Biomimicry for Greener Energy

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Imperial College London

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Mika Marisol Smith
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1 What is Biomimicry?

You could look at nature as being like a catalog of products, and all of those have benefited from a 3.8 billion year research and development period. And given that level of investment, it makes sense to use it

– Pawlyn M [1]

In 1987 the Japanese Railway Group set out to design a high-speed bullet train for their public transport system [2]. Two years later, the 100 Series Shinkansen ('new trunk line') train was opened, which was able to reach speeds of up to 210km per hour. Compared to the Metropolitan line (the fastest line of the London Underground), whose top speed is only 97km per hour [3], Shinkansen was one of the fastest public transport trains of its time. However, the original design had a major flaw: noise. Due to the high speed, whenever the train entered a tunnel it would create waves of high atmospheric pressure that upon exit, creating a loud sonic boom. Luckily, the general manager of the technical developments department was a bird watcher.

By redesigning the nose of the train to mimic the kingfisher's beak, the rig that connected the train to the electrical wires to imitate the serrations found on the feathers of the owl, and the base of the rig connector to copy the body of the adelie penguin, the 500 Series Shinkansen train was born [4]. The improved model integrated features of the three birds that made them aerodynamic and importantly, quiet. As a result, the shape of the 500 Series reduced air pressure built up in tunnels by 30%. In addition, the new design required 15% less power while achieving speeds that were 10% faster than the original model [5]. The nature-inspired Shinkansen train is an excellent example of biomimicry in action.

Biomimicry describes a field of research dedicated to improving the design of man made structures, processes and even whole systems by mimicking those that organically occur in the natural world. Biomimicry has been used to design more efficient technologies, self-preserving architectures and greener methods of fuel production, though this is not an exhaustive list. The application of bio-mimetic design in the context of renewable energy sources will be explored here, as well as comparisons of traditional energy production methods to emerging technologies.

2 Current Renewable Sources

As the availability of fossil fuels decreases, we must seek alternative, greener ways of powering our modern world. While fossil fuels run out and the demand grows, the cost of them will keep increasing. Aside from the economic issues posed by our dependence on fossil fuels, the major drawback is of course their contribution to global warming.

The demand for renewable energy has increased in recent years, with a record-breaking figure of 161GW of power being produced world-wide from renewable sources in 2016 [6]. However, power from renewable sources still only represents 20% of global power consumption [7], and our carbon dioxide emissions are ever growing.

In 2017 in the UK, energy consumption from renewable sources accounted for approximately 30% of the total, with the majority coming from wind and solar power [8]. While an improvement on previous years, the major issue facing wind and solar power is the incapability of current methods to harness the full potential of energy from wind or sunlight. According to Betz theory, the maximum efficiency of any wind turbine is only 59.3% [9]. With wind power, the effect of turbulent and inconsistent wind speeds affecting the performance of turbines means that their actual efficiency is lower than this. Of course, the variation of the weather with season and time of day means that both wind and solar power are not always feasible methods of energy production on their own. However, employing bio-mimetics to improve the design of current technology could enable a range of different renewable sources to supply the majority of global power.

3 Harvesting Energy

> *The energy sector in industrialized societies is probably the single largest economic contributor to global environmental degradation*
>
> – Benyus JM [10]

With wind power providing the majority of renewable energy of power consumed in the UK in 2017 [8], harvesting power from the kinetic energy of wind appears to be viable method of powering the world. Studies into the aerodynamics has provided insight as to how we may access as much of this energy as possible.

3.1 The Humpback Whale

Despite having masses of up to 35 tonnes [12], the humpback whale proves to be a marvel of aerodynamics. They are able to spiral about their axes in tight circles with apparent ease. The fluid dynamics governing the motion of the humpback whale gave inspiration for the wind turbines developed by WhalePower Corporation. The aptly named marine biologist Dr. F. Fish, one of the core founders of the company, was first drawn to the humpback whale after a trip to a gift shop in Boston [14]. Upon inspecting a figurine of a humpback whale, he found that on the leading edge of the whale′s fins there were round protrusions. Believing these to have been sculpted on the wrong side of the fin based on his knowledge of fluid dynamics, it was a surprise to find that the figurine had indeed been made accurately. Fish′s subsequent research into the fluid dynamics of the humpback whale would ultimately lead to the birth of WhalePower Corporation.

