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How has biomimicry enabled the advancement of sustainable energy?

Introduction

Scientists have been exploring the natural world in hope of inspiration to further our technology, and recently, the urgent problem of climate change has paved the way to a host of developments concerning renewable energy. Solar and wind power are two of the top sustainable energy sources growing rapidly in worldwide use over the last decade. However, in order for these sources to have a significant contribution to energy supply, the efficiency must be improved and the costs decreased. Fortunately, the design and structure of certain species are holding answers to advancements in the engineering world that can be applied to renewable energy technology. From studying impressive adaptations of animals, researchers and engineers have found ways to implement these features into energy harvesting structures which has proved beneficial in increasing efficiency**.** Examples of this include the discovery of tubercles on a humpback whale's flippers which can be integrated into wind turbine design, and butterfly wings which contain nanostructures allowing effective light absorption that can be mimicked for photovoltaic cells. These will be addressed below.

The irony is that climate change is contributing to mass extinction of certain species which may hold the answers for a cleaner, more sustainable future.

Whale fins and wind turbines

Wind turbines are one of the main innovations for sustainable energy accounting for 2.5% of the total worldwide electricity production (1). Wind is a clean, free energy source once built and is leading the way in the boom of renewable energy technology. The Global Wind Energy Council has stated 'from 2000-2015, cumulative wind capacity around the world increased from 17,000 megawatts to more than 430,000 megawatts' highlighting the major potential wind technology has to offer (2). Already, technology is rapidly developing and mass production of wind turbines worldwide has allowed the cost of manufacturing them to decrease by 80% since 1980 (1), as well as many governments offering tax incentives to create growth for the wind energy sector (2). However, the most notable drawback to turbines is wind reliability. A modern wind turbine can begin to generate energy with wind speeds of 6-9 miles per hour(mph) but has to stop if the wind exceeds 55mph (3). Wind is constantly changing speeds, angles, and displays turbulence hence scientists need to develop turbine technology to maximise aerodynamic performance and exploit as much energy as possible if we plan to eventually become a fossil-fuel free world.

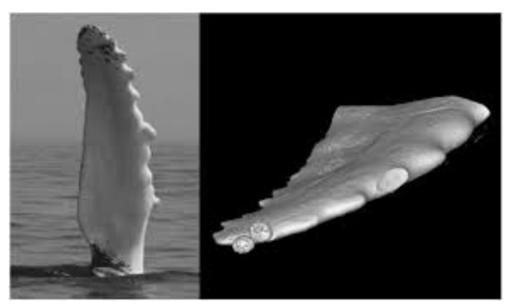
Figure 1 – humpback whale flipper profile (16)

Professor Frank E. Fish from the University of West Chester is a scientist who, when observing a sculpture of a humpback whale, noticed sinusoidally arranged bumps on the leading sides of its fins triggering the idea of a whole new design for wing-like structures (4). The humpback whale (*Megaptera novaeangliae*) has the longest flippers of any cetacean with lengths varying from 0.25-0.33 of their total body length. The flippers have unique bumps called tubercles as seen in Figure 1 which benefit the species greatly for performing loops underwater and particularly when it comes to feeding. A humpback whale will tend to create columns of bubbles underwater using its blowhole whilst swimming in a circular motion allowing the prey (most commonly Antarctic krill and schooling fish) to congregate, before making a sharp U-turn to pivot and swim through the centre of the circle – a method called 'bubble net fishing'. This method of catching prey requires extreme manoeuvrability and so the flippers act like 'biological hydroplanes' for tight turns (5).

During these turns, the body of the whale will roll, which in turn allows a hydrodynamic force perpendicular to the flipper**,** supplying a centripetal force vital to maintain the sharp turn. The bigger the force, the sharper the turn and this force is increased by the angle of attack from the fins (5). The angle of attack is the 'angle between the flow of water and the face of the flipper' (6). Increasing the angle of attack pushes down the water flow and therefore, increases the force. This occurs up to a certain angle until the angle becomes too steep and there isn't enough water flowing over the top of the fin resulting in a 'stall' (6). This causes increased drag and a loss of hydrodynamic force with a reduced centripetal force making the turns ineffective. Stall is a phenomenon observed in aircraft, causing a loss of lift on the wing, as demonstrated in Figure 2. The same behaviour is observed with the hydrodynamic force from the whale flipper. Here, 'lift' is equivalent to this hydrodynamic force. Figure 3 shows a typical lift curve slope of an aerofoil which governs the behaviour seen in Figure 2. The lift coefficient of the aerofoil increases linearly with angle of attack up until a maximum angle beyond which there is a loss of lift (stall).

