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Mingkang Zhu^{1,2}, Jianwen Guo¹, Daxing Zeng¹, Yong Zhong², Jianyang Zhu³, Hengyu Li⁴ (✉), Chao Wang¹ (✉), Tinghai Cheng^{4,5} (✉)

¹ School of Mechanical Engineering, Dongguan University of Technology, Dongguan 523808, China

² Shien-Ming Wu School of Intelligent Engineering, South China University of Technology, Guangzhou 511442, China

³ Key Laboratory of Metallurgical Equipment and Control Technology Ministry of Education, Wuhan University of Science and Technology, Wuhan 430081, China

⁴ Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 101400, China

⁵ Guangzhou Institute of Blue Energy, Guangzhou 510555, China

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³ Key Laboratory of Metallurgical Equipment and Control Technology Ministry of Education, Wuhan University of Science and Technology, Wuhan 430081, China

⁴ Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 101400, China

⁵ Guangzhou Institute of Blue Energy, Guangzhou 510555, China

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 Address correspondence to Hengyu Li, lihengyu@binn.cas.cn; Chao Wang, wangchao@dgut.edu.cn; Tinghai Cheng, chengtinghai@binn.cas.cn



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ABSTRACT: Traditional wind turbines have struggled to efficiently harvest broadband wind energy due to significant velocity fluctuations. To address this challenge, this study innovatively proposes a bio-inspired cluster wind turbine-driven hybrid triboelectric-electromagnetic generator (CWT-TEHG). The design synergistically combines multi-rotor cluster effects with Magnus effect induced orbital motion to enhance wind energy harvesting. An adaptive adjustment mechanism coordinates with an energy storage-release system to regulate the triboelectric layer interface behavior of the triboelectric nanogenerator (TENG) and optimize the operation of the electromagnetic generator (EMG), achieving efficient broadband wind to electricity conversion. Computational fluid dynamics analysis reveals the energy harvesting mechanisms, guiding parametric optimization. Experimental results demonstrate a low cut-in wind speed of 2 m s⁻¹, and achieves a 92.4% improvement in TENG output at 10 m s⁻¹ compared to TENG without orbital motion and adaptive gap regulation, with the regulated EMG reaching a peak power of 665.6 mW, and CWT-TEHG achieves a peak instantaneous wind-to-electricity conversion efficiency of 24.3% at 4 m s⁻¹. Field applications including self-powered bridge structural health monitoring validate the system's practicality. This work establishes a novel strategy for low-speed and broadband wind energy harvesting while demonstrating the potential of environmental micro-energy utilization for Internet of Things self-powered applications.

KEYWORDS: triboelectric nanogenerator, triboelectric–electromagnetic hybrid generator, cluster wind turbine, magnus effect, wind energy harvest

1 Instruction

As a ubiquitous and abundant renewable resource, wind energy holds great potential among clean energy sources. Although current wind energy harvesting relies predominantly on large-scale turbines for high-altitude and high-power-density wind resources [1], significant unexploited potential remains in near-ground and urban environments [2]. This gap originates from low-energy wind region characterized by mean velocities below 3 m s⁻¹, high turbulence intensity, and stochastic directionality—all of which limit the effective operation of conventional electromagnetic generator (EMG) [3]. In Internet of Things (IoT) ecosystems with tens of billions of deployed micro-sensors, conventional power solutions (batteries and cabled grids) face inherent limitations: exorbitant lifecycle costs, infrastructure complexity, and unsustainable maintenance demands. Harvesting ambient breeze energy for electricity conversion emerges as an innovative pathway toward energy-autonomous IoT devices, effectively addressing these power supply

constraints [4]. Consequently, developing novel methodologies to harvest distributed broadband wind energy—a vastly abundant but underexploited resource—holds strategic significance for advancing high-quality development in wind power technologies.

Triboelectric nanogenerators (TENGs) [5–8] are an emerging energy harvesting technology that can effectively convert mechanical energy (particularly low-frequency mechanical energy) into electrical output [9–12]. Thanks to their unique working principles [13,14], TENGs possess advantages including broad material selection [15], simple structure [16], environmental sustainability [17], high efficiency in harvesting low-frequency/irregular mechanical energy [18], high output voltage [19], multifunctionality [20], strong adaptability [21], and self-driven sensing [22]. Extensive research has validated TENGs' efficacy in harvesting diverse low-frequency energy sources including oceanic waves [23], mechanical vibrations [24], human motion [25], and wind flows [26], highlighting their transformative potential. Furthermore, the complementary

operational bandwidths of TENGs in low-frequency regimes (0.1-5 Hz) and EMGs in high-frequency domains (>5 Hz) have validated hybrid system integration as a strategically optimized research approach [27-31].

Current wind energy harvesting research via TENGs predominantly employ rotary blade structures [32-34] or flow-induced vibration mechanisms [35-37] for aerodynamic energy conversion. Nevertheless, the predominant research focus remains confined to structural design and performance enhancement of TENGs [38], while critically neglecting aerodynamic optimization of wind-harvest mechanisms. This oversight perpetuates dual challenges of elevated cut-in speeds and suboptimal wind-to-electricity conversion efficiency in existing systems [39]. Although several studies have achieved progress in TENG-based wind energy harvesting under low-speed wind regimes [40], practical implementation remains impeded by the inherent temporal stochasticity of natural wind flows [41].

To address the challenges of harvesting broadband wind energy and the limited conversion efficiencies of conventional TENGs, this work innovatively proposes a synergistic cluster-magnus effects-enhanced wind turbine-driven triboelectric-electromagnetic hybrid generator (CWT-TEHG). Inspired by the aerodynamically efficient collective flight patterns of avian species, the proposed design arranges three conventional Savonius rotors in a clustered configuration and introduces Magnus-effect-induced coordinated orbital motion of the rotor ensemble. Through synergistic operation of TENGs and EMGs across varying wind velocities, coupled with adaptive adjustment mechanisms for power-generation units, CWT-TEHG achieves efficient broadband wind energy harvesting and conversion. The research process encompasses: (1) mechanistic elucidation and optimization of cluster wind turbine (CWT) via computational fluid dynamics (CFD) simulations; (2) systematic electrical characterization of generator output performance; and (3) validation of field-deployment capabilities through constructed self-powered systems, demonstrating the practical viability of CWT-TEHG. This work not only confirms the distinct advantages of TENGs in low-speed wind-energy harvesting but also provides a promising strategy for broadband wind-energy capture and self-powered systems in IoT applications.

2 Results and discussion

2.1. Structure design and working mechanism of CWT-TEHG

This study proposes a CWT-TEHG-based wind-powered monitoring paradigm that can efficiently harvest fluctuating broadband wind energy, which is difficult to utilize with conventional methods, while enabling self-sustained operation in IoT ecosystems. The system converts broadband wind energy into regulated electrical output that directly power micro-scale wireless sensor nodes, thereby enabling autonomous remote monitoring. As illustrated in **Figure 1a**, the demonstrated applications include smart urban infrastructure, structural health monitoring of civil assets, precision agriculture, and resilient grid operations.

The proposed CWT-TEHG system integrates three core functional components, as depicted in **Figure 1b**: the CWT, mechanical transduction mechanisms, and power generation

units. The CWT configuration employs three helically modified Savonius rotors interconnected by support brackets. Coordinated rotor rotation drives the TENG through a precision gear transmission, while simultaneously actuating the EMG via the support shaft. This design provides two aerodynamic advantages. First, it enhances the autorotation of each rotor through cluster-induced flow interactions and orbital motion, thereby improving TENG output. Second, it exploits Magnus-effect-induced lift to drive the EMG, collectively improving overall wind-energy utilization efficiency. To simultaneously reduce the activation threshold and enhance the high-wind-speed output of TENGs, a centrifugal control mechanism is introduced to adaptively regulate the triboelectric layer spacing and regulate the contact state, enabling efficient broadband wind-to-electricity conversion across varying wind regimes. In parallel, a store-release mechanism optimizes EMG performance by effectively converting low-frequency orbital energy into usable electrical power through controlled energy accumulation and discharge.

Figure S1 in the Electronic Supplementary Material (ESM) presents physical photographs of the fully assembled CWT-TEHG prototype and its subassemblies.

The detailed structure of the regulated TENG is shown in **Figure 1c**. The TENG rotor disk is coated with grid-shaped rabbit fur, which serves as the electropositive material and is connected to the central axis of the adaptive mechanism through a slider-and-slideway structure, enabling vertical displacement with spring support. The TENG stator disk is covered with patterned copper foil and fluorinated ethylene propylene (FEP), which serve as the electrodes and electronegative materials, respectively. The adaptive mechanism co-rotates with the TENG rotor disc. Its working principle is as follows: at low wind speeds, the rotor disk and rabbit fur remain in slight contact with the FEP layer on the stator disk under spring force, resulting in small friction and enabling the TENG to start at low wind speed. As wind speed increases, the steel roller gradually moves outward under centrifugal force, pressing the rotor fur into closer contact with the FEP layer and thereby increasing the electrical output. By actively controlling the contact-separation behavior of the triboelectric interface, efficient wind-to-electricity conversion can be achieved over a wide wind-speed range.

The detailed structure of the regulated EMG is shown in **Figure 1d**. The EMG consists of six pairs of magnets and coils, with the magnets fixed to the coil-spring shaft as the rotor. The orbital motion of CWT is transmitted to the irregular gear and the end gear through a driving tooth, causing the coil spring to contract and store kinetic energy. To better store orbital kinetic energy, the driving gear advances the irregular gear by one tooth per revolution. It is worth noting that the upper half of the irregular gear meshes with a pawl, allowing rotation in only one direction, while the lower half is an incomplete gear that meshes with the end gear. When the coil spring completes a preset number of rotations and energy storage reaches its limit, the incomplete gear disengages from the end gear. The stored potential energy is then released, driving the magnet to rotate at high speed and converting low-frequency orbital kinetic energy into the electrical output of the EMG. A demonstration of the operating process of the CWT-TEHG is provided in **Movie S1** in the ESM.

The simplified operational principle of the TENG in the

CWT-TEHG is illustrated in **Figure S2** in the ESM. In Phase I, the rabbit fur layer is initially aligned above the left electrode, establishing electrostatic equilibrium. The positive charges on the fur surface balance the negative charges on both the FEP film and left electrode, resulting in zero potential. During Phase II, the fur moves rightward relative to the FEP film under the rotation of the CWT. The induced potential difference drives charge migration between the two electrodes to maintain equilibrium, generating current in the external circuit. In Phase III, all negative charges accumulate on the right electrode. In Phase IV, further movement of the fur reestablishes the potential difference, causing charge migration in the opposite direction and producing a reverse current. This cyclic process generates sustained alternating current output.

The biomimetic architecture of the CWT and the wind-to-electricity conversion process of the CWT-TEHG are schematically illustrated in **Figure 1e**. Inspired by the

aerodynamically efficient collective motion of bird flocks, multiple rotors are arranged in a cluster, and the flow field interaction and cooperative motion between the rotors are exploited to improve system-level performance. The multi-rotor cluster effect is mainly attributed to Magnus-effect-induced wake deflection, which enhances downstream rotor output, together with localized fluid coupling between adjacent rotors. Wind-driven rotation is further strengthened by the cluster effect, which activates the adaptive mechanism to dynamically modulate the contact pressure between the TENG tribolayers. This enables low cut-in wind-speed operation with improved output efficiency. Meanwhile, the Magnus effect drives the orbital motion of the CWT, allowing the store-release mechanism to convert low-frequency kinetic energy into high-frequency EMG rotation. Overall, this integrated system enables efficient and stable conversion of broadband wind energy into electricity.