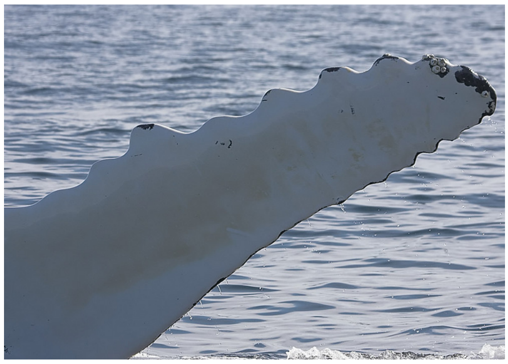

Figure 3.1: Tubercles on the leading edge a humpback whale's fin [11]

The perturbations along the humpback whale′s fins (shown in Fig. 3.1), referred to as tubercles, act to improve the efficiency of their motion mainly by reducing the effects of dynamic stall [12].

3.2 Dynamic Stall

The pressure gradients around the leading edge of a body determine the lift produced. In the case of the humpback whale, the fins are structured such that the water above the leading edge flows at a higher velocity, thus having a lower pressure according to Bernoulli's principle [16]. The converse is true of the water below the leading edge. The difference in pressures produces a resultant lift force on the body [17].

Dynamic stall describes the phenomenon in which the lift coefficient of an object reduces once the critical angle of attack is exceeded [18]. The angle of attack is defined to be between the chord line of the object and the direction of fluid flow. The lift coefficient, C_L, for a cylinder is given by [19]:

$$C_L = \frac{8\pi r}{A} sin(\alpha) \quad (3.1)$$

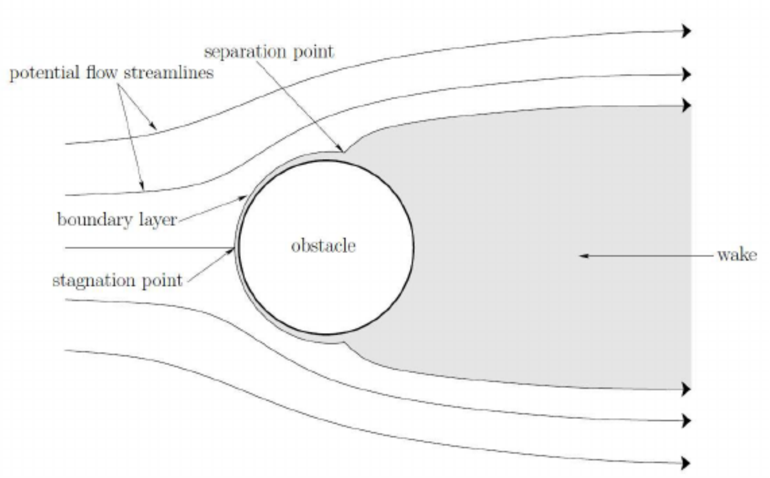

Figure 3.2: An object moving through a fluid disturbs the fluid flow. The separation point determines the size of the wake. [13]

where r is the radius of the cylinder, A is the area of the projection of the foil on the plane containing the chord line, and α is the angle of attack. A foil is any object that when placed in a fluid at a suitable angle of attack, the lift force produced is much greater than the drag force acting on it. Therefore, for small α, the lift coefficient is proportional to α. Fig. 3.3 shows a typical plot of C_L against the angle of attack.

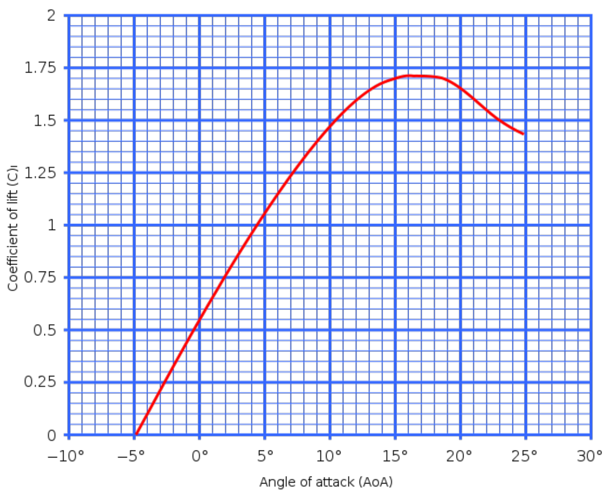

Figure 3.3: A plot of the lift coefficient against angle of attack [20]