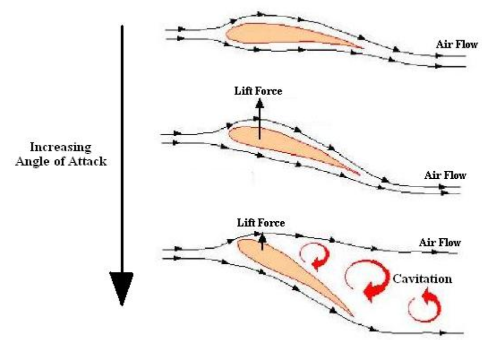

Figure 2 – diagram showing the change in lift force with increasing angle of attack (17)

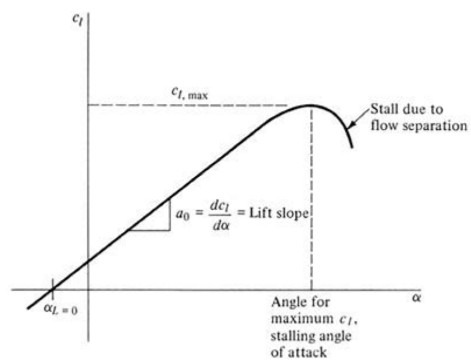

Figure 3 – lift curve of angle of attack(x) against lift(y) (18)

The tubercles on the whale's fins help to avoid stall by improving hydrodynamic performance. The variation of tubercles in placement and number cause an irregularity in pressure along the fin which can delay stall and increase 'lift' without increasing drag (5), proven by a team at Harvard. Previously, Miklosovic et al who studied two wing models with and without tubercles, showed that the bumps can increase stall angle by up to 40% without compromising lift or drag. This was later proven using an aerodynamic model by Ernst A. van Nierop, Silas Alben, and Michael P. Brenner from Harvard University, who carried out wind tunnel experiments to produce the mathematical proof supporting the observed phenomenon (7). They also managed to demonstrate from these experiments that a stall typically with an angle of attack of 12° is increased to 18° with tubercles, whilst the drag is reduced by almost a third and lift is increased by 8% (6).

Fish stated 'engineers have previously tried to ensure steady flow patterns on rigid and simple lifting surfaces, such as wings. The lesson from biomimicry is that unsteady flow and complex shapes can increase lift, reduce drag and delay stall' (8). These principles can be adapted for future designs of wing-like structures such as hydrofoils, airplane wings and helicopter blades, and progress in engineering new wind turbine blades to maximise efficiency is already underway. By creating turbines with tubercles, the angle of attack will increase and therefore so will the lift meaning more power is being extracted from the wind by the turbine. It is estimated this will boost energy production by up to 20% in wind farms (9). Fish founded the 'WhalePower corporation' in Toronto in 2005 to develop tubercle-technology which has successfully improved stability, decreased noise and enabled an increased amount of energy to be harnessed from the wind. The new turbines are able to capture wind at lower speeds, for example a turbine with tubercles can generate the same energy at 10mph as a conventional turbine at 17mph (6). This turbine technology has been studied by the German Aerospace Centre who discovered that the noise produced by these turbines is reduced by at least 2 decibels and the material wear decreased by 8%, therefore extending life span by 25% (three to six more years). Global sales in the wind turbine market are also rapidly increasing with WhalePower's first licenced product expected to be worth EUR 8.5billion by 2022, highlighting the potential this technology has for the future of renewable energy (9).

Butterfly wings and solar panels

Solar panels are another attractive source of renewable energy on the forefront of the fight to a cleaner world. It is said 'the Sun can emit enough power onto Earth each second to satisfy the entire human energy demand for over two hours' (10). Thus, it is understandable that humans look for ways to harness energy from this constant power source. Bell Labs created the first silicon solar cell in the mid 1950's which was only 6% efficient. This has increased to roughly 32% efficiency in the modern day which is supposedly the maximum theoretical efficiency of a silicon solar cell discovered by Shockley-Queisser in 1961 (11). Efficiency needs to be as high as possible to reduce the energy lost, mainly as heat, when light is absorbed by solar panels. Classic solar panels are made of thick, crystalline solar cells and are fixed at a certain angle to absorb the most light throughout the day. Radwanul Siddique and his team from the California Institute of Technology noticed the inefficiency and high cost of this design and studied the wings on Rose butterflies. This inspired them to create panels with thin film solar cells copying the structure of the wing which 'can harvest light twice as efficiently as before' (12).

The male Rose butterfly, also known as the Black butterfly (*Pachliopta aristolochiae*) is mainly found in Asia, being the most common butterfly in India. As butterflies are ectothermic, they are dependent on external heat from the sun to warm up their muscles in order to take flight (13). Owing to this, the Black butterfly has adapted its wings to absorb as much sunlight as possible. Firstly, the wings are matte black, the optimum colour for light absorption, as black can absorb all wavelengths of light and will reflect almost none, hence more light energy can be radiated out as heat. The wings were also discovered to have nanostructures on their scales using a scanning electron microscope (SEM). Figure 4 shows this structure, captured by an SEM. From images like this, scientists were able to distinguish longitudinal ridges at regular intervals spanning the scales connected by horizontal cross-ribs. Together these create a '2D network of disordered nanoholes' that lie above the scale interior. These nanoholes have a mean diameter of 300nm and are randomly distributed on the scales (14).

