection of wings[3].

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Thermal Analysis of White Butterflies

- Thermal image shows temperature seen on body of butterfly
- Graph showing max temps see on the body of butterfly at different wing angles
- 17◦ is optimal angle

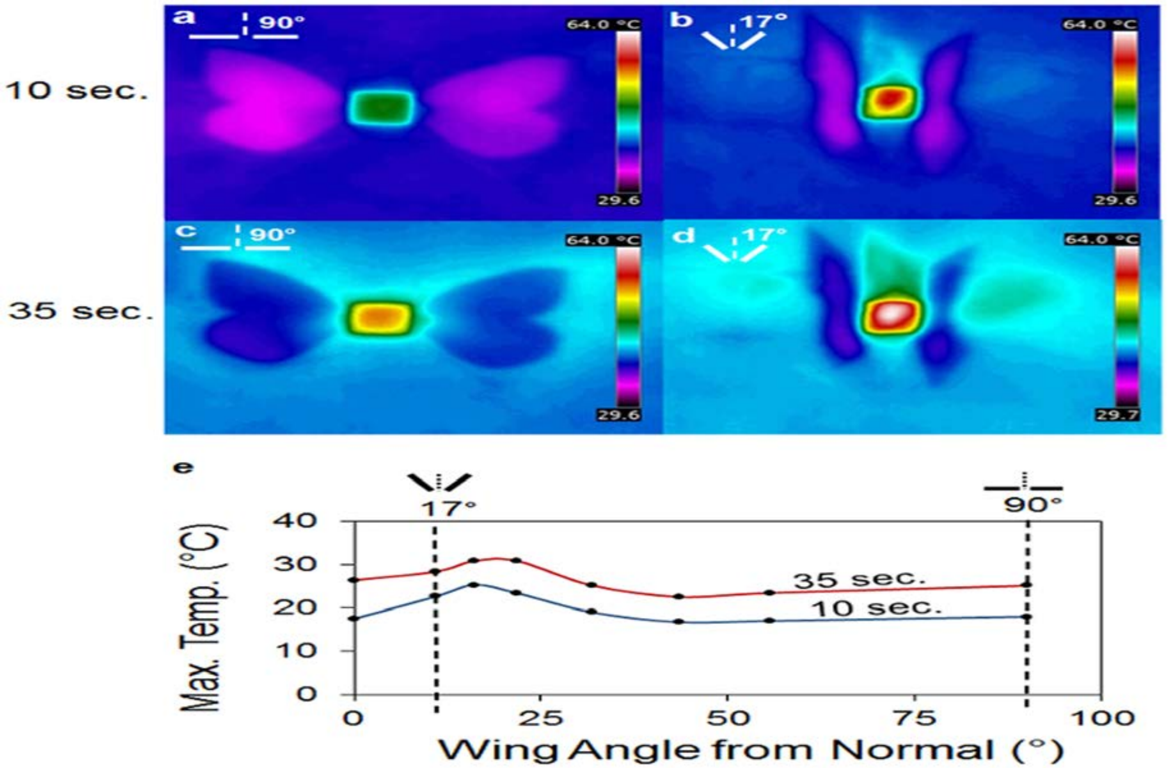

Figure 3. Thermal image of butterfly thorax and graph of max temp vs. wing angle[3].

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Reflectance Mapping of White Butterfly Wing

- Average percentage reflectance map for wings of the large white butterfly shows how wing appears in normal daylight. Reflectance spectrum for specific notable areas (maximum, minimum and black spot areas)