While α is small, the empirical relationship agrees with the theory. This is due to there being no separation in the boundary layer of fluid around the foil. At the critical angle, the lift coefficient is at a maximum. As the angle of attack increases past this, the small angle approximation can no longer be assumed and the point of separation in the boundary layer moves closer to the leading edge, thus increasing the size of the wake of the foil. A diagram demonstrating the effect of a foil moving through a fluid is given in Fig. 3.2. As a continuous boundary layer is required to generate lift, as the angle of attack increases, separation increases, thus causing a decrease in lift. Dynamic stall occurs as a result of a sudden change in fluid velocity, causing an increase in angle of attack [18].

The tubercles on the leading edge of the humpback whale′s fins reduce the effect of dynamic stall. The tubercles direct flow in-between the bumps, which encourages the boundary layer to stay close to the fin, and generates a greater lift force [14]. Therefore the point of separation for a given angle of attack is further from the leading edge of the fin. This allows dynamic stall to be delayed to greater angles of attack. This is what enables the humpback whale to spiral in such tight circles so smoothly; without the tubercles it would be akin to turning on an icy road: instead of following the curve of the road you would continue at a tangent.

3.3 Designing a Whale-y Good Turbine

The design of the wind turbines produced by WhalePower Corporation mimic the tubercles of the humpback whale: the leading edge of their turbines have a sinusoidal structure, see Fig. 3.4. A study conducted in 2012 by J. Borg explored the effect of varying the amplitude and wavelength of the sinusoid on the dynamic stall [21]. For angles of attack in the range 1° to 21°, it was found that low amplitude and low wavelengths gave optimal post-stall performance in wind tunnel tests. This has been implemented in the design of the turbine.

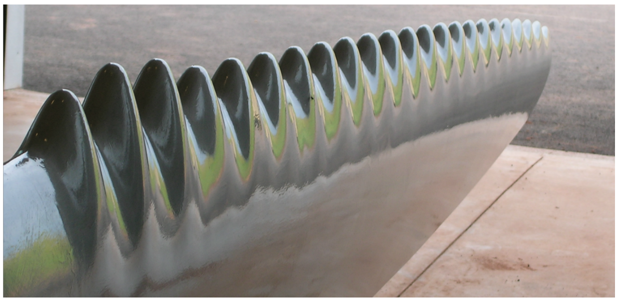

Figure 3.4: WhalePower turbine design [15]

The prototype tests for the whale inspired turbines nearly doubles the performance of traditional wind turbines; the WhalePower turbines were able to generate the same amount of power for wind speeds of 10mph as conventional turbines at 17mph [22]. This technology surpasses traditional wind turbines, as the improved performance under dynamic stall will mean that for rapidly changing wind speeds, there will be less of a detrimental effect on the power output.

4 Storing Energy

What's science fiction for us – clean burning fuel and chemistry in sunlight – is commonplace for plants

– Benyus JM [10]

A major limitation of most renewable energy sources is the need for immediate use of power produced. While power production methods such as wind or solar power are useful to supplement the national grid during peak energy consumption hours, the storing of energy produced poses an issue. Solar cells require large batteries to store energy, but by looking to plants for inspiration, a much more elegant solution can be found.

4.1 MEMBRANE POTENTIAL

Photosynthesis is the process by which a plant takes carbon dioxide and water to produce glucose for growth and oxygen as a byproduct. This process takes place within the chloroplasts in the green pigment chlorophyll. Contained within the chloroplasts are membrane-bound structures called thykaloids. The potential difference produced across the thykaloid membrane during photosynthesis allows light independent reactions to take place [23]. This potential energy can be stored for long periods of time stably and is a process, if replicated artificially, could provide an elegant way of harvesting and storing energy much more efficiently than conventional solar cells.

