Nature-Inspired Designs in Wind Energy: A Review

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The field of wind energy stands at the forefront of sustainable and renewable energy solutions, playing a pivotal role in mitigating environmental concerns and addressing global energy demands. Biomimetics, drawing inspiration from biological systems, has long intrigued engineers and designers, tracing back to Leonardo da Vinci's studies of bird flight and even earlier to myths like Daedalus and Icarus. Historical references, including King Solomon's throne adorned with mechanical creatures and the Talmud's tales of the Golem, illustrate this enduring fascination.

biomimetics bio-inspired design biomimicry wind energy systems

1. Introduction

With 3.8 billion years of evolution, nature has developed technologies that rival or outperform those developed by humans [1]. Biomimetics, also known as biomimicry, bio-inspired, or biologically inspired [2], is a burgeoning research field that draws inspiration from natural models, systems, and elements to provide innovative design solutions for various problems [3][4]. The approach aims to integrate designs inspired by biological organisms into engineered technologies. As an interdisciplinary field, biomimetics connects the collaborative efforts of biologists, physicists, chemists, engineers, and architects, offering the potential to deliver sustainable solutions [5], and enables the development of machines that imitate the performance of organisms, especially when their performance surpasses current mechanical technology or offers innovative solutions to existing challenges [6]. The term "biomimetics" was coined by Otto Schmitt in the 1950s to describe the process of drawing inspiration from nature to address practical challenges we face [7]. In 1997, Janine M. Benyus introduced the term "biomimicry" in her book *Biomimicry: Innovation Inspired by Nature* [8].

Biomimetics, drawing inspiration from biological systems, has long intrigued engineers and designers, tracing back to Leonardo da Vinci's studies of bird flight and even earlier to myths like Daedalus and Icarus. Historical references, including King Solomon's throne adorned with mechanical creatures and the Talmud's tales of the Golem, illustrate this enduring fascination [9][10]. Bar-Cohen has compiled a comprehensive review that explores the intricate technological applications of various biological systems in the field of engineering [11]. The fundamental inclusive principles inherent in nature can be broadly categorized into ten key aspects, forming the foundation of bioinspiration [12][13].

Nature's 10 principles [13] emphasize sustainable and efficient practices. Energy efficiency is key, with only essential energy used for functions. Recycling and reuse transform waste into resources, while resilience and diversity ensure balance amidst chaos. Nature optimizes resource use for equilibrium and fosters collaboration for collective success. Continuous learning and adaptation are achieved through feedback mechanisms. Safe materials and chemicals are used, with a reliance on abundant resources and cautious use of scarce ones. Nature’s adaptability to its environment ensures survival, integrating function and form for minimal energy and material use.

One promising application of biomimetics lies in the design of advanced materials, thanks to their remarkable mechanical, hydrodynamic, optical, and electrical properties, which have evolved over time [10][14][15][16][17][18][19][20]. Interest in biomaterials and biostructures has grown, driving the development of intelligent biological systems, inspired by a variety of notable examples [21][22]. However, the challenge extends beyond imitating nature’s materials and structures; it involves understanding the principles and mechanisms behind biological systems and their functions [23]. Additionally, engineering often faces unique conditions and constraints, potentially resulting in different materials [24][25][26]. Biomimicry-inspired self-healing materials encompass methods from vascular-like systems to nanoparticle-based delivery [27][28]. Techniques in self-healing concrete, like adhesive conduits and shape-memory alloys [29][30], replicate biological materials, resulting in synthetic versions with improved strength and durability, suitable for aerospace, construction, and manufacturing applications.

Biomimetics has significantly influenced the field of robotics and automation [31][32]. By mimicking the locomotion and sensory mechanisms observed in animals and insects, engineers have developed highly agile and efficient robots [33][34][35][36][37].