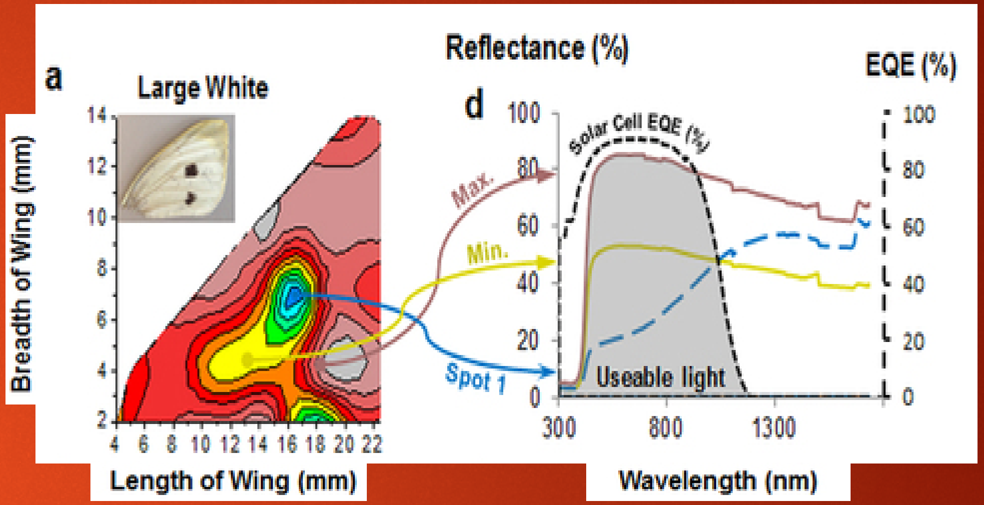

Figure 4. Reflectance map of wings for White Butterfly[3].

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Reflectance Mapping of White Butterfly Wing

- Scale windows of Butterfly Wings(gaps in the scale structure) are partially filled with ovoid shaped granules or ‘beads’.
- Beads contain the white pigment pterin which absorbs light in the short-wavelength range but strongly scatters light outside the pigment absorbtion range.