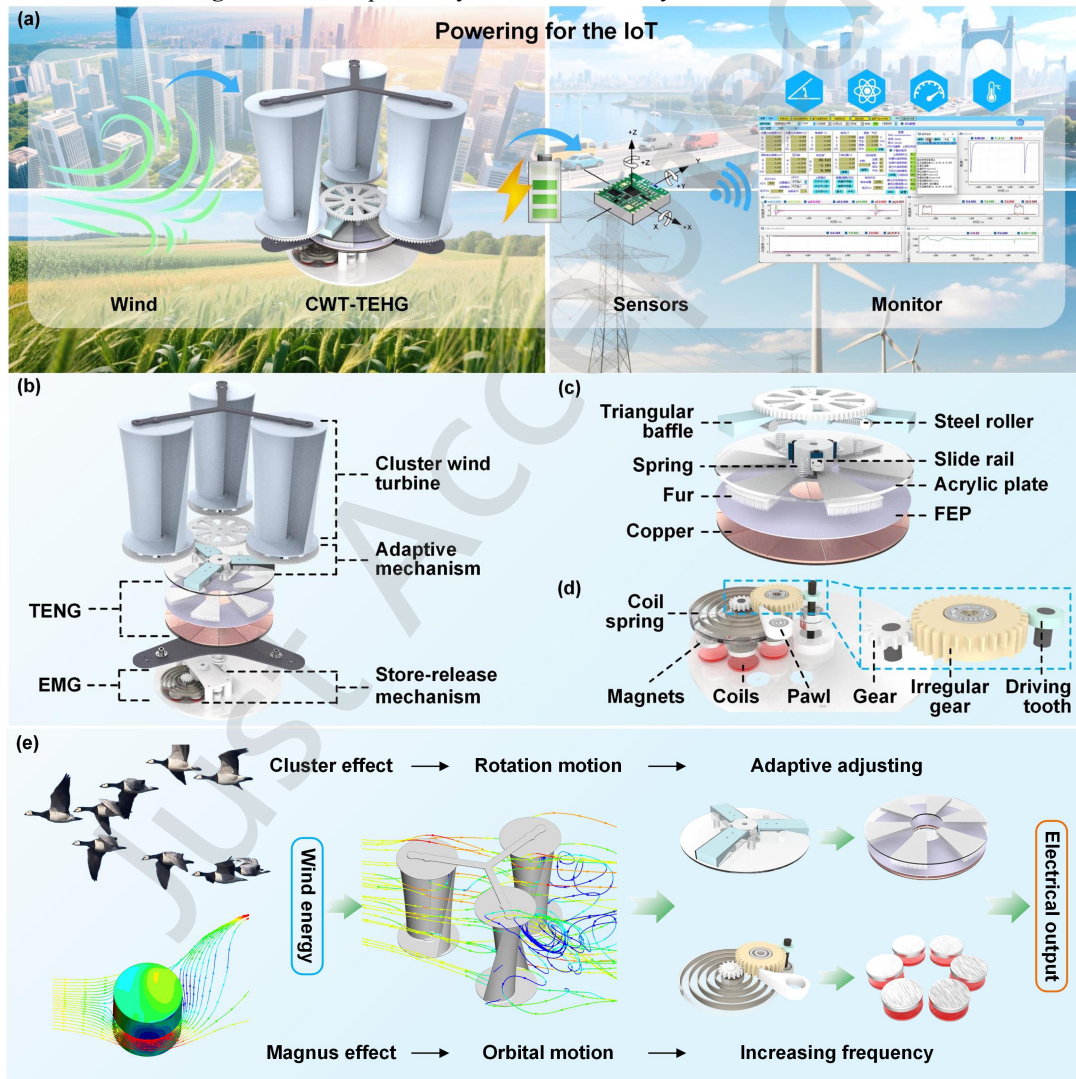


Figure 1. Structure and principle of CWT-TEHG. (a) Application concept of CWT-TEHG as a self-powered system. (b) Overall structure of CWT-TEHG. (c-d) Detailed structure of the regulated TENG and EMG. (e) Biomimetic architecture of the CWT and wind-to-electricity conversion process of the CWT-TEHG.

2.2. Blade design and parameter optimization of CWT

As the primary wind energy harvesting component, the aerodynamic performance of the CWT directly determines its power generation capacity and therefore requires optimization. Unlike traditional arrays with fixed layouts, the proposed clustered three-rotor Savonius turbine exhibits coordinated

orbital motion, which is achieved through cluster-induced flow interactions, Magnus effect-induced lateral force, and mechanical coupling. This introduces an additional degree of freedom and provides a unique energy harvesting mechanism that goes beyond static wake interactions.

The Magnus effect originates from pressure differentials generated by asymmetric flow velocities around a rotating cylinder, producing a lift forces (Magnus forces) perpendicular to drag direction (**Figure 2a**). Based on potential flow theory and Bernoulli's equation, the Magnus force acting on a rotating cylinder can be derived. By introducing an equivalent correction factor, and the Magnus force ($F_{M,R}$) is expressed as:

$$F_{M,R} = C_{eff} 2\pi\rho W r^2 \omega \quad (1)$$

where C_{eff} is a coefficient related to geometry and operating conditions, ρ is the air density, W denote the fluid velocity, r is the rotor radius, and ω is the angular velocity. This expression indicates that the Magnus force induced by rotor rotation increases with wind speed, rotor size, and rotational speed. A detailed aerodynamic analysis of the rotor under flow-field interaction, as well as the derivation of the Magnus-force expression, is provided in **Note S1** in the ESM.

Although Magnus forces are inherently generated during wind turbine blade operation, their utilization has been largely overlooked. In this work, the Magnus forces generated by multiple rotors are exploited to drive the orbital motion of the CWT, achieving two benefits simultaneously: flow-field modulation through optimized rotor placement and additional energy extraction through electromagnetic conversion of orbital kinetic energy.

The rotational direction of CWT rotors exerts significant influence on the flow field characteristics. To optimize the system parameters, CFD simulations were performed for the CWT configuration. Five rotor rotation combinations (Group A–E) were investigated (**Figure S3** in the ESM). In addition, a control group (Group F) maintaining Group A's rotor retained the rotor arrangement of Group A but excluded orbital motion, allowing the aerodynamic effect of revolution to be isolated. The computational domain settings for CFD are given in **Figure S4** in the ESM. Mesh size and time step independence verification is presented in **Figure S5** in the ESM, and the solution details are provided in **Note S2** in the ESM. Fully passive wind-driven rotation was simulated for all six models at a wind speed of 5 m s^{-1} . **Figure 2b** presents the self-rotation torque of each rotor, while **Table S1** in the ESM summarizes the average torque for each rotor and the absolute sum of the average torques for the three-rotor groups. Counterclockwise rotation and torque are defined as positive according to the right-hand rule.

Analysis of the torque profiles in **Figure 2b** reveals that for Rotor-i, Group D achieves the highest torque output. This is attributed to the counter-rotating configuration of the other two rotors in Group D, whose wake flows enhance the local velocity field around Rotor-i. For Rotor-ii and iii, Group C produces the maximum torque values. Unlike other groups, which show noticeable torque differences among the three rotors, Group A exhibits a relatively balanced torque distribution, with the highest average torque of $0.1723 \text{ N}\cdot\text{m}$. Compared with Group F, which lacks orbital motion, Group A shows a 3.46% increase in average rotor torque, indicating that Magnus-effect-induced

orbital motion improves the self-rotation performance of the CWT. Moreover, compared with the single-rotor turbine average torque of $0.1263 \text{ N}\cdot\text{m}$, the three-rotor system in Group A achieves a 36.42% improvement, confirming that the multi-rotor cluster can enhance the performance of individual rotors through aerodynamic interactions.

Figures 2c and **2d** respectively display the rotational speeds of the rotors and the orbital speeds for each model groups, with complete datasets provided in **Figure S6** in the ESM. **Figure 2e** presents the orbital torque contributions of each rotor and the total orbital torque for Group A, while the corresponding data for the other groups are shown in **Figure S7** in the ESM. The results show that Group A exhibits rotational and orbital motions of equal magnitude but opposite directions compared with Group E. Groups B-D show smoother rotor rotational speeds, but their orbital motions are nearly zero. This is because the coupling effect among the rotors stabilizes their rotation, whereas the lift generated by the Magnus effect lacks uniform directionality; as a result, the resultant force is too small to drive noticeable orbital motion.

To further elucidate the aerodynamic enhancement mechanisms of the CWT, **Figure S8** in the ESM presents pressure contours of the flow field for each model group, and **Figure 2f** displays the corresponding vorticity contours and streamline diagrams. Because the simulations were conducted under fully passive wind-driven rotation, the rotational speeds of each rotor group and their orbital speeds were not identical, making it impossible to compare them at a uniform cycle. Therefore, the comparison was performed at the moment when Rotor-i in each group was near its initial position. Analysis of **Figure S8** reveals that Rotor-i and the single rotor (**Figure S8** (vi)) exhibit significant positive pressure on the windward convex surface, whereas the pressure on the windward convex surface of Rotors-ii and iii is markedly reduced. Combined with the vorticity and streamline distributions in **Figure 2f**, this occurs because the shed vortices and wake of Rotor-i accelerate the inflow to Rotors-ii and iii. As a result, the pressure distribution on the downstream rotor changes, with increased pressure on its windward convex surface and altered pressure on its leeward concave surface, thereby enhancing aerodynamic performance.

In addition, the vorticity and streamline results indicate that the wake of the upstream rotor strongly affects the aerodynamic performance of the downstream rotor, whereas the downstream rotor has little influence on the upstream rotor. This conclusion is further supported by the torque data of the non-orbital control group F, in which Rotor-i exhibits a markedly lower torque than Rotors-ii and iii. Orbital rotation not only captures and utilizes the torque generated by the Magnus effect, but also adaptively adjusts the relative rotor positions. This leads to more uniform rotor output and improves the smoothness of the wind turbine's power generation. Consequently, Group A exhibits the most favorable aerodynamic performance. The CFD simulation animation of the CWT is presented in **Movie S2** in the ESM.

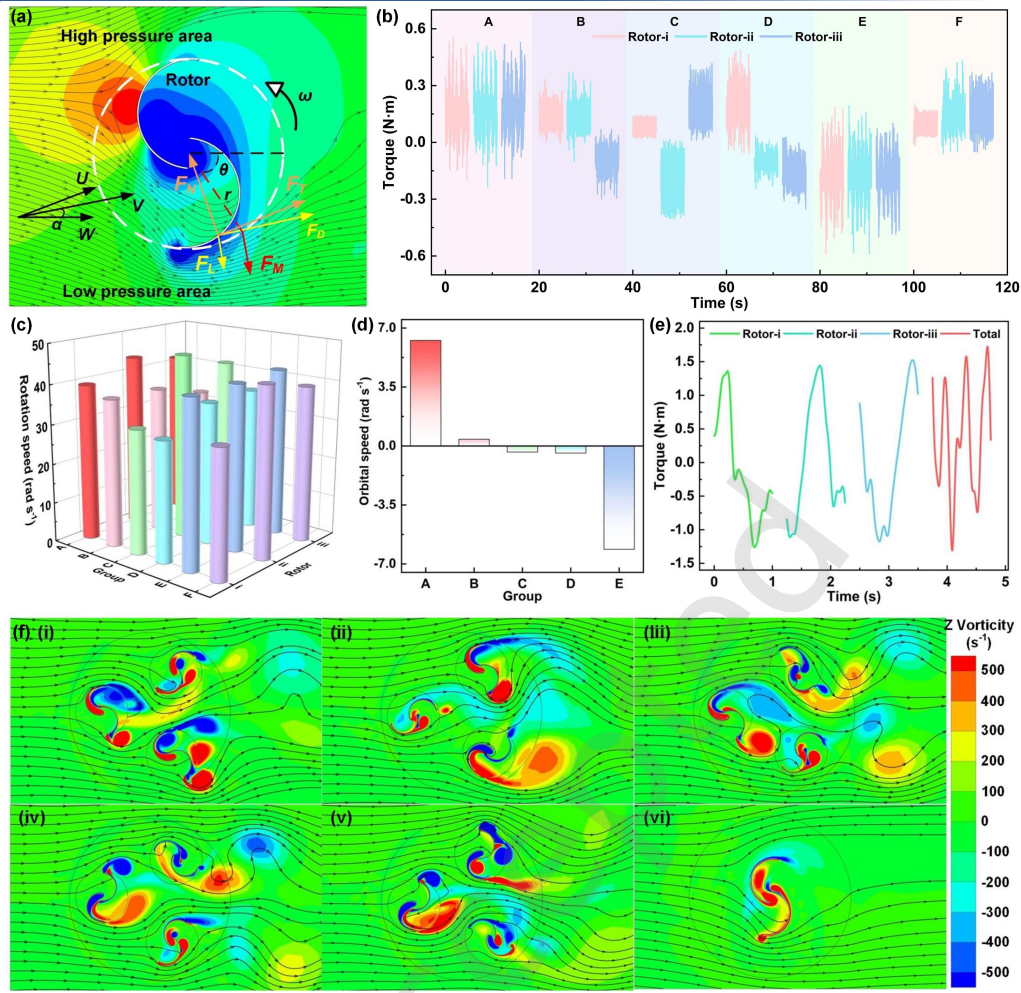


Figure 2. Design and Simulation of CWT. (a) Principle of the Magnus effect. (b) Simulation results of self-rotational torque for rotors in Groups A-F. (c-d) Rotational speeds of the rotors and the orbital speeds for each group. (e) Orbital torque contributed by each rotor and the total orbital torque for the models in Group A. (f) Vorticity contours and streamline diagrams for each model group at the moment when Rotor-i of each group was near its initial position.