Biomimetics is revolutionizing sustainable energy technologies, particularly in solar panel and wind turbine design, in response to the growing global energy demand and the surge in renewable energy exploration [38][39]. In the past decade, the field of automobile design has expanded its influence beyond aesthetics, extending to functionality, exemplified by DaimlerChrysler’s bionic concept car inspired by the boxfish’s exterior shape [40]. The Japanese bullet train’s design, inspired by the kingfisher’s beak, reduces sonic booms and air resistance, mirroring the bird’s splash-minimizing dive. This biomimicry enhances the train’s acceleration and energy efficiency, earning it the “bullet train” nickname [40][41][42].

Wind energy has witnessed rapid expansion in recent years. Projections indicate that wind energy could constitute over 40% of all renewable energy sources by 2030 [43] and contribute to fulfilling approximately 20% of the world’s energy requirements [44].

The development of wind turbines and their aerodynamic modeling has been a focal point in recent research, with considerable advancements and reviews documented over the past few decades [45][46][47]. In the realm of biomimetics, Roy et al. [48] contributed significantly to wind turbine research by comprehensively reviewing the application of bio-inspired tubercles on horizontal axis wind turbine (HAWT) blades, highlighting their potential to enhance aerodynamic performance, especially in post-stall regimes and varying wind conditions. Siram et al. [49] reviewed small wind turbines (SWTs), particularly for off-grid and decentralized energy systems, emphasizing their operation under low Reynolds number and tip speed ratio (TSR) conditions. It addresses key aspects like airfoil selection, blade design, and aerodynamic enhancements, including bio-inspired profiles, suitable for low-Re and low-k SWTs.

2. Learning from the Plant Kingdom in Wind Energy

2.1. Movement of Tree Branches and Leaves

Plants have long served as a profound source of inspiration in the realm of biomimetic engineering, particularly within the context of sustainable energies. One of the most prominent examples is the development of solar photovoltaic technology, which draws inspiration from the way leaves capture sunlight and convert it into chemical energy [50][51]. Engineers have endeavored to replicate the efficiency of photosynthetic systems by designing advanced solar cells that emulate the molecular structures found in plants.

In the pursuit of sustainable energy, biomimicry extends beyond energy generation to energy storage. Researchers are exploring biomimetic solutions for efficient energy storage systems by looking at how plants store and release energy through processes like transpiration and ion transport [52][53]. These innovations hold the promise of more efficient and eco-friendly energy storage solutions.

Plants have also inspired breakthroughs in wind energy [54]. Biomimetics has led to the creation of wind turbine designs inspired by the swaying of palm fronds or the aerodynamic efficiency of leaves [55][56]. The Aeroleaf® [57], a French company, represents a micro wind turbine with a patented design influenced by leaves and trees. Within this design, a synchronous generator with permanent magnets makes up each Aeroleaf. The maximum power per leaf is reported around 300 W.

Within the realm of sustainable energy solutions, novel approaches have gained prominence, including the utilization of tree movement to harvest energy. Harvesting energy from the movement of trees has the potential to provide power for wireless devices deployed in densely wooded environments where other energy sources, such as solar, may be limited. The study by McGarry et al. [58] focused on investigating the amount of energy and power available from the motion of a tree in a sheltered position, specifically through Beaufort 4 winds.

Several methods for extracting energy from tree movement have been explored, including harvesting energy from the tree’s horizontal acceleration, lean angle, and force/displacement, and the force/displacement approach showed the greatest potential for harvesting energy. The tree’s average power output, over 900 s, to lift and lower the mass in only one (arbitrarily selected) direction, was calculated to be 44.7 mW in one axis. According to the results of this study from analysis of tree movement energy harvesting methods, the total wind power dissipated by the tree was around 496 W [58].

McCloskey et al., in their study [59], focused on the potential of using plant-inspired designs to convert wind energy. The goal of their study was to explore alternative methods to traditional wind turbines to overcome their limitations, such as noise, visual impact, and restricted deployment in residential areas. They investigated the use of artificial plants containing piezoelectric elements, which can generate electrical energy from wind-induced vibrations.

