WinDTurbinePower: A Novel Hybrid Dimple-Tubercle Blade Configuration Integrating Physics-Informed Gaussian Process (PIGP) for Power Coefficient (Cp) Optimization

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The growing need for an efficient small-scale wind energy system led to the investigation of a biomimetic combination of hammerhead shark-inspired tubercles and golf ball dimple surface roughness to enhance aerodynamic performance and energy generation. The 3D models of four NACA0012 airfoil blade configurations: smooth, tubercles 58/10, dimples full hexagon (FH), and hybrid (a combination of dimples and tubercles), were designed in OnShape and simulated in SimScale. Thus, CFD results indicate that the smooth blade generated the highest drag due to significant flow separation, whereas the hybrid blade demonstrated enhanced aerodynamic efficiency by reducing flow separation. Furthermore, the Subsonic Wind Tunnel evaluated the 3D printed blades, confirming their aerodynamic performance in a controlled environment. Also, the controlled laboratory tests conducted with a small-scale Vertical-Axis Wind Turbine (VAWT) prototype demonstrated a power coefficient (Cp) of 0.48 for the hybrid, 60% higher than 0.30 for the smooth blade. Additionally, the hybrid achieved a Cp of about 80% of the Betz limit (0.593) compared to the smooth at 51%. The Physics-Informed Gaussian Process (PIGP) validated these results, with the hybrid having the highest predicted Cp at 0.44. The recorded Mean Squared Error (MSE) of 0.0008 and an average R2 of 0.957 indicate strong predictive accuracy with minimal error. Moreover, analytical calculations suggest that an up-scaled hybrid-blade VAWT mounted on residential rooftops could generate 159W, a calculated output that could potentially sustain a Philippine household consuming 400kWh per month. Overall, the novel hybrid dimple-tubercle blade demonstrated a highly efficient aerodynamic performance and power coefficient.

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