2.3. Optimization and electrical characterization of the CWT-TEHG

The short-circuit current (I_{SC}) and resisting torque of the TENG were measured at different rotational speeds and friction layer gaps, which reflect the contact tightness of the dielectric interface, as shown in **Figure 3a**. The I_{SC} increased gradually with increasing rotational speed and decreasing gap, while the resisting torque also increased as the gap decreased. Notably, the resisting torque was nearly independent of rotational speed at larger gaps but it increased rapidly with rotational speed at smaller gaps. Test results indicate that the contact tightness of the dielectric layers directly affects the output performance of the TENG: tighter contact leads to higher output but also greater friction resistance. adaptive regulation of the TENG output through a centrifugal force based adjustment mechanism is both feasible and necessary.

The working principle of the proposed centrifugal force adaptive adjustment mechanism is illustrated in **Figure 3b**. Under the combined action of centrifugal force and spring tension, the roller adaptively adjusts the gap between the acrylic plate coated with rabbit fur and the FEP film in response to wind speed variations. The derivation of the relationship between the displacement of the acrylic plate (Δx) and the rotor rotation speed is presented in **Note S3** in the ESM, leading to the

following expression:

$$\Delta x = \frac{(m_1 g + m_2 g + m_1 \omega^2 l \sin \theta \cos \theta)}{k} - l_2 \quad (2)$$

where m_1 and m_2 represent the masses of the roller and acrylic disc, respectively; g is the gravitational acceleration; θ is the angle of the inclined plane; l is the distance from the roller's center of roller to the center of the rotational axis; l_2 and k denote the initial length and spring constant of spring-ii, respectively. The results demonstrate that Δx and ω are positively correlated. Figure 3b depicts the relationship between the gap and wind speed, indicating that the TENG can start easily at low wind speeds while achieving higher output at high wind speeds.

A prototype was constructed to evaluate the output performance of TENGs with different configurations in the CWT-TEHG system at various wind speeds, as illustrated in **Figures 3c** and **3d**. **Figure S9** in the ESM provides photographs of the prototype TENG during adaptive adjustment of the friction layer gap under different wind speeds. To isolate the effect of the centrifugal force adaptive adjustment mechanism on TENG output, tests were conducted with a fixed friction layer gap of 12 mm, with results presented in Figures 3c(i) and 3d(i). Owing to the large frictional resistance, the TENG was

activated only when the wind speeds exceeded 4 m s^{-1} . When the wind speed increased to 10 m s^{-1} , I_{SC} increased from 6.9 to $26.3 \mu\text{A}$, and the transferred charge (Q_{SC}) increased from 147 to 175 nC . In principle, the Q_{SC} of a TENG is independent of rotational speed. In this study, however, the increase in Q_{SC} with wind speed is likely due to improved contact between the rabbit fur and the FEP film, resulting from stronger electrostatic adhesion and more complete interfacial contact.

To further verify the effect of adaptive gap regulation on TENG output performance, experiments were conducted on the CWT operating with adaptive adjustment but without orbital motion. The results are shown in Figures 3c(ii) and 3d(ii). With an initial friction layer gap of 20 mm , the reduced frictional resistance enabled TENG activation at a low wind speed of 2 m s^{-1} , which is the lowest wind speed to effectively provide output power. As wind speed increased from 2 to 10 m s^{-1} , I_{SC} increased from 2.0 to $46.1 \mu\text{A}$, and Q_{SC} increased from 62.9 to 204.4 nC . Comparison of Figure 3c(ii) and 3d(ii) shows that adaptive gap regulation changes the increase in Q_{SC} from modest to substantial, thereby producing a more pronounced increase in I_{SC} . Compared with the fixed-gap condition, the TENG with

adaptive adjustment exhibited a 75.3% increase in I_{SC} at 10 m s^{-1} .

Subsequent tests evaluated the TENG performance when the CWT operated with both adaptive adjustment and orbital motion, as shown in Figure 3c(iii) and 3d(iii). As the wind speed increased to 10 m s^{-1} , I_{SC} increased from 2.0 to $50.6 \mu\text{A}$, Q_{SC} increased from 63 to 210 nC , and the open-circuit voltage (V_{OC}) increased from 61 to 215 V (Figure S10 in the ESM). These results demonstrate that the orbital motion of the CWT enhances rotor self-rotation, thereby improving TENG output performance. Specifically, compared with the fixed-gap TENG without orbital motion or adaptive gap regulation, the TENG with both adaptive control and orbital motion achieved a 92.4% increase in I_{SC} at a wind speed of 10 m s^{-1} .

Furthermore, the surface morphology of the FEP film after long-term operation of TENG under the two conditions of adaptive interface control and a fixed friction layer gap was observed by scanning electron microscopy (SEM). The results are shown in Figure S11 in the ESM, indicating that adaptive control not only improves TENG output performance but also reduces wear on the FEP film, thereby enhancing durability.

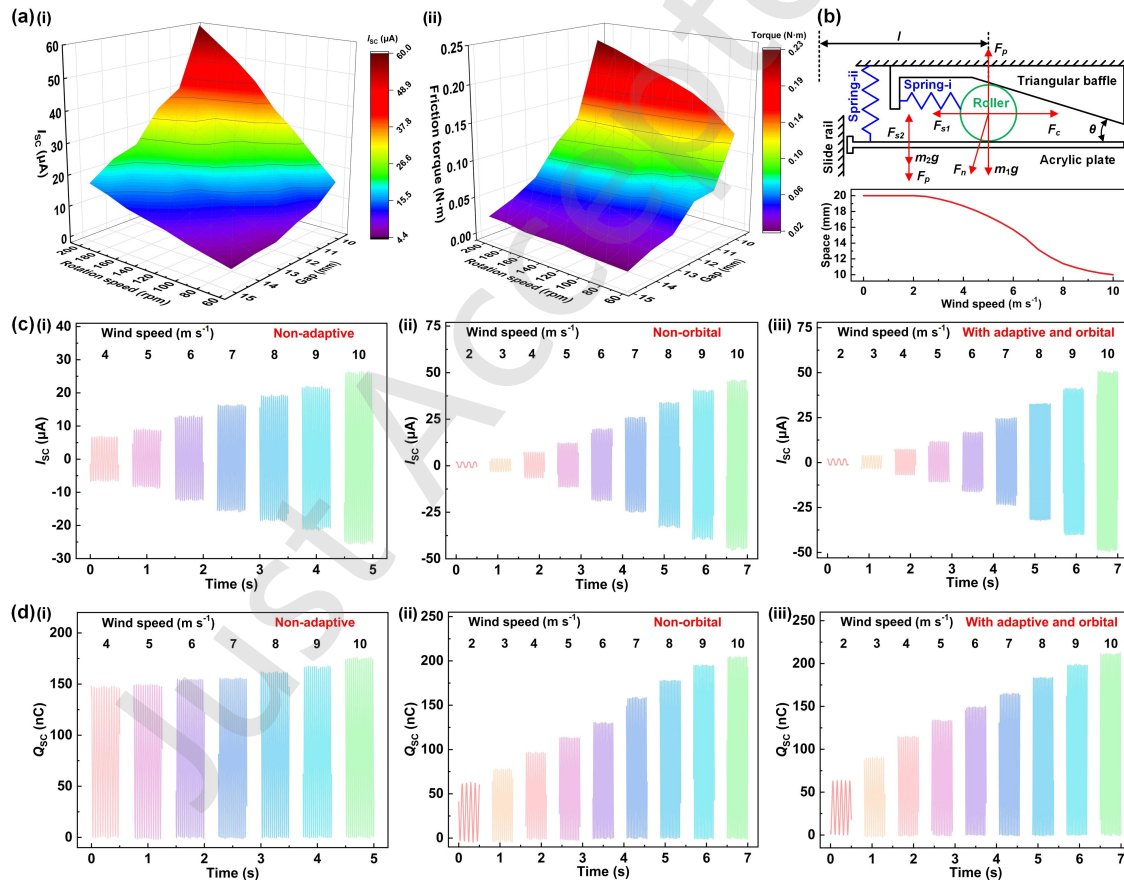


Figure 3. Experimental testing of TENG with different configurations. (a) Effect of TENG friction layer gap and wind speed on output and friction torque. (b) Principle of centrifugal force adaptive adjustment mechanism. (c-d) Effects of adaptive control and orbital motion on TENG output performance.

CFD simulation results indicate that the proposed CWT exhibits relatively high orbital torque but low orbital speed. Driving an EMG directly with such motion would therefore lead to suboptimal output performance. To address this limitation, an energy storage and release mechanism was designed to convert low-frequency orbital motion into high-frequency excitation. The working principle of this mechanism is illustrated in Figure 4a. Utilizing the inertia of orbital motion, the CWT drives the coil spring to store energy once per revolution through a single-

tooth gear. The complete segment of the irregular gear is continuously driven by the single-tooth gear, whereas the incomplete segment periodically meshes with the end gear. This enables a cyclic transition between the energy storage and release phases of the coil spring.

Experimental tests were carried out to evaluate the effect of different coil spring thicknesses on energy storage duration, as shown in Figure 4b. The results indicate that thicker coils provide better energy storage performance, but a thickness

greater than 0.6 mm increases the required cut-in wind speed. Therefore, a 0.5 mm thick coil spring was selected as the optimal design. In addition, the V_{OC} was measured for different numbers of magnets and coils, as shown in **Figure 4c**. The results indicate that increasing the number of magnets leads to a higher peak V_{OC} but a shorter output duration. Accordingly, six pairs of magnet-coil assemblies were determined to be optimal.

The output performance of the EMG driven by the CWT-TEHG at different wind speeds was evaluated, as shown in **Figure 4d**. Since orbital motion of the CWT starts only when the wind speed exceeds 4 m s^{-1} , the EMG produces output only above this threshold. The results indicate that the peak EMG output remains nearly unchanged across different wind speeds, with a peak V_{OC} of 56 V and a I_{SC} of 25 mA. However, the output frequency increases with wind speed. This occurs because the rotational speed during spring unwinding remains essentially constant, while the energy storage duration decreases as wind speed increases. Figure 4d(iii) illustrates the operating

process of the EMG at a wind speed of 7 m s^{-1} . Energy is stored for approximately 22 s before release, and low-frequency electrical energy output is maintained throughout the energy storage phase.

The peak and average output power of the CWT-TEHG at different wind speeds were quantified, as shown in **Figure 4e**. The TENG reached its maximum output power of 27.2 mW at a matched resistance of $100 \text{ M}\Omega$ under a wind speed of 10 m s^{-1} . Because the peak current of the EMG remained nearly constant across all wind speeds, its peak power also remained stable, achieving a maximum output power of 665.6 mW at a matched resistance of $1 \text{ k}\Omega$. At a wind speed of 4 m s^{-1} , the average output power of the TENG and EMG were 5.6 and 53.2 mW, respectively. In a single energy storage and release cycle, the CWT-TEHG achieves an instantaneous wind-to-electricity conversion efficiency of 24.3% based on peak power and a cycle-averaged conversion efficiency of 2.1%. The detailed calculation process is provided in **Note S4** in the ESM.