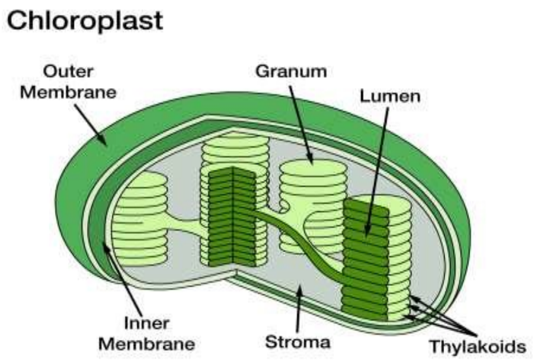

Figure 4.1: Structure of the chloroplast [24]

To harness as much solar energy as possible, the thykaloid contains two photosystems of photosynthetic pigment; Photosystem I (PSI) and Photosystem II (PSII), which absorb photons of wavelength 700nm and 680nm, respectively [10]. The photons absorbed by these photosystems excite delocalised electrons within the pigment.

Photons of wavelength 680nm excite electrons in PSII. These excited electrons are transferred to PSI along an electron transport chain, where they lose energy by translocating H^+ ions produced in the photolysis of water into the thykaloid lumen [23]. The build up of hydrogen ions within the lumen creates an electrochemical gradient across the membrane; a membrane potential.

In PSI, the electrons are excited once again by photons of longer wavelengths, and are used to convert $NADP^+$ (nicotinamide adenine dinucleotide phosphate) into its reduced form, NADPH. It is NADPH which is used in the light independent reactions to produce organic compounds for plant growth. As this takes place without solar energy, the potential energy stored across the thykaloid membrane is required to drive the reactions. H^+ ions return to the stroma through the thykaloid membrane via the enzyme ATP (adenosine triphosphate) synthase. ATP synthase enzymes use the passage of hydrogen ions to add a third phosphate to ADP (adenosine diphosphate) to produce ATP in a process called chemiosmosis [23]. Glucose, used for plant growth and reproduction, can then be produced from NADPH and ATP:

$$ATP + NADPH + CO_2 \rightarrow ADP + NADP + C_6H_{12}O_6. \quad (4.1)$$

An experiment conducted in 2012 by Gervaldo M. et. al. successfully produced a molecular triad that mimics the natural electron transfer process in PSII [25], which achieved a charge-separated state (membrane potential) that was thermodynamically capable of oxidizing water, to produce clean burning hydrogen. The lifetime of the charge-separated state was found to be sufficiently long such that the molecule could be incorporated with pre-existing water oxidizing molecules to produce a clean fuel production method.