2.2. Lotus Flower Inspiration

In engineering, the study of flower petals has inspired the development of lightweight and resilient materials. Mimicking the microstructures and properties of petals, researchers have created materials that are not only strong but also flexible, making them ideal for applications in aerospace, automotive, and construction industries [60]. Flowers also influence biomimetic designs in robotics and medical devices. The study of flower-like structures has informed the development of soft robots and medical implants that mimic the flexibility and adaptability of petals, offering solutions for minimally invasive procedures and patient comfort [61][62]. Furthermore, the self-cleaning properties of some flower surfaces, like the lotus leaf, have inspired the creation of superhydrophobic materials. These materials have a wide range of applications, from self-cleaning surfaces to water-resistant coatings on textiles and electronics.

The Nile's Lotus flower, abundant in Egypt, holds cultural and historical significance [63][64].

Abdelrahman et al. [63] investigated the development of a new design for HAWT blades, drawing inspiration from the flower of Nelumbo nucifera. Recognizing the aerodynamically favorable structure of the lotus flower, the study aimed to enhance the efficiency of wind turbine blades by integrating these natural design elements. The authors claimed that the lotus-inspired turbine model exhibited a 31.7% increase in output power compared to the traditional NACA 2412 airfoil turbine model and that the design is suitable for small- and medium-scale wind turbine projects.

2.3. Insights from Seeds

The maple tree (Acer) is adapted to habitats with poor nutrients in temperate climates [65]. Maples disperse their seeds by wind, updrafts, and turbulent gusts, like many other pioneer trees [66][67]. In windy conditions, maple seeds disperse quickly and start to autorotate within 1 m of detaching from the tree. The wing-shaped seed autorotates because the heavy nut, and hence the center of gravity, are located at the base [68][69][70][71]. Inertial and aerodynamic properties of maple and other rotary seeds interact to create stable autorotation, which is still poorly understood [68][72][73]. Supposedly, autorotation creates lift to allow seeds to descend for longer periods. Autorotating seeds, despite their small size and slow velocity, generate surprising lift forces according to detailed performance studies [68][69].

The aerodynamic characteristics of auto-rotating maple and Triplaris samara seeds were extensively investigated by Lentink et al. [74]. Their study revealed that these seeds exhibit a notable capacity for generating unexpectedly high lift during their descent. The findings indicate that the "helicopter" seeds of maple trees and other similar autorotating seeds rely on the aerodynamic mechanism of generating lift as they descend slowly through the air. However, the specific means by which this lift generation occurs have remained unclear.

Holden et al. analyzed the flow field around a maple seed as it rotates and draws comparisons to wind turbine blades [75]. Experimental measurements and high-speed video imaging were used to determine the physical values of a real maple seed sample. The power coefficient (C_P) of the maple seed was found to be 0.59, comparable to the range from 0.45 to 0.48 for many wind turbines and close to the Betz limit of 0.593.

Inspired by the study by Lentink et al. [74], Seidel et al. focused in their study on designing blades that mimic the shape of maple and triplaris samara seeds [76], which are known to generate extra lift due to their geometrical properties.

Herrera et al. investigated the structural design and manufacturing process of a low-scale bio-inspired wind turbine blade based on the Triplaris americana tree seed [77]. The blade design was derived from an analysis of the seed's curvature and airfoil along its wingspan, resulting in a nonconventional HAWT with three blades.

The blade's geometry and composite structure showed potential for clean energy generation, surpassing commercial wind turbines in terms of C_P and energy conversion factor with a peak C_P of 0.55 during testing. The authors mention that this bio-inspired design is particularly promising for areas with low wind speeds, offering a cost-effective alternative for electricity generation in developed countries.

Carré et al. [78] present the design and experimental testing of a SWT inspired by the shape and behavior of maple samaras. The blade angles and the number of propeller blades were optimized, and a miniature generator with low-friction ceramic bearings was used for power conversion.

The performance of the 44 mm diameter HAWT was tested under wind speeds ranging from 1.2 to 8 m/s. The electrical power output, measured in resistive load, ranged from 41 μW to 81.7 mW, resulting in an overall efficiency between 2.6% and 17.8%. The C_P reached 28.4%, which is among the highest rates in terms of efficiency and power density compared to other miniature wind turbines in the literature.