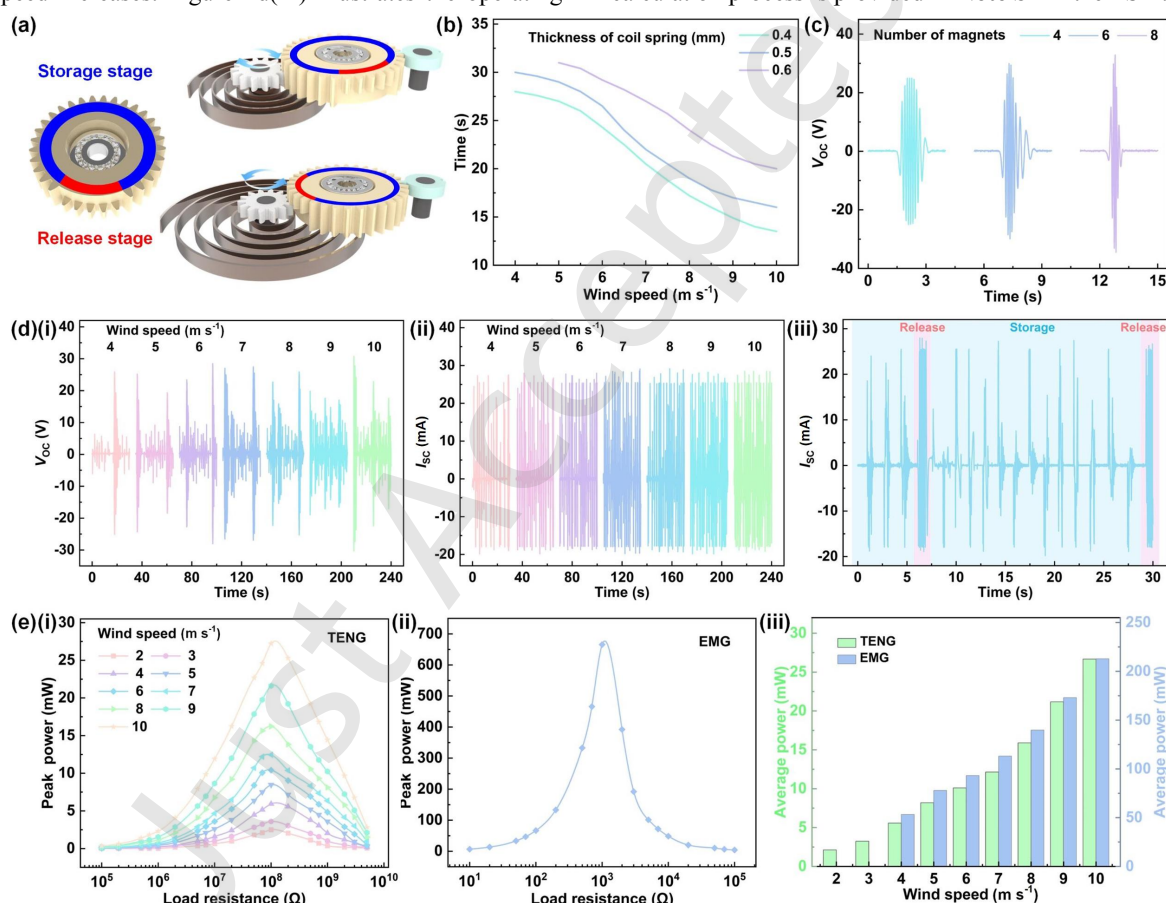


Figure 4. Design and output performance of the controlled EMG. (a) Principle of the energy storage-release mechanism. (b) Impact of different coil spring thicknesses on energy storage duration. (c) Effect of magnet quantity on EMG output performance. (d) EMG output performance at varying wind speeds. (e) Peak power and average power of TENG and EMG

To demonstrate the advantages of the energy storage and release mechanism, the load voltage, current, and charging capacity of the EMG were compared under direct driving by the CWT, as shown in **Figures S12** and **S13** in the ESM. The average power output was found to be 31.5 mW. The results demonstrate that the energy storage and release mechanism not only provides a higher peak output, but also increases the average power by 68.9% and improves the charging performance. This improvement is attributed to the higher energy conversion efficiency of the EMG at higher frequencies.

The energy balance and conversion efficiency of each component in the proposed energy storage and release mechanism during operation are provided in **Note S5** in the ESM.

When the CWT-TEHG operates at a wind speed of 10 m s^{-1} , the TENG exhibits a power density of 0.9 W m^{-2} , and the entire prototype achieves a power density of 27.3 W m^{-3} . **Note S6** in the ESM provides a comprehensive comparison between the CWT-TEHG and recent triboelectric-electromagnetic hybrid power-generation studies, demonstrating the superior energy

harvesting performance of the CWT-TEHG over a broad wind speed range.

2.4. Application demonstration of the CWT-TEHG

The charging performance of the CWT-TEHG under wind-driven conditions was evaluated, as shown in **Figure 5a**. At a wind speed of 5 m s^{-1} , the TENG charged a $100 \mu\text{F}$ capacitor to 5 V within 135 s, whereas the TEHG charged a 1 mF capacitor to 5 V in 10 s, as shown in **Figure 5b**. Compared with the 11 s required by EMG alone (Figure S13), the TEHG significantly improves charging performance, owing to the TENG's high-voltage characteristics.

The durability of the CWT-TEHG was tested at 20°C and 30% relative humidity, as shown in **Figure 5c**. After approximately 1×10^5 cycles (about 30 h) of continuous operation driven by the CWT, the TENG retained 94.9% of its output performance. After 4×10^5 cycles (about 120 h), it still retained 93.2% of its output performance. This durability is attributed to the flexible contact between rabbit fur and FEP, which reduces frictional wear of the dielectric layer. The superior output retention of the adaptive structure can therefore be ascribed to its reduced friction-induced wear. As shown by the SEM images in Figure S11, the fixed-gap condition leads to more severe scratches and surface damage on the FEP film, whereas the adaptive contact mode alleviates interfacial friction and preserves surface integrity, thereby improving durability.

In addition, the effect of humidity on TENG performance was investigated. As the ambient humidity was gradually increased from 30% to 90%, the TENG was operated for 5 min at each humidity level, and the corresponding output variations are shown in **Figure S14** in the ESM. The results show that the TENG still retained 75% of its output performance at 90% humidity. This is attributed to the high density and hydrophobicity of rabbit hair. The durability of the TENG under harsh conditions was further evaluated. As shown in **Figure S15**, after 4×10^5 cycles at 40°C and 80% humidity, the TENG retained 84.5% of its output performance.

Subsequently, a self-powered wind energy application system based on the CWT-TEHG was constructed, as shown in **Figure 5d**. The CWT-TEHG converts wind energy into electric energy, which is rectified and stored by the power management circuit. The LTC3588 energy harvesting module regulates the

capacitor voltage to a 5 V threshold and then outputs a stable 3.6 V supply to automatically power small sensor devices. Using this self-powered system, the performance of the CWT-TEHG was evaluated in a laboratory environment. The CWT-TEHG was driven by a wind tunnel at a wind speed approximately 5 m s^{-1} , and a $470 \mu\text{F}$ energy-storage capacitor was charged through the power-management circuit. As shown in **Figure 5e**, after 21 s of charging, the capacitor voltage exceeded the 5 V threshold. The power management circuit then output a stable 3.6 V output to light the warning light, which consumed approximately 1 mW. After the lamp operated for 2 s, the capacitor voltage dropped to 4 V, triggering the next charging cycle. In subsequent cycles, because only 4 to 5 V charging was required, the capacitor reached the threshold approximately every 11 s, enabling continuous self-powered operation of the warning lamp. When the energy storage capacitor was replaced with a larger 10 mF unit, the CWT-TEHG could continuously power a wireless temperature and humidity sensor module consuming approximately 10 mW after about 44 s of charging. This enables real-time self-powered monitoring of multiple meteorological parameters. A demonstration video (**Movie S3** in the ESM) shows the CWT-TEHG powering the warning light and the wireless meteorological sensor, validating its applicability as a self-powered system.

Finally, CWT-TEHG was demonstrated to harvest random wind energy generated by roadside vehicles and the surrounding environment for self-powered bridge structural health monitoring, as shown in **Figure 5f**. The outdoor demonstration procedure is presented in **Movie S4** in the ESM, and the test conditions are given in **Note S7** in the ESM. The CWT-TEHG and power management circuit charged a 20 mF energy storage capacitor. After approximately 43 s, the system began supplying power to a wireless gyroscope mounted on the bridge, with a power consumption of approximately 30 mW. This operation lasted about 11 s, during which the receiver acquired approximately three sets of bridge vibration monitoring data. These data included triaxial angular position, triaxial angular velocity, and triaxial acceleration, which can be used to evaluate whether the bridge structure contains cracks or loose components. This demonstration verifies that the CWT-TEHG can efficiently capture random wind energy and support self-powered bridge structural health monitoring, highlighting its strong potential for outdoor environmental monitoring and IoT sensing applications.

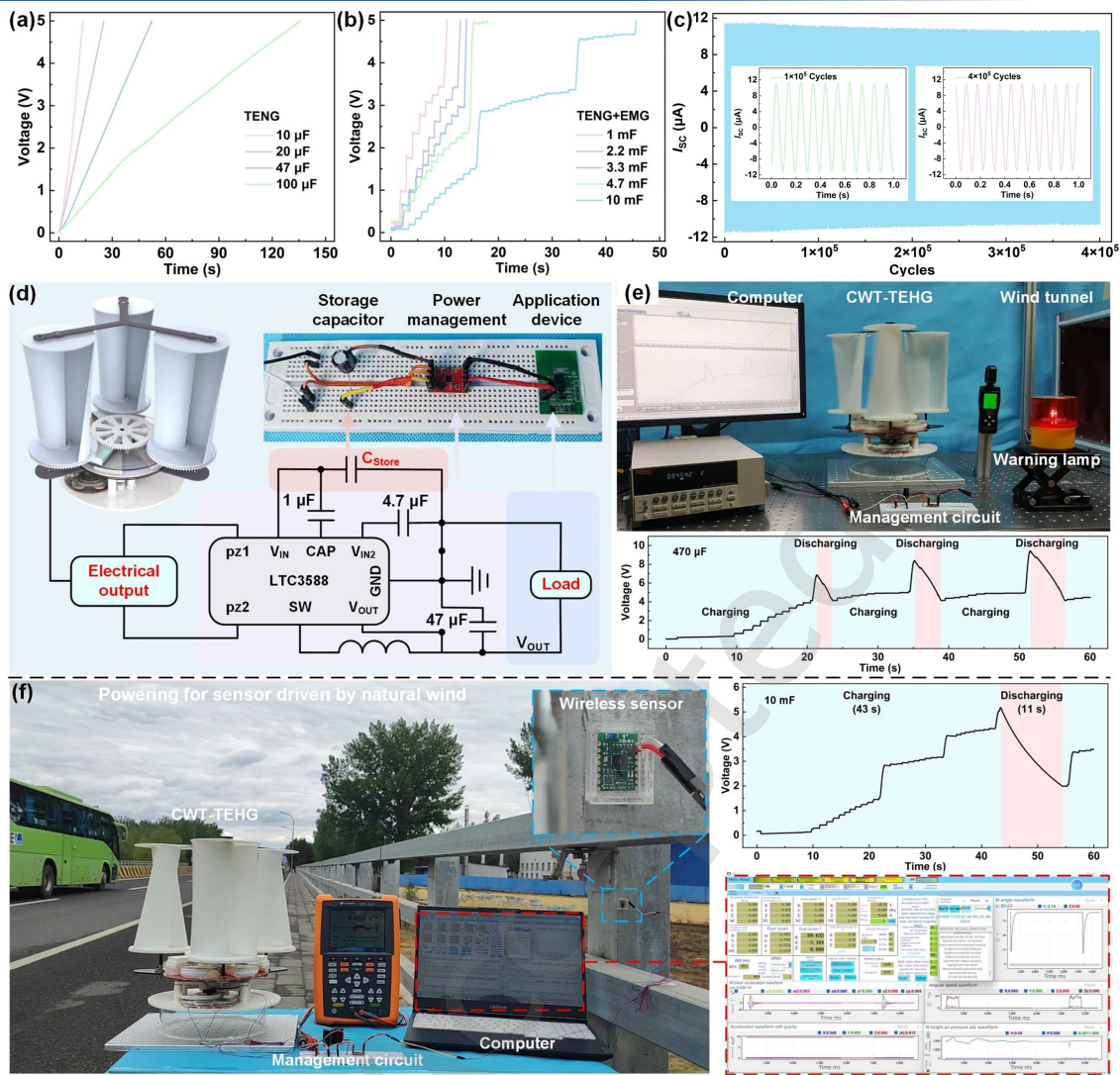


Figure 5. Application demonstration of CWT-TEHG. (a-b) Charging capacitance of TENG and TEHG. (c) Durability testing of CWT-TEHG. (d) Principles of a wind energy self-powered application system based on CWT-TEHG. (e) CWT-TEHG supplies power to the warning light. (f) CWT-TEHG harvests outdoor natural wind for self-powered bridge safety monitoring.