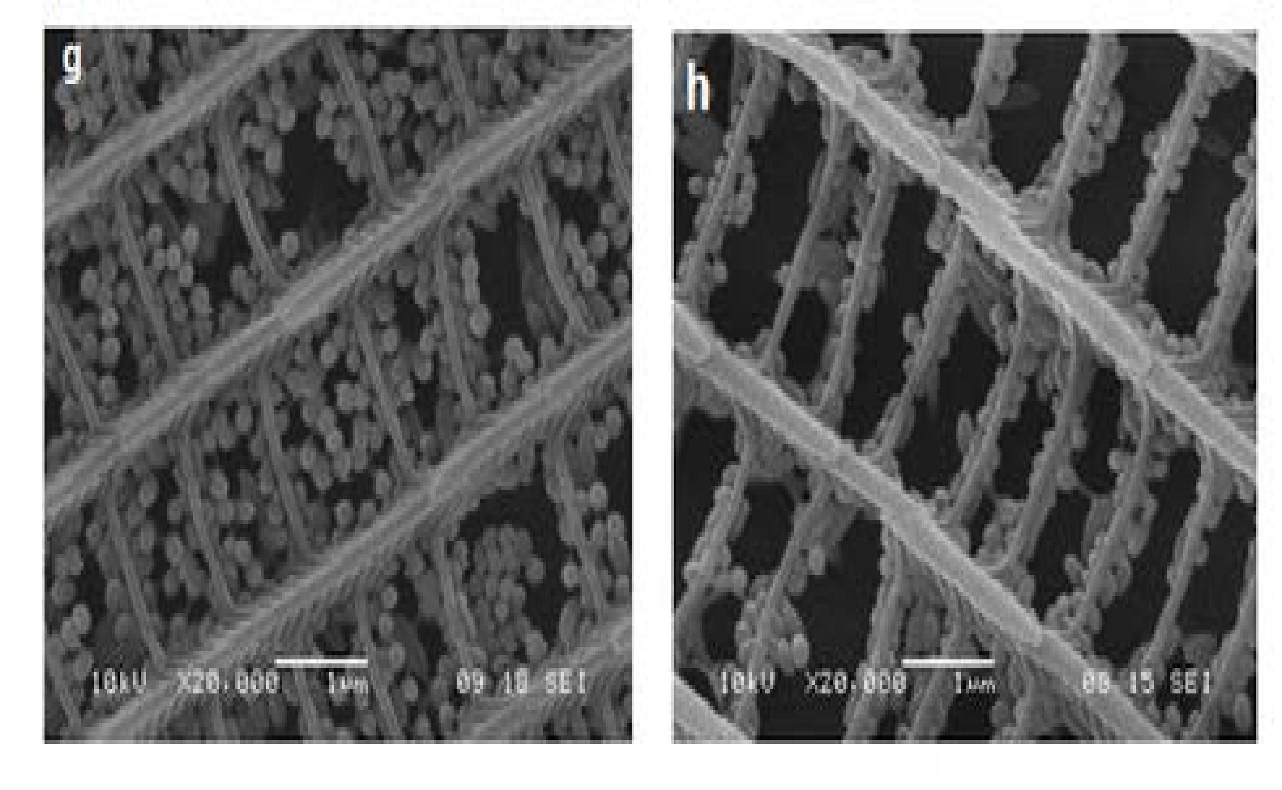

Figure 5. (**g)**, SEM of wing scale containing packed pterin beads. (**h)**, SEM of black spot area of wing scale containing significantly less pterin beads[3.]

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Increasing power output from a solar cell using the wings of the White Butterfly

- Highest reflectance comes from the forewings and this reflectance is well matched to the input requirements of a mono-crystaline silicon cell which average 78.9% reflectance over 400-950 nm range
- Attaching wings to a 1cm x 1cm mono-crystaline solar cell increased maximum efficiency by 42.3%(16.9mW to 23.9mW)
- Compared to reflective film increased power to weight ratio x17(readings were found using full multilayer of butterfly wing)
- Monolayer of scale cells removed from wing onto adhesive tape maintained similar but somewhat less, maintainimg 69% reflectance (400-950nm) suggesting only a single layer of scale cells is necessary to generate high levels of reflectance rather than a complex multi layered structure as found in the wing itself.

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So why use White Butterfly wings?

- Butterfly wings increase both the output power and the final power to weight ratio of solar cells
- Power to weight ratios are shown to increase by a multiple of x17