The samara-based wind energy harvester demonstrates an extended range of airspeeds for energy harvesting, with an operating speed as low as 1.2 m/s. It offers potential applications in areas where regular maintenance is challenging or batteries cannot be used, such as difficult-to-access locations, buildings, and houses.

The biomimicry principles by drawing inspiration from maple samara seeds' morphology and flight capabilities were explored by Çalışkan et al. [77]. Employing mathematical modeling, the team translated these natural features into a virtual environment, yielding a biomimetic wing model. The wing exhibited a stall angle range of 40°–45°, a substantial improvement compared to conventional wings. Also, the biomimetic wing design demonstrated stability across changing wind velocities, with minimal variations in aerodynamic performance parameters.

Chu et al. [79] investigated the performance of a rigid biomimetic HAWT rotor blade inspired by the Dryobalanops aromatica seed. They compared the C_P, thrust coefficient (C_T), and blade root bending stresses of the proposed biomimetic wind turbine with a tapered and twisted blade from Krogstad and Lund [80]. The simulation results revealed that the biomimetic wind turbine showed a maximum C_P of 0.386 at a TSR of 1.5 and a free stream velocity (U ∞) of 10 m/s. It exhibited a better self-starting ability and higher torque compared to the reference turbine.

Chu et al. [81] proposed a new thin-cambered bent biomimetic wind turbine blade design inspired by the 3D geometry of the wing of a Borneo camphor seed. The wings of the Borneo camphor seed exhibit thinness, camber, and bending, which enable autorotation during propagation and slow down the seed's falling speed. By mimicking these wing characteristics, they proposed a high-performance biomimetic wind turbine design that shares a similar rotating mechanism with the Borneo camphor seed.

In another study Chu et al. [82] conducted a comparative study by examining the performance of a bio-inspired flexible-bladed wind turbine (FBWT) mimicking the wings of a Borneo camphor seed against a traditional rigid-bladed wind turbine (RBWT) at a centimeter scale. The primary objective was to evaluate and contrast various aspects of these wind turbines, including electrical power output, start-up behavior, blade coning, and yawing characteristics.

Regarding electrical power output, the FBWT consistently outperformed the RBWT, yielding a maximum power output of 7.33 mW compared to the RBWT's 6.52 mW. The FBWT achieved a higher maximum C_p of 0.0870, achieved at a TSR of 3.20 and a wind speed of 1.83 m/s, surpassing the RBWT's 0.0576 at a TSR of 3.56 and a wind speed of 2.04 m/s.

Gaitan-Aroca et al. [83] investigated a biomimetic wind rotor design inspired by the Petrea volubilis seed in terms of its performance as a HAWT. The biomimetic wind rotor design exhibited vorticity generation and a predominant tangential vortex motion. The C_p of the biomimetic wind turbine model reached its highest value which was higher than that of the benchmark case, while the C_T at the peak C_P for the biomimetic wind turbine cases was lower than that of the benchmark case.

Venkataraman et al. conducted a numerical investigation on the stand-still characteristics of a bio-inspired vertical axis wind turbine (VAWT) rotor designed for an urban environment [84]. The rotor shapes were inspired by the seed pods of two commonly found trees in India, Mimosa and Bauhinia variegata. The simulations revealed that a single-bladed helical rotor generated torque of approximately 0.26 Nm at a wind speed of 2 m/s, which exceeded the typical cogging torque of a 500 W permanent magnet generator.

Ashwindran et al. [85] studied an unsteady numerical analysis on a novel biologically inspired VAWT designed for offshore regions of Malaysia. The turbine's blade shape was derived from a hybrid design inspired by the maple seed and Epilobium hirsutum. The turbine exhibited favorable performance at $\lambda = 1.3$ and $\lambda = 1.7$, yielding $C_P = 0.245$ and $C_P = 0.262$, respectively.

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