3 Conclusions

In summary, to enable the efficient harvesting and utilization of natural broadband wind energy, this work proposes a cluster wind turbine-driven triboelectric-electromagnetic hybrid generator. CFD simulations confirm that the CWT enhances wind energy harvesting through the combined effects of clustering and the Magnus effect. The underlying mechanism is that the shed vortices and wake of the upstream rotor accelerate the flow field around the downstream rotors, thereby modifying the surface pressure distribution. Orbital motion further strengthens this effect by dynamically adjusting the relative positions of the rotors. Experimental results further demonstrate that, with the adaptive adjustment mechanism and the energy storage and release mechanism, the CWT-TEHG reduces the TENG cut-in wind speed to 2 m s^{-1} and achieves peak output values of 215 V , 50.6 μA , 210 nC , and 27.2 mW at a wind speed of 10 m s^{-1} , representing a 92.4% improvement compared with a conventional fixed-gap TENG. The peak power of the regulated EMG remained constant at 665.6 mW over the tested wind speed range. At a wind speed of 4 m s^{-1} , the CWT-TEHG achieves a wind-to-electricity conversion efficiency of 24.3%. A self-powered application system based on CWT-TEHG was also

constructed. Laboratory experiments verified its ability to power warning lights and meteorological sensors, while outdoor demonstrations confirmed its applicability in self-powered bridge structural health monitoring by harvesting natural wind energy to drive wireless gyroscopes. These results validate the feasibility of the CWT-TEHG for self-powered IoT devices. Overall, this work provides novel strategy for the efficient harvesting and utilization of natural broadband wind energy, as well as for self-powered IoT applications.

4 Experimental section

4.1. Fabrication of the CWT-TEHG

The CWT-TEHG primarily consists of five components: the cluster wind turbine, centrifugal force adaptive adjustment mechanism, the TENG, the storage-release mechanism, and the EMG. The CWT comprises three twisted Savonius blades, which were 3D-printed from PLA. Each blade has a height of 200 mm , a diameter of 120 mm , and a twist angle of 90° . The rotor can rotate around its own axis is connected as a single unit via a Y-shaped bracket, enabling orbital motion around the bracket axis with an orbital radius of 120 mm . The centrifugal force adaptive adjustment mechanism consists of triangular

baffles (3D-printed from PLA material), steel rollers, springs, and slide rail sliders. The TENG is composed of an upper acrylic plate, six rabbit fur pieces, FEP film, two pairs of copper electrodes, and a lower acrylic plate. The overall diameter of the TENG is 200 mm. The rabbit fur was cut into fan-shaped pieces and evenly attached to the back of the upper acrylic plate. The FEP film, copper electrodes, and lower acrylic plate are all ring shaped, with an outer diameter of 200 mm and an inner diameter of 50 mm. The copper electrodes were cut into 12 identical pieces and arranged alternately to form two pairs. The storage-release mechanism consists of a single-tooth gear, an irregular gear, a ratchet pawl, an end gear, and a torsion spring, all 3D-printed from PLA. The complete segment of the irregular gear has 32 teeth, whereas the incomplete segment has 27 teeth. The EMG consists of six pairs of magnets and coils, each measuring 5 mm in height and 30 mm in diameter, with an installation gap of 2 mm between magnets and coils. The key dimensional parameters of the CWT-TEHG prototype are summarized in **Table S2** in the ESM.

4.2. Electrical measurement

A centrifugal blower (4-72, Zifeng, China) was used as the wind source, and the wind speed was measured using a digital anemometer (AS816, SMART, China). The open-circuit voltage, short-circuit current, and transferred charge of the CWT-TEHG were measured using a programmable electrometer (6514, Keithley, USA). The data were acquired using a data acquisition system (USB-6211, National Instruments, USA) and processed in LabVIEW. The surface morphology was characterized by scanning electron microscopy (SEM; ZEISS GeminiSEM 300, Germany).

Electronic Supplementary Material: Supplementary material (please provide the brief detail of the ESM) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94909016>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and/or the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

Mingkang Zhu: Conceptualization, Methodology, Funding acquisition, Writing - original draft. Jianwen Guo: Investigation, Validation, Formal analysis. Daxing Zeng: Data curation, Formal analysis, Writing - original draft. Yong Zhong: Data curation, Investigation, Visualization. Jianyang Zhu: Methodology, Software, Validation. Hengyu Li: Supervision, Visualization, Project administration. Chao Wang: Software,

Supervision, Resources. Tinghai Cheng: Conceptualization, Funding acquisition, Resources, Writing - review & editing. All the authors have approved the final manuscript.

Informed consent

Not applicable.

Ethics statement

Not applicable.

Use of AI statement

None.

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Effective wind energy harvesting by a triboelectric-electromagnetic hybrid generator via coupled cluster-magnus effects

Mingkang Zhu ^{1,2}, Jianwen Guo¹, Daxing Zeng¹, Yong Zhong², Jianyang Zhu³, Hengyu Li⁴ , Chao Wang¹ , and Tinghai Cheng^{4,5} 

¹ School of Mechanical Engineering, Dongguan University of Technology, Dongguan 523808, China

² Shien-Ming Wu School of Intelligent Engineering, South China University of Technology, Guangzhou 511442, China

³ Key Laboratory of Metallurgical Equipment and Control Technology Ministry of Education, Wuhan University of Science and Technology, Wuhan 430081, China

⁴ Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 101400, China

⁵ Guangzhou Institute of Blue Energy, Guangzhou 510555, China

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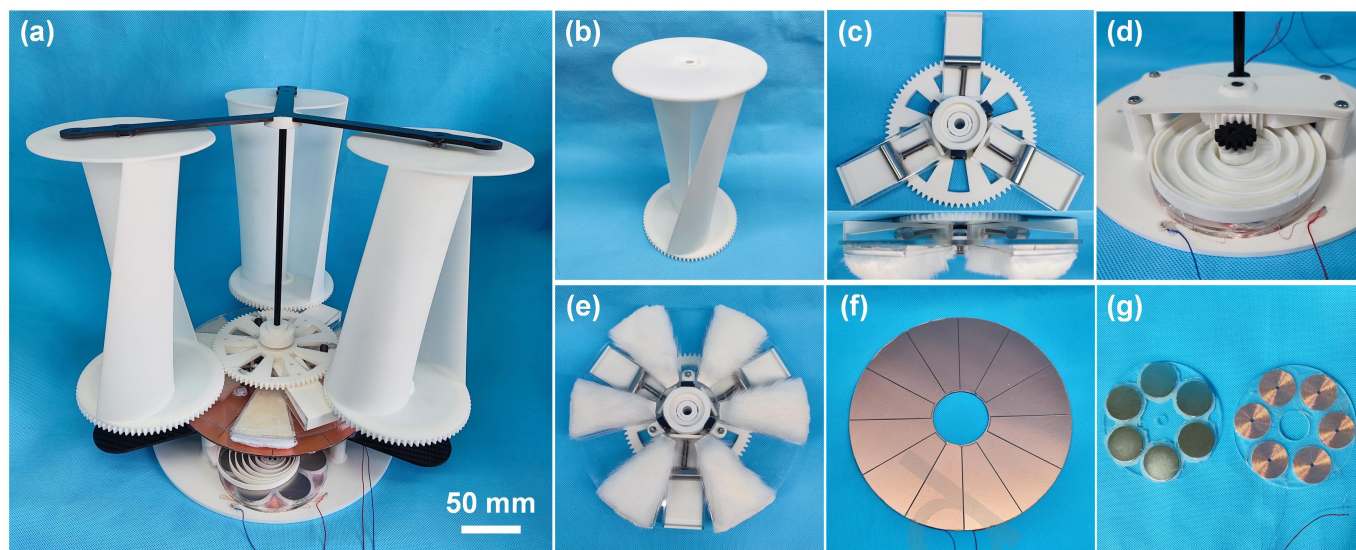


Figure S1. Prototype of the CWT-TEHG. (a) Prototype assembly. (b) Spiral Savonius rotor. (c) Centrifugal adaptive adjustment mechanism. (d) Storage-release mechanism. (e) Rabbit fur of the TENG. (f) FEP film and copper electrodes of the TENG. (g) EMG unit.

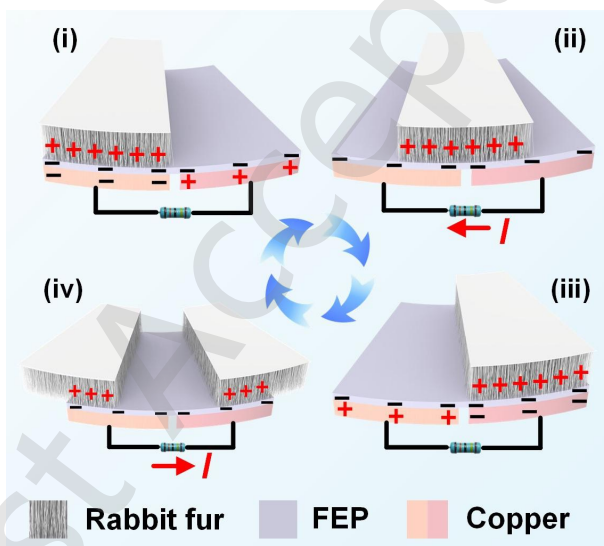


Figure S2. Operational principle of the TENG in the CWT-TEHG

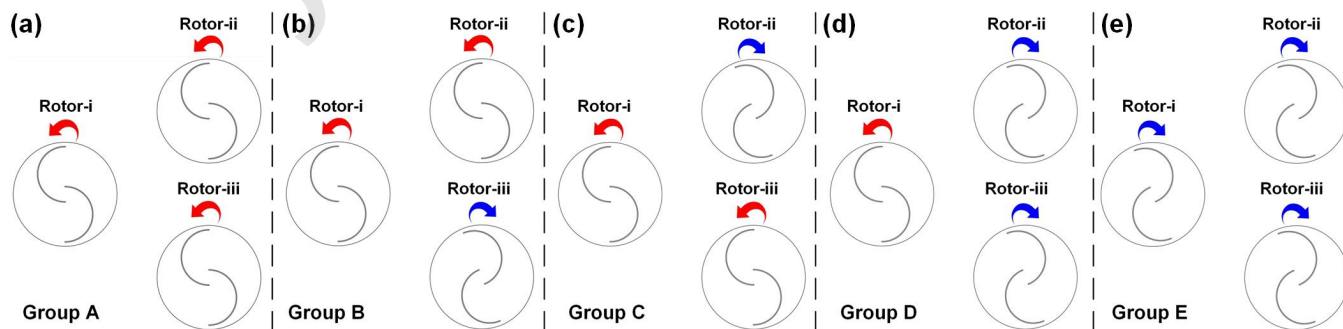


Figure S3. Five different rotor configurations of CWT

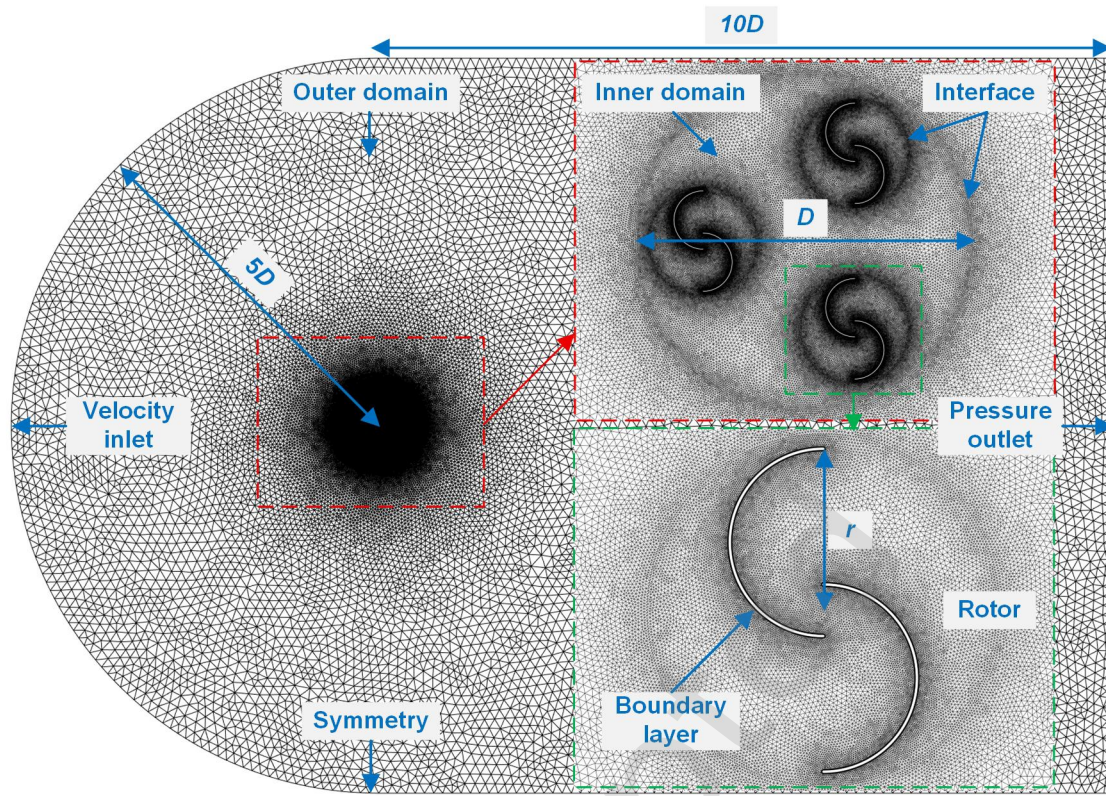


Figure S4. Computational domain settings for CFD.