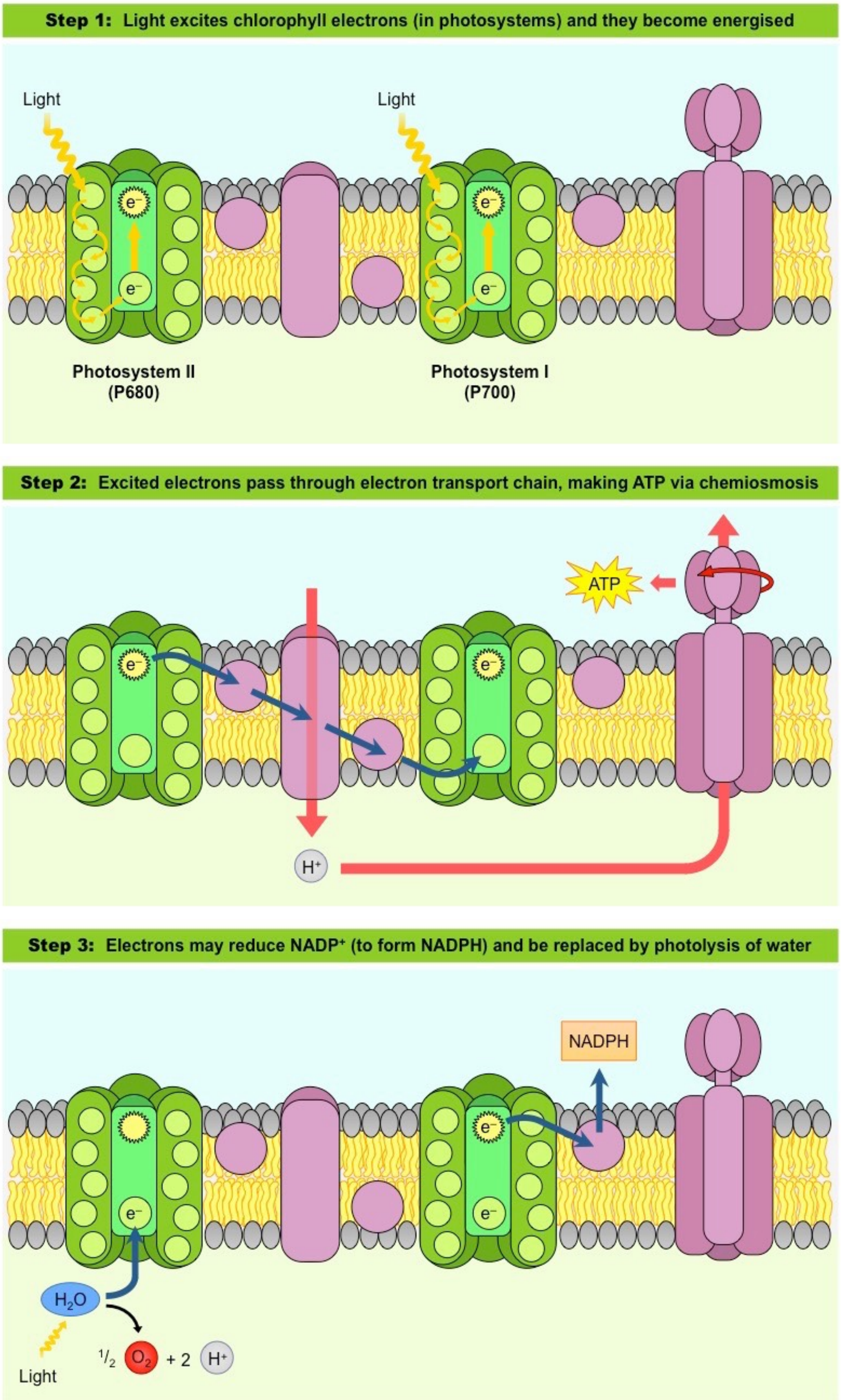

Figure 4.2: Electron transfer process in the thykaloid membrane to create a membrane potential [23]

4.2 Fractal Structure of Fern Leaves

Most commercially used solar panels use crystalline silicon photovoltaic cells (PVCs) to produce energy. In 2011, they represented 85% of photovoltaic cells sold worldwide [26]. A disadvantage of silicon PVCs is the space they occupy. In 2018, solar panels spanning an area of 1.6m^2 were able to produce 320W of power at only 18.7% efficiency [27]. In context, this is only enough to power approximately five 60W light bulbs . Furthermore, due to the structure of the PVCs, solar panels must be flat to harness solar power. This limits the application of solar panels for domestic use, as there is a need for a large area in direct sunlight. On an industrial scale, solar 'farms' have been built, but this comes at the cost of destroying natural habitats and indirectly polluting the environment with hazardous byproducts from producing and cleaning the solar panels. To produce the crystalline silicone required for PVCs, silane gas must be used. This results in the toxic waste product silicon tetrachloride [28].

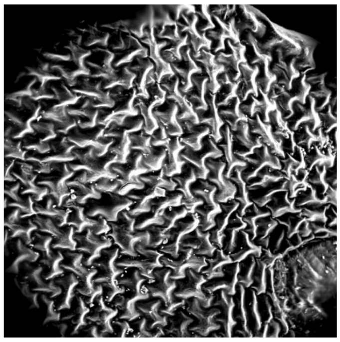

Figure 4.3: The vein structure of polystichum munitum [31]

In 2017, ground-breaking work was done to improve the efficiency of traditional solar cells. *Polystichum munitum*, or the western sword-fern, has an extremely space efficient vein structure. The veins have a self repeating, fractal-like structure which enables the fern to absorb high densities of solar energy in extremely small surface areas [30]. RMIT university in Melbourne, Australia has produced a laser-scribed graphene (LSG) electrode who's structure mimics that of the sword-fern's veins. The active surface area to volume ratio for increasingly complex fractal structures were tested and compared to the sword-fern. The Hilbert fractal, shown in Fig. (Hilbert fractal), was scribed into a 20μm thick layer of graphene to produce an electrode that could achieve an energy density over 30 times that capable of conventional planar solar panels [31]. This electrode allows both energy production and storage in relatively little space. With further development, not only could this technology be used to replace and improve existing solar panels, but its applications exceed those of photovoltaic cells: as this LSG is extremely thin and flexible, the need for a plane surface is surpassed. This could be therefore be implemented to charge anything from a smart phone, to a hybrid car.