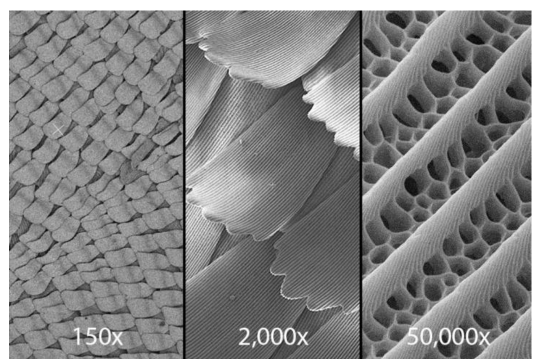

Figure 4 – magnified images of butterfly wing using an SEM (19)

The combined effects of the different nanostructures allow for extremely efficient light absorption. This was demonstrated when the team from Caltech used field mapping to investigate the propagation of light incident on the wing. They used a selection of four different wavelengths; 350nm being marginally

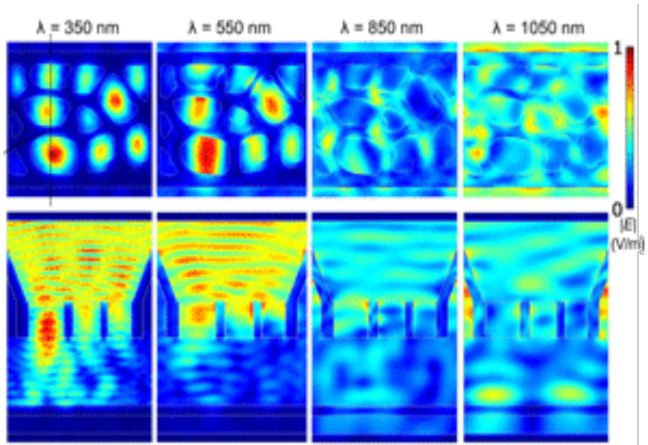

Figure 5 – electric field intensity distribution calculated for normal incidence and wavelengths of 250, 550, 850, and 1050nm (14)

higher than the mean diameter of a nanohole, 850nm being the maximum diameter of a nanohole, 1050nm being the length of several nanoholes and an additional 550nm which is similar to solar irradiance (14). Figure 5 displays the simulated mapping they produced. From these images the team concluded two ways the nanostructures propagate light. The first is 'vertical channelling' seen from the 350nm wavelength in which the light travels along the sidewalls of the ridges to the nanoholes where it is then partially absorbed at their surface. This is beneficial as the channelling of the photons allows the mean refractive index of the nanostructures to decrease becoming more similar to air. As a consequence, reflection decreases. The other effect is called 'in-plane scattering' as seen by the 850nm wavelength, where the photons are completely scattered across the nanostructure (14), also allowing for better absorption. The team then investigated the light harvesting capability of photonic structures with different hole arrangements and diameters on absorbers made of hydrogenated amorphous silicon (a commonly used material for thin film photovoltaic cells). They concluded that disordered holes with varying diameters, as seen on the Rose butterfly, have the most stable integrated absorption (of 63.9%) over the light spectrum with varying angles of incidence, as expected. This is more than double compared to an unstructured layer, highlighting how efficient these nanostructures are (14).

From the positive results, attempts have been made to incorporate the nanostructure design into photovoltaic cells. The team at Caltech, as well as researchers from the Karlsruhe Institute of Technology in Germany, have adapted thin film solar cells which are usually incorporated into smaller domestic technology such as watches, since they absorb considerably less light than crystalline technology. However, these thin film solar cells are a thousand times thinner than crystalline cells and therefore significantly cheaper (15). By altering the design to mimic the features of the Rose butterfly, they added cylindrical holes onto a hydrogenated amorphous silicon slab standing on glass which increased the integrated absorption by up to 93% compared to a smooth slab, highlighting a substantial increase in performance. The Caltech team acknowledged that the 'scalability of these structures over large areas makes this fabrication route a promising candidate for the integration of bioinspired disordered ensembles of nanoholes as a light in-coupling and light-trapping nanostructures'. With this advancement of technology, the design may pave the way for improvements in other photovoltaic applications as well as inspire scientists to discover new nanostructures found in nature that can help with optimum efficiency for solar power.

<u>Conclusion</u>

In conclusion, both of these innovations are examples of how implementing biomimicry in the energy sector has led to increases in efficiency of renewable energy generation. Whilst these techniques are not yet the standard, they have the potential to help advance renewable energy such that it sustains the ever-increasing needs of the world's population. In turn, this is vital to reduce climate change that is impacting not only our natural world, but our chance for future inspiration.

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