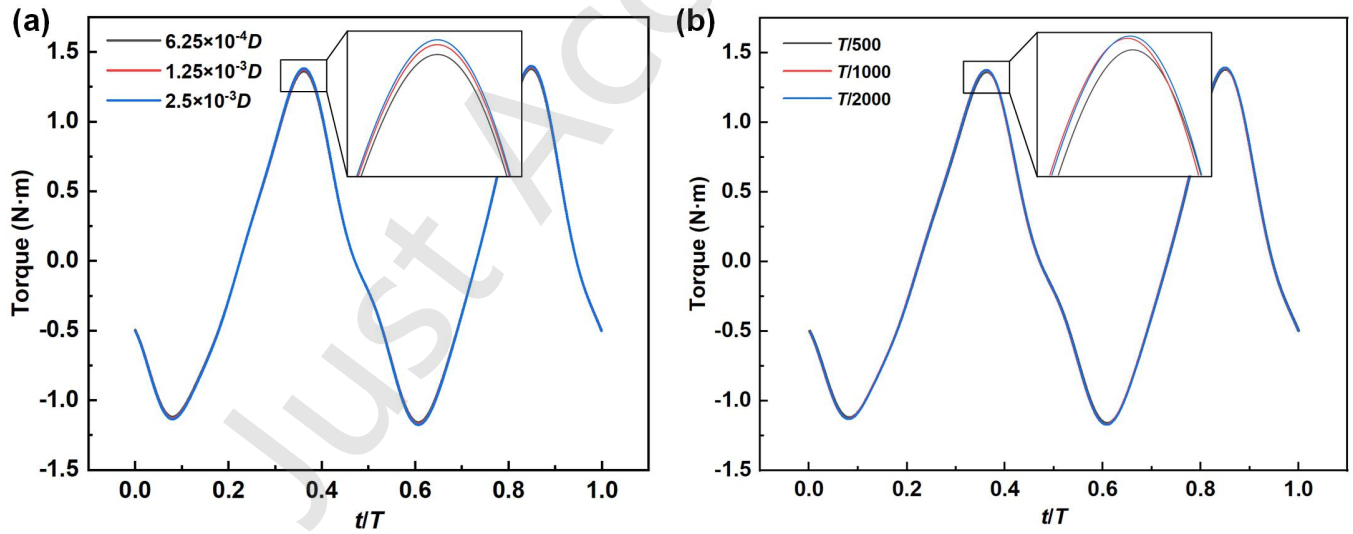


Figure S5. Verification of the independence of mesh size and time step. Numerical calculation results with (a) different minimum grid sizes and (b) different time steps. The results show that the minimum grid size of 1.25×10^{-3} (with grids number of 198693) and the time step $T/1000$ are the most suitable.

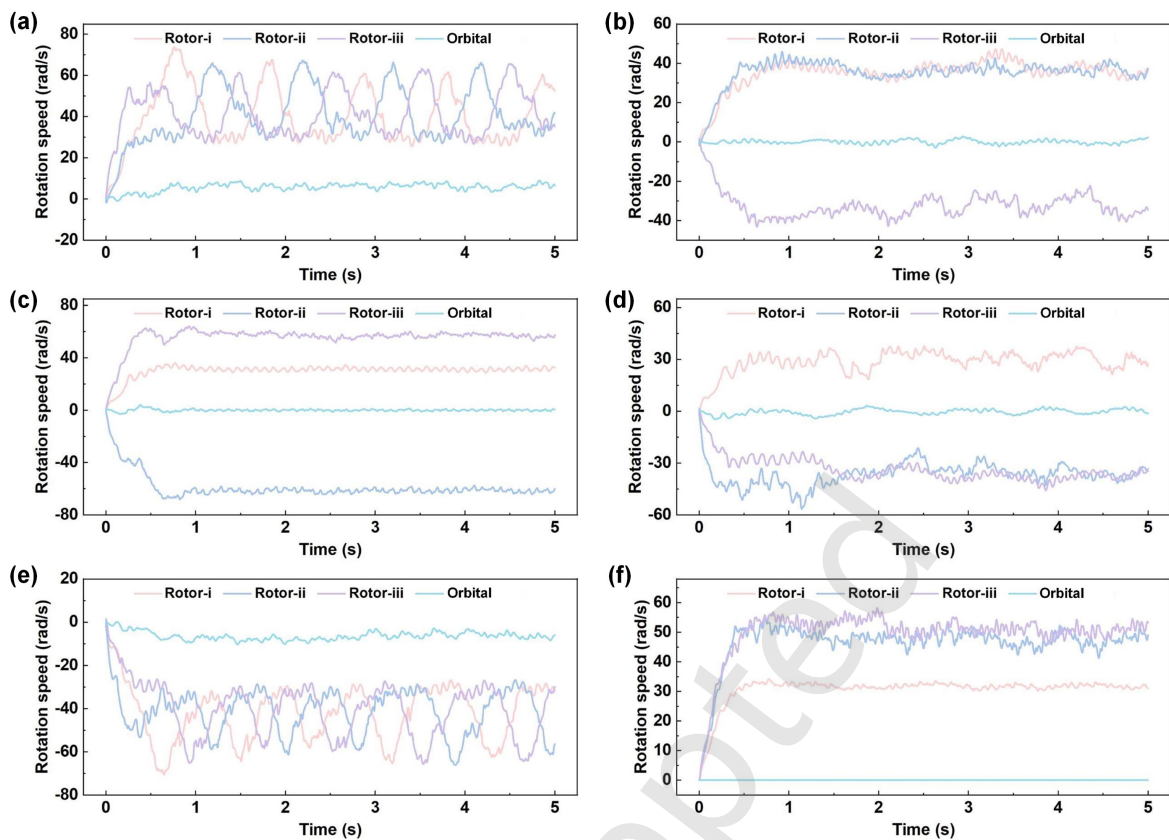


Figure S6. Rotational speeds of the rotors and the orbital speeds for each model groups.

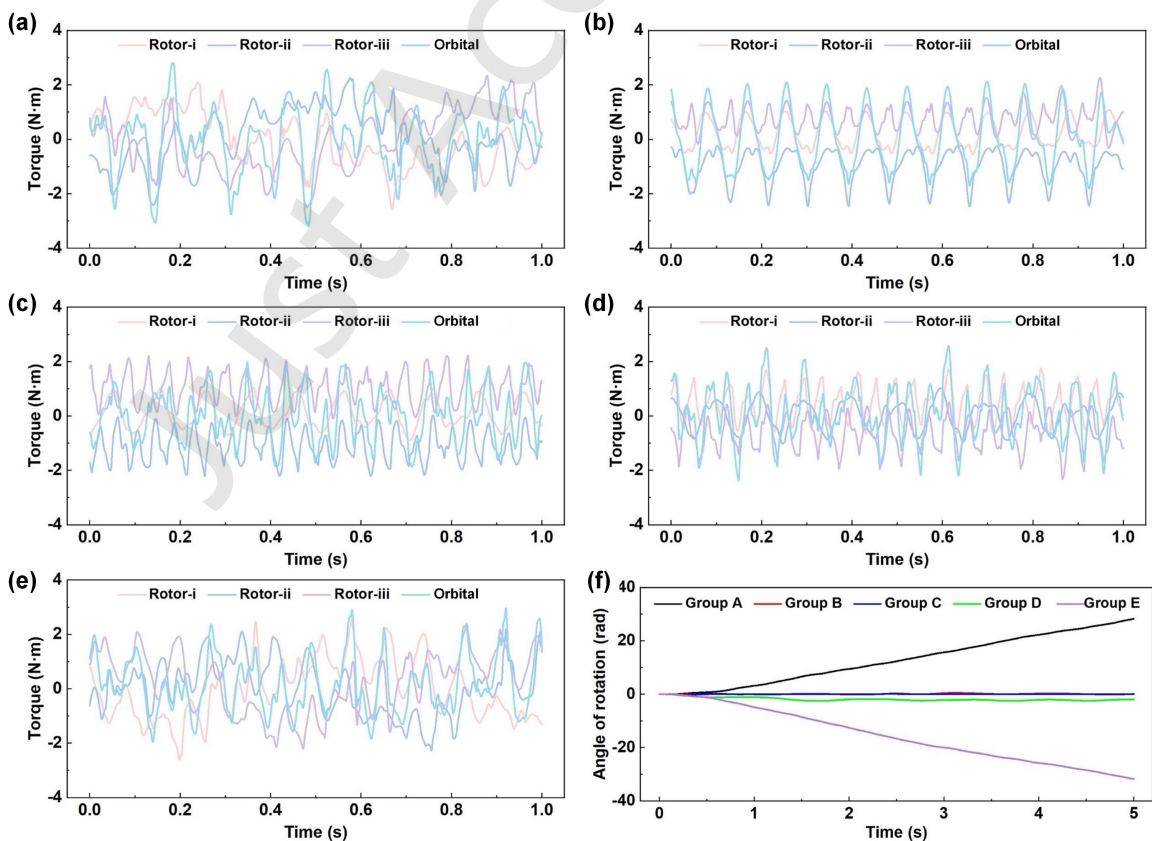


Figure S7. (a-e) Orbital torque contributed by each rotor and the total orbital torque for each model groups. (f) Orbital angles of each group during simulation.

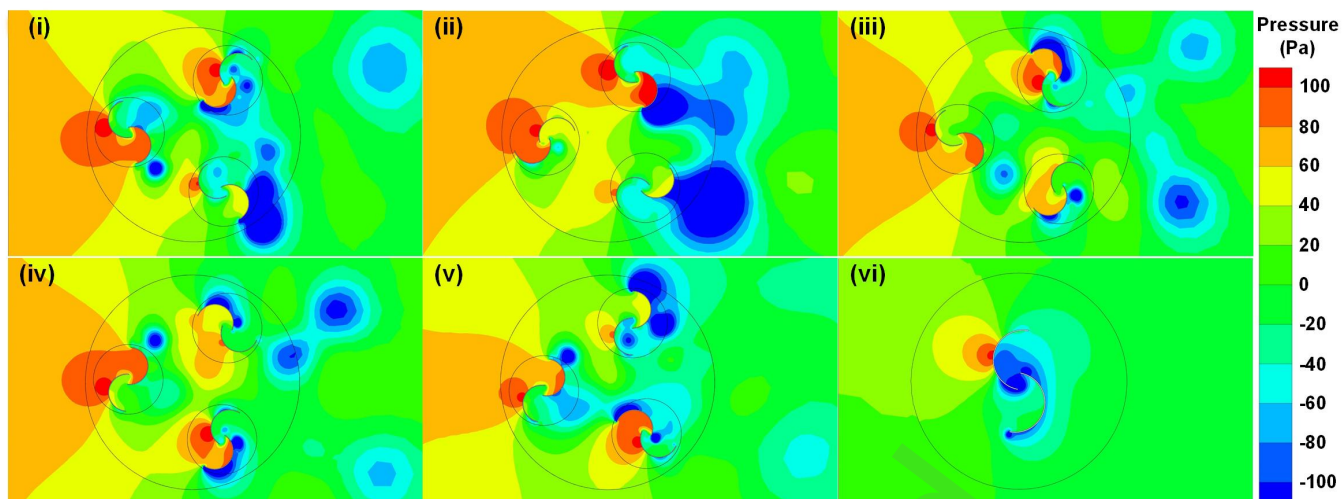


Figure S8. Pressure contours of the flow field for each model group.