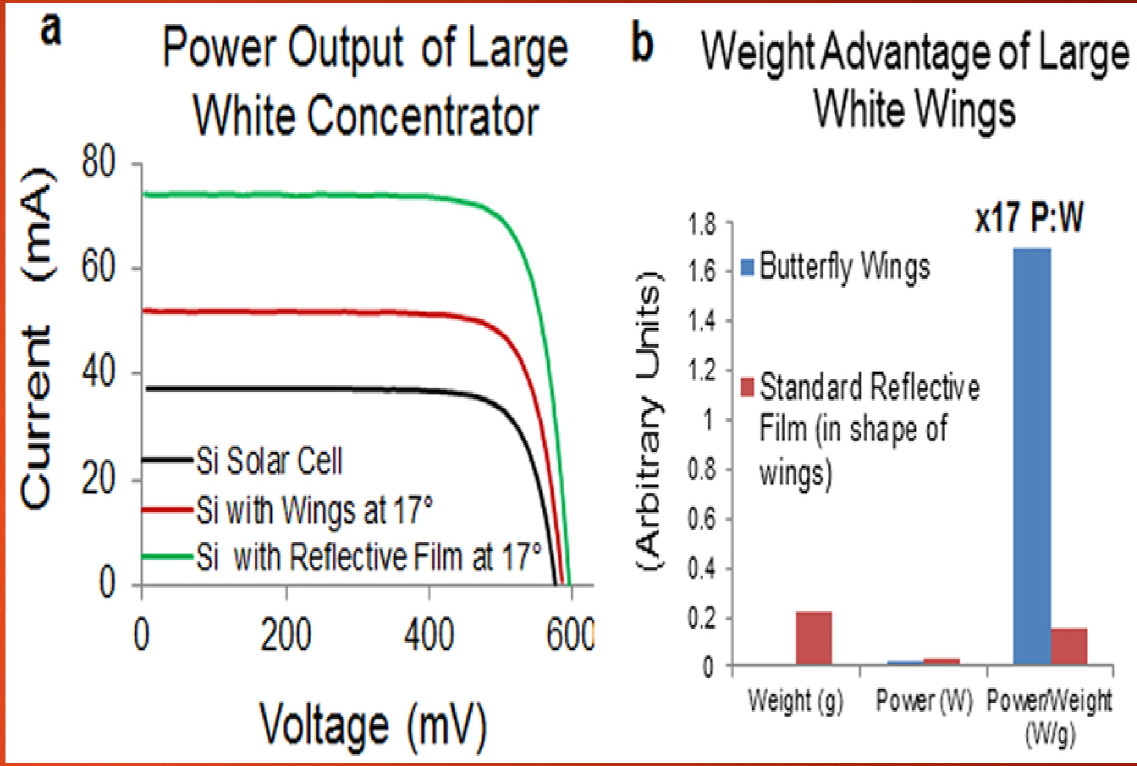

Figure 6. Power output and Weight adbantage of Large White Wing Butterfy vs. Reflective Film Concentrator[3].

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Light Concentration Theory Equations and how they relate to Butterflies

- Given that the V-shape is known to concentrate light as long as there is light reflectance and an acute angle between the reflectors then much of the theory of solar concentrators can be applied to the butterflies. The geometric concentration ratio (C) of a solar concentrator can be estimated using Eqn. 1 and hence an estimation of the potential concentration ratio of the butterflies and of a combination of butterfly wings and solar cell can be calculated.
- An estimation of the potential concentration ratio of the butterflies and of a combination of butterfly wings and solar cell can be calculated.

$$C = \frac{\text{Light Entry Aperture Area}}{\text{Reciever Area}} \quad (1)$$

$$C_{Butterfly} = \frac{\text{Wing Opening Area}}{\text{Thorax Area}} \quad (2)$$

$$C_{Cell+Wings} = \frac{\text{Wing Opening Area}}{\text{Solar Cell Active Area}} \quad (3)$$

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Light Concentration Theory Equations and how they relate to Butterflies

- The concentration ratio is a value used to categorise and analyse the efficiency of solar concentrators. The power of light incident on a receiver (P_r on butterfly body or solar cell) is dependent upon the optical efficiency (η_o), concentration ratio (C), incident irradiance on the system (I_i), and the receiver area (A_r), such that:

$$P_r = \eta_0 C I_i A_r \qquad (4)$$

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Light concentration theory equations and how they relate to butterflies

- In the case of concentrator photovoltaic systems; where the receiver is 1 or more solar cells, the final power output produced from the solar cell(s) would be the efficiency of the cell multiplied by the power incident on the cell(s), (P_r). Similarly the term effective concentration ratio should equal the geometrical concentration ratio minus optical and solar cell losses, or in other words, multiplied by their efficiencies[28] as in Eq.5.

$$C_{eff} = \eta_0 \eta_{cell} C \qquad (5)$$

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Light concentration theory equations and how they relate to butterflies

- The possible optical losses in the butterfly wing configuration include; light rays incident upon the wings but which are reflected to the front or rear -where there is no wing or body coverage- or even back out the top opening area, and also the efficiency at which the wings reflect the light—the reflectance. Instead of solar cell efficiency, the butterflies presumably would have heat transfer efficiency, dependent on their initial body temperature, incident temperature/energy from sunlight, and the ambient temperature of their environment.

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Conclusion

- First, the infra-red measurements of butterfly body temperature confirm the assumption that the thermal basking exhibited by pierid butterflies really does provide an increase in thorax temperature proving that their V-shaped posture is an effective thermal basking method
- Second, butterfly wings are both highly reflective and much lighter than any current reflective material. Mimicking these reflective structures with similar power to weight properties will be extremely useful in the design of new reflective materials for use in applications where weight is a limiting issue, such as flight
- Nano-fabrication of a layer of ovoid pigment containing beads will also form a reflective and light weight mimic of a pierid scale cell, provided that the nano-beads are presented in their correct orientation. Not only could this potentially enhance the properties and application of reflective materials but it could also expand the application of technologies such as solar concentrators which are currently severely limited by power to weight issues.

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