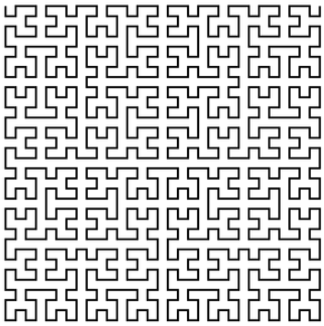

Figure 4.4: The Hilbert fractal [29]

5 The Future of Renewable Energy?

The ultimate aim of bio-mimetics is to design the modern world so that is is functionally identical to processes mastered by the natural world after billions of years of evolution. In recent years, research into natural processes has increasingly influenced the design of renewable energy production methods. While the technologies discussed here do offer improvements to traditional renewable energy sources, they are not without their flaws. For example, to produce the graphene needed for LSGs requires the heating of copper substrate to 1000° C [30], which itself requires energy that may come from burning fossil fuels. Developing a molecular triad that mimics membrane potential is a fine art that requires more laboratory testing before it might be implemented on a wide scale. And of course, the inherent dependence on weather for wind and solar power will always limit the power output of such sources. However, with further testing and development, these technologies may prove to be sufficient enough that burning fossil fuels will become a thing of the past.

REFERENCES

[1] Biomimicry Institute. *What is Biomimicry?*. Available from: https://biomimicry.org/what-is-biomimicry/ [Accessed 8th January 2019]

[2] Encyclopaedia Brittanica. *Shinkansen*. Available from: https://www.britannica.com/topic/ Shinkansen [Accesseed 8th January 2019]

[3] Coldwell W. 150 FACTS FOR 150 YEARS OF THE LONDON TUBE. *The Independent*. January 9 2013. Available from: https://www.independent.co.uk/life-style/history/150-facts-for-150-years-of-the -london-tube-8444153.html [Accessed 8th January 2019]

[4] Vox. *The world is poorly designed. But copying nature helps.* [Video] 2017. Available from: https://www.youtube.com/watch?v=iMtXqTmfta0 [Accessed 8th January 2019]

[5] AskNature Team. *Beak provides streamlining: Kingfisher*. Available from: https://asknature.org/strategy/beak-provides-streamlining/.XDIUgs$_7T - Z[Accessed 8th January$2019]

[6] Johnston I. World renewable energy production increases by record levels in 2016 – enough to power half of Western Europe. *The Independent*. June 7 2017. Available from: https://www.independent.co.uk/environment/world-renewable-energy -production-record-increase -2016-green-power-western-europe [Accessed January 9th 2019]

[7] Merchant EF. 2017 Was Another Record-Busting Year for Renewable Energy, but Emissions Still Increased. *Green Tech Media*. June 4 2018. Available from: https://www.greentechmedia.com/articles/read/2017-another-record-busting -year-for-global-renewable-energy-capacitygs.H47m7R5W [Accessed 8th January 2019]

[8] GreenMatch. *Renewable Energy in the United Kingdom*. Available from: https://www.greenmatch.co.uk/blog/2018/03/renewable-energy-in-the-united -kingdom [Accessed 8th January 2019]

[9] Energy Education. *Betz limit*. Available from: https://energyeducation.ca/encyclopedia/Betz_limit [Accessed 8th January 2019]

[10] Benyus JM. *Biomimicry: Innovation Inspired by Nature*. New York:Perennial;2002

[11] AskNature Team. *Flippers provide lift, reduce drag*. Available from: https://asknature.org/strategy/flippers-provide-lift-reduce-drag/.XDQAnc_7T-Z [Accessed 8th January 2019]