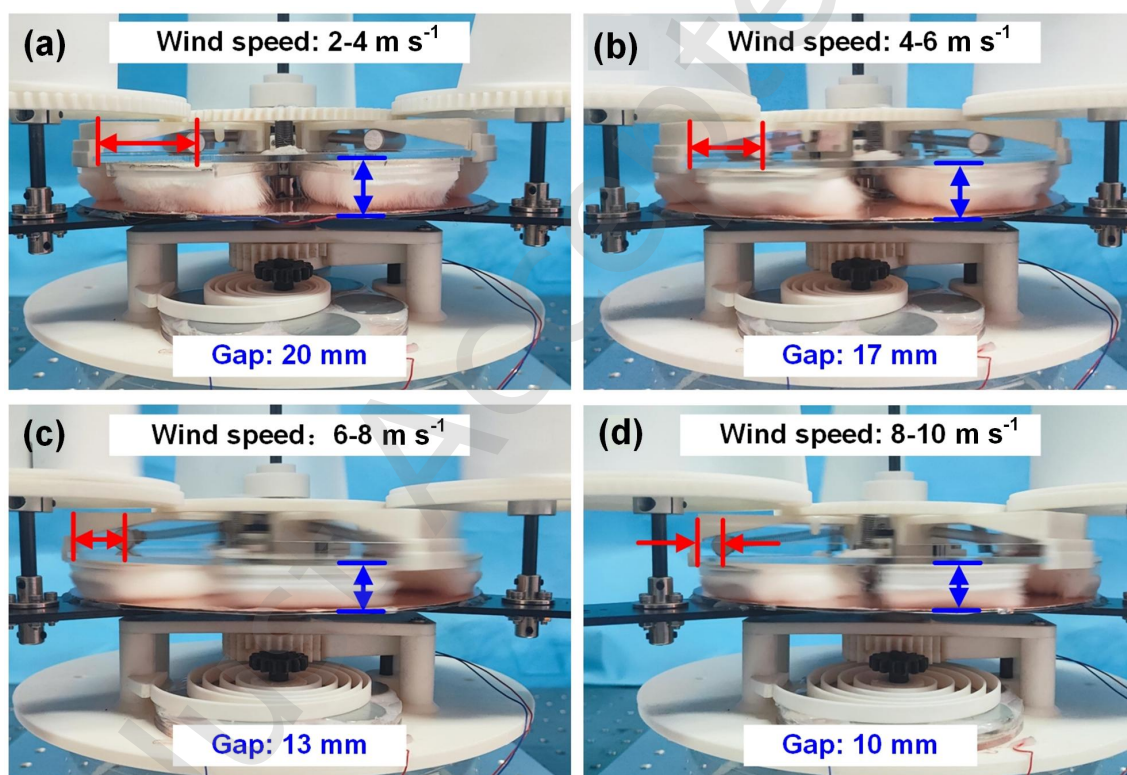


Figure S9. Photographs of the prototype TENG device undergoing adaptive adjustment of the friction layer gap in response to varying wind speeds during testing.

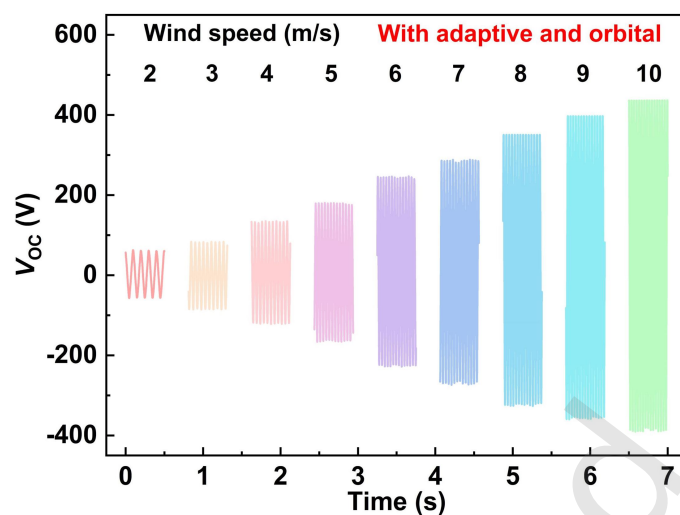


Figure S10. Open-circuit voltage of TENG under different wind speeds.

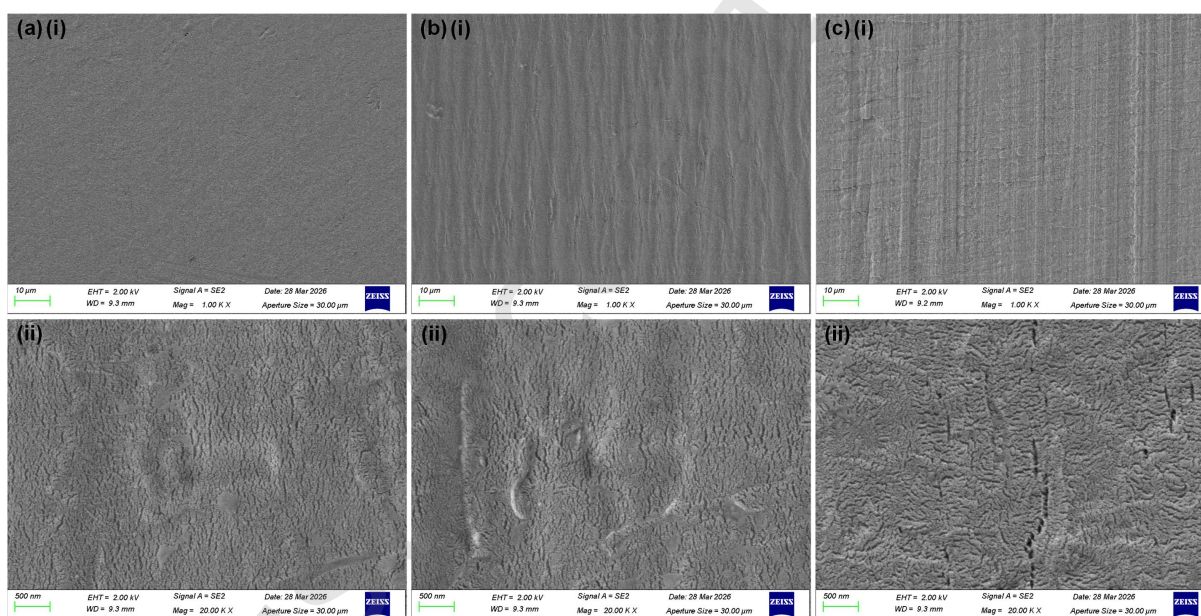


Figure S11. Surface morphology of the FEP film after long-term operation. (a) Initial state with 0.846% of the damaged area. (b) With adaptive interface control, the damage area accounts for 4.861%. (c) With fixed friction layer gap, the damage area accounts for 9.004%.

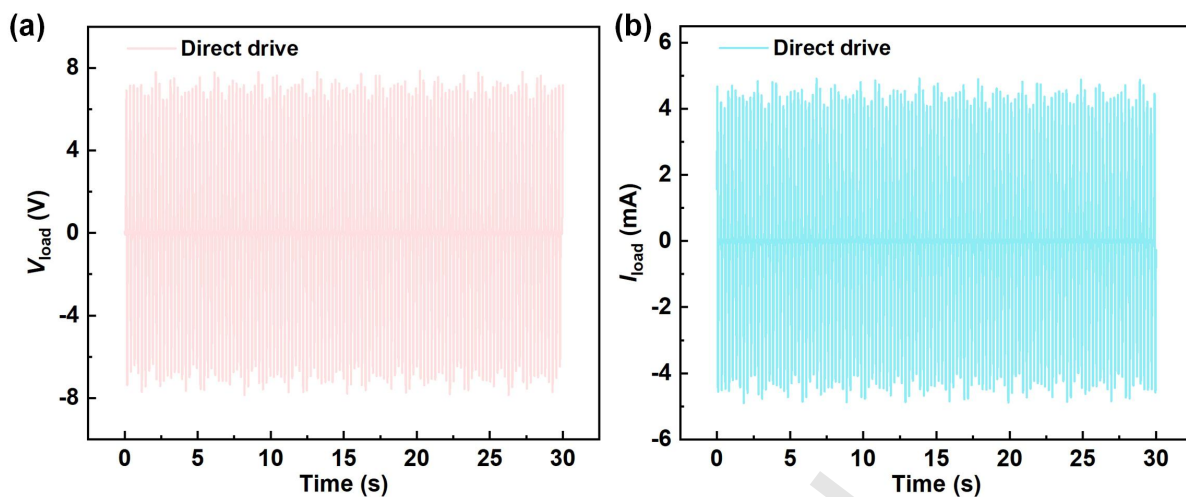


Figure S12. Load voltage and current of the EMG when directly driven by the CWT.

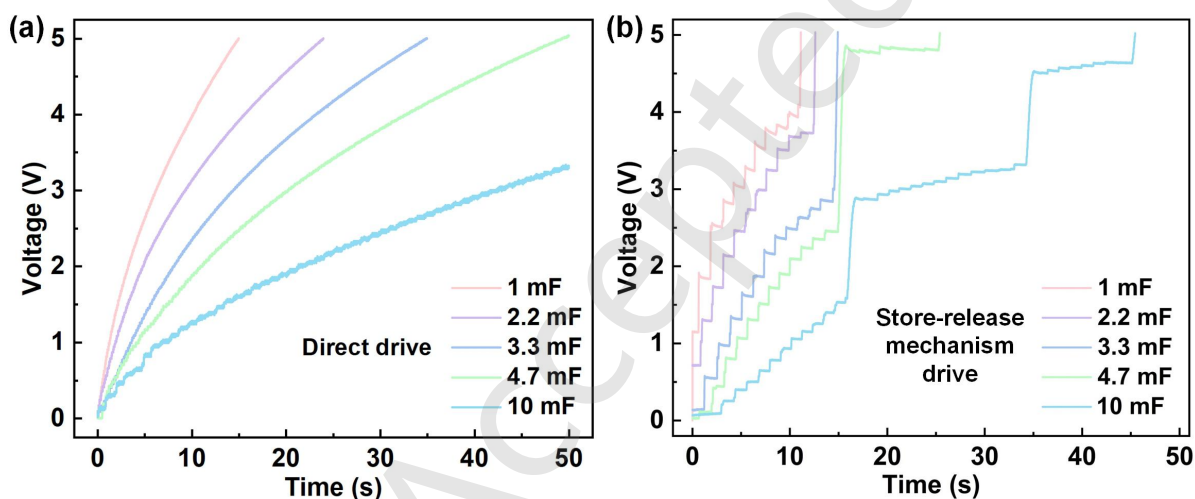


Figure S13. EMG charging capacity under different driving modes. (a) Directly driven. (b) Driven by energy storage-release mechanism.

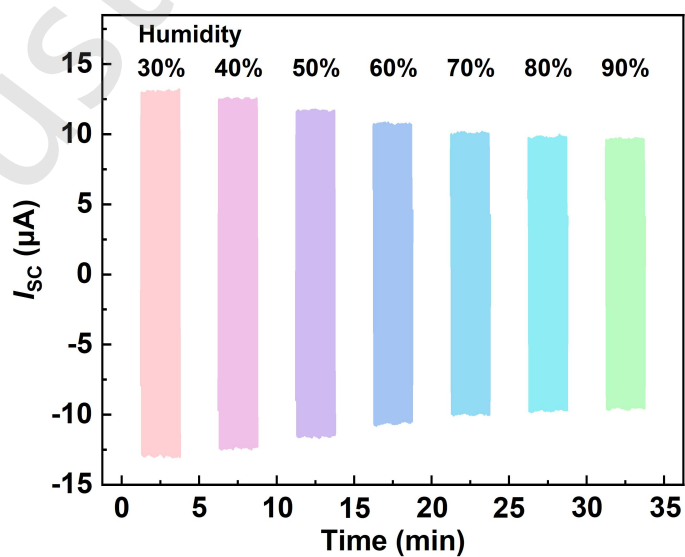


Figure S14. Effect of air humidity on the output performance of TENG.

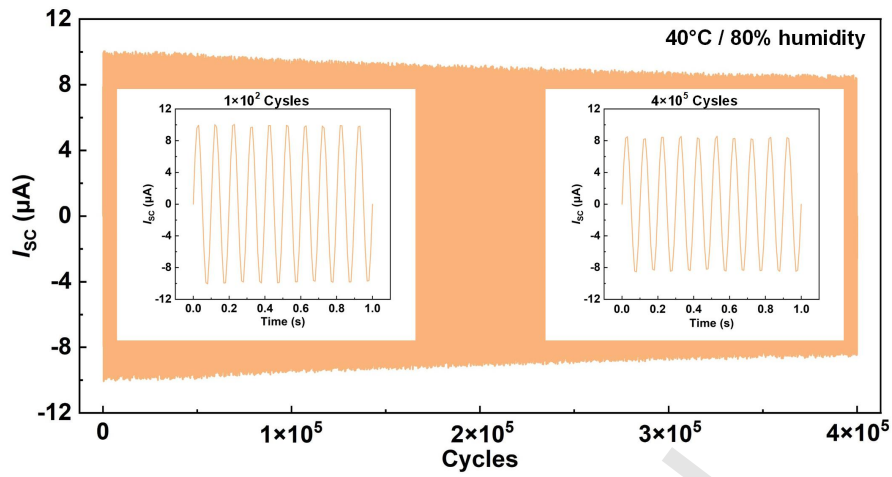


Figure S15. Durability testing of TENG under stringent conditions of 40°C and 80% humidity.

Table S1. Mean torque values per rotor and the absolute sum of mean torques for triple-rotor groups.

Rotor		$\overline{M}$ (N·m)	Rotor		$\overline{M}$ (N · m)	Rotor		$\overline{M}$ (N · m)
A	Rotor-i	0.1696	C	Rotor-i	0.0879	E	Rotor-i	-0.1785
	Rotor-ii	0.1726		Rotor-ii	-0.2162		Rotor-ii	-0.1686
	Rotor-iii	0.1748		Rotor-iii	0.1971		Rotor-iii	-0.1619
	Mean	0.1723		Mean	0.1671		Mean	0.1697
B	Rotor-i	0.1466	D	Rotor-i	0.2327	F	Rotor-i	0.1206
	Rotor-ii	0.1416		Rotor-ii	-0.1129		Rotor-ii	0.1828
	Rotor-iii	-0.1316		Rotor-iii	-0.1658		Rotor-iii	0.1963
	Mean	0.1340		Mean	0.1705		Mean	0.1666

Table S2. Key dimensional parameters of the CWT-TEHG prototype.

Cluster wind turbine			Adaptive mechanism		
Radius of single rotor	Orbital diameter of cluster rotor	Rotor height	Angle of triangular baffle	Size of the steel roller	Size of stretching spring
60 mm	360 mm	200 mm	15°	M10×30 mm	0.3×4×30 mm
TENG					
Radius of rotor	quantity of rabbit fur	thickness of rabbit fur	thickness of FEP film	Area of copper electrode	Relative spacing range between rotor and stator discs
100 mm	6	25 mm	100 μm	0.02945 m ²	10-20 mm
Store-release mechanism			EMG		
Irregular gear transmission ratio	Storage-release cycle ratio	Size of the coil spring	Radius of rotor	Size and quantity of magnets and coils	relative gap between the magnet and the coil
15	5.4	1×4×300 mm	50 mm	Φ30×5 mm, 6	2 mm

Note S1

For the rotor of a Savonius wind turbine, the direction of drag force experienced in the flow field aligns with the direction of the resultant velocity vector formed by the blade's rotational velocity and the inflow velocity. Furthermore, the drag force on the concave surface of the blade is significantly greater than that on the convex surface, as shown in Figure 2b. The drag force F_D and lift force F_L of the blade can be expressed by the following equations:

$$F_D = 0.5\rho C_D S V^2 \quad (S1)$$

$$F_L = 0.5\rho C_L S V^2 \quad (S2)$$

where ρ represents the air density, C_D and C_L denote the drag coefficient and lift coefficient of the blade respectively, and S is the blade area. V is the resultant velocity vector formed by the blade's rotational velocity vector U and the fluid velocity W .

The resultant force of blade drag and lift can be decomposed into a tangential thrust force F_T along the motion trajectory and a normal tensile force F_N , expressed as:

$$F_T = F_L \sin \alpha - F_D \cos \alpha \quad (S3)$$

$$F_N = F_L \cos \alpha + F_D \sin \alpha \quad (S4)$$

where α represents the blade angle of attack. The torque M generated by the wind turbine under aerodynamic force can be expressed by the following formula:

$$M = 0.5\rho C_M V^2 (2r)^2 \quad (S5)$$

where C_M is the torque coefficient of the wind turbine, and r is the rotational radius of the wind turbine.

Based on potential flow theory, a mechanical model for the Magnus force acting on the rotor of a Savonius wind turbine is derived. A force analysis of the Magnus effect on the rotor is established. A rotor model with radius r is constructed in polar coordinates (r, θ) . At any point on the rotor's rotational circumference, where the normal velocity of the fluid at this point is zero, according to the parallelogram law, V can be expressed as:

$$V = \sqrt{U^2 + W^2 + 2UW \sin \theta} \quad (S6)$$

The rotation of the rotor induces eddy currents, represented by the flux Γ , which is related to the angular velocity ω . By matching the surface-averaged tangential velocity, the expression is obtained as:

$$\Gamma = 2\pi r^2 \omega \quad (S7)$$

In momentum flow theory, flow is described by the flow function ψ . Thus, the tangential velocity U of the fluid at this point can be expressed as:

$$U = -2W \sin \theta + \frac{\Gamma}{2\pi r} = -2W \sin \theta + r\omega \quad (S8)$$

Then, apply Bernoulli's equation to solve for the pressure distribution. Let the pressure at this point be P_θ and the pressure at infinity be P_∞ . According to Bernoulli's principle, the expression is obtained as:

$$p_\theta + \frac{1}{2}\rho V^2 = p_\infty + \frac{1}{2}\rho W^2 \quad (S9)$$

Substituting Equations (S6) and (S8) into Equation (S9) yields:

$$\begin{aligned} p_\theta &= p_\infty + \frac{1}{2}\rho W^2 - \frac{1}{2}\rho(U^2 + W^2 + 2UW \sin \theta) \\ &= p_\infty + \frac{1}{2}\rho W^2 - \frac{1}{2}\rho[4W^2 \sin^2 \theta - 4r\omega W \sin \theta + r^2\omega^2 + W^2 \\ &\quad + (-4W \sin \theta + 2r\omega)W \sin \theta] \\ &= p_\infty - \frac{1}{2}\rho r^2 \omega^2 + \rho r \omega W \sin \theta \end{aligned} \quad (S10)$$

By integrating the pressure, the force exerted by the fluid on the cylinder can be obtained. Thus, the Magnus force at that point (manifesting as lift) can be expressed as:

$$F_M = -r \int_0^{2\pi} p \sin \theta d\theta \quad (S11)$$

Finally, substituting the pressure expression from Equation (S10) into Equation (11) and integrating term by term, and introducing correction coefficients, the final expression for the Magnus force at this point on the circumference of the Savonius rotor can be expressed as:

$$F_M = C_{eff} 2\pi \rho W r^2 \omega \quad (S12)$$

where C_{eff} is a coefficient related to geometry and operating conditions.

In numerical calculations, a separate rotation domain was set for each rotor, and a common rotation domain was set for the cluster of rotors. The turbulence model adopted Standard $k-\omega$, and the mesh was updated using dynamic meshing technology. The fluid-structure interaction of the rotors' fully passive rotation and orbital was realized through UDF. First, according to the flow control equations, the torque of each rotor at the rotation center and orbital center under the action of the flow field was obtained. Then, according to the rotor's motion control equations, the rotation and orbital displacement angles and speeds of the rotors were calculated, and the rotor's position in the flow field was updated using dynamic meshing technology. Finally, the fluid characteristic parameters in the flow field were updated, and the calculation for the next time step was performed. The calculation was repeated until the flow field converged.

Note S3

To achieve adaptive adjustment of the TENG, a centrifugal force-based adaptive adjustment mechanism was designed to regulate the friction layer gap according to wind speed. The force diagram of the centrifugal adjustment mechanism is shown in Figure 4b. At the system's equilibrium position, neglecting roller friction, the horizontal forces acting on the roller can be expressed as:

$$F_{s1} = F_c - F_n \sin \theta \quad (S13)$$

where F_{s1} represents the tensile force of spring-i, while F_c and F_n denote the centrifugal force of the roller and the supporting force exerted by the inclined ramp plate on the roller, respectively. They can be expressed as:

$$F_n = F_c \sin \theta = m_1 \omega^2 l \sin \theta \quad (S14)$$

where m_1 is the mass of the roller, ω is the rotational speed of the rotor, and l is the distance from the roller's center of gravity to the center of the rotational axis. The vertical force acting on the roller can be expressed as:

$$F_p = m_1 g + F_n \cos \theta = m_1 g + F_c \sin \theta \cos \theta \quad (S15)$$

where F_p is the force exerted by the roller on the rabbit fur disc, g is the gravitational acceleration, and θ is the angle between the inclined plane and the horizontal plane. The vertical force acting on the rabbit fur disc can be expressed as:

$$F_{s2} = F_p + m_2 g \quad (S16)$$

Assuming the initial length of spring-ii is l_2 , and the displacement of the rabbit fur disc from its initial position is Δx , the relationship between Δx and the rotor speed can be expressed as:

$$\Delta x = \frac{(m_1 g + m_2 g + m_1 \omega^2 l \sin \theta \cos \theta)}{k} - l_2 \quad (S17)$$

where k is the spring constant of spring-ii. Therefore, the displacement of the rabbit fur disc is directly proportional to the rotational speed.

Note S4

The equation for wind power (P_w) can be expressed as:

$$P_w = \frac{1}{2} \rho v^3 S \quad (S18)$$

where ρ is the air density (taken as 1.2 kg m^{-3}), v is the wind speed, and S is the area of the air flowing through the wind turbine. The equation for calculating the wind energy to electrical energy (P_E) conversion efficiency can be expressed as:

$$\eta = \frac{P_E}{P_w} \times 100\% \quad (S19)$$

In this work, S is the entire area covered by the rotor cluster when it rotates, with a width of 0.36 m and a height of 0.2 m, and an area of 0.072 m^2 . At a wind speed of 4 m s^{-1} , the peak power P_{peak} and average power P_{avg} of the hybrid generator during one energy storage-release cycle are 692.8 mW and 58.8 mW, respectively. Therefore, the peak and average conversion efficiency of the hybrid generator from wind energy to electrical energy are 24.3% and 2.1%.

Note S5

The experiment tested the closed-loop energy balance of an energy storage-release cycle, clearly calculating the mechanical input, spring energy storage, mechanical losses, and electrical output, providing the energy conversion efficiency of the energy storage-release mechanism.

The torque (T) and rotational speed (ω) of the shaft were measured using a dynamic torque sensor (DYN-200, China). The average mechanical power of each component was calculated using integral forms:

$$\overline{P_M} = \frac{1}{t} \int_0^t T \omega dt \quad (S20)$$

and the average output power of the EMG was calculated using integral forms of the load voltage (V) and load current (I):

$$\overline{P_E} = \frac{1}{t} \int_0^t V I dt \quad (S21)$$

The results of testing and calculating one complete cycle under a wind speed of 4 m/s are shown in Figure S15.