[12] Aftab et al. Mimicking the humpback whale: An aerodynamic perspective. *Progress in Aerospace Sciences*. 2016;84:48–69. Available from: https://www-sciencedirect-com.iclibezp1.cc.ic.ac.uk/science/article/pii/S0376042115300063 [Accessed 4th January 2019]

[13] ResearchGate. *A flow separation on the surface of a circular cylinder*. Available from: https://www.researchgate.net/figure/A-flow-separation-on-the-surface-of-a-circular-cylinder-illustration-by-Fitzpatrick [Accessed 8th January 2019]

[14] EPOfilms. *Stephen Dewar, Philip Watts Frank Fish – Turbines and fans inspired by whales*. [Video] 2018. Available from: https://www.youtube.com/watch?v=55K9j4om4DU [Accessed 4th January 2019]

[15] WhalePower Corporation. *Wind Turbines*. Available from: https://whalepowercorp.wordpress.com/wind-turbines/ [Accessed 8th January 2019]

[16] Clancy LJ. *Aerodynamics*. India:Himalayan Books;1978

[17] National Aeronautics and Space Administration. *Dynamics of Flight*. Available from: https://www.grc.nasa.gov/www/k-12/UEET/StudentSite/dynamicsofflight.html [Accessed 4th January 2019]

[18] MNDOT Office of Aeronautics. *Dynamic stall basics*. Available from: https://www.mnflyer.com/story/2013/12/01/news/dynamic-stall-basics [Accessed 4th January 2019]

[19] Douglas JF et. al. *Fluid Mechanics Fifth Edition*. Edinburgh:Pearson Education Limited;2005.

[20] Aviation. *Does lift coefficient vary with the wind velocity for a given angle of attack?*. Available from: https://aviation.stackexchange.com/questions/23173/does-lift-coefficient-vary-with-the-wind-velocity-for-a-given-angle-of-attack [Accessed 8th January 2019]

[21] Borg J. *The effect of leading edge serrations on dynamic stall*. Masters Thesis. University of Southampton; 2012

[22] MIT Technology Review. *Whale-Inspired Wind Turbines*. Available from: https://www.technologyreview.com/s/409710/whale-inspired-wind-turbines/ [Accessed 4th January 2019]

[23] Bioninja. *Light Dependent Reactions*. Available from: http://ib.bioninja.com.au/higher-level/topic-8-metabolism-cell/untitled-2/light-dependent-reactions.html [Accessed 9th January 2019]

[24] ResearchGate. *Chloroplast structure*. Available from: https://www.researchgate.net/figure/Chloroplast-structure [Accessed 8th January 2019]

[25] Gervaldo, Miguel et al. Mimicking the electron transfer chain in photosystem II with a molecular triad thermodynamically capable of water oxidation. *Proceedings of the National Academy of Sciences*. 2012;109:15578–15583. Available from: 10.1073/pnas.1118348109 [Accessed 8th January 2019]

[26] Office of Energy Efficieny Renewable Energy. *Crystalline Silicon Photovoltaics Research*. Available at: https://www.energy.gov/eere/solar/crystalline-silicon-photovoltaics-research [Accessed 8th January 2019]

[27] Solar Power Rocks. *How much electricity does a solar panel produce?*. Available from: https://www.solarpowerrocks.com/solar-basics/how-much-electricity-does-a-solar-panel-produce/ [Accessed 8th January 2019]

[28] Centre for Alternative Energy. *What is the environmental impact of photovoltaic (PV) solar panels?*. Available from: http://info.cat.org.uk/questions/pv/what-environmental-impact-photovoltaic-pv-solar-panels/ [Accessed 8th January 2019]

[29] Wolfram Mathworld. *Hilbert Curve*. Available from: http://mathworld.wolfram.com/HilbertCurve.html [Accessed 8th January 2019]

[30] Lempriere M. Could biomimicry revolutionise renewable energy? *Power Technology*. April 26 2017. Available from: https://www.power-technology.com/features/featurecould-biomimicry-revolutionise-renewable-energy-5796192/ [Accessed 8th January 2019]

[31] Thekkekara LV Gu M. Bioinspired fractal electrodes for solar energy storages. *Scientific Reports*. 2017:7;45585. Available from: ttps://www.nature.com/articles/srep45585 [Accessed 8th January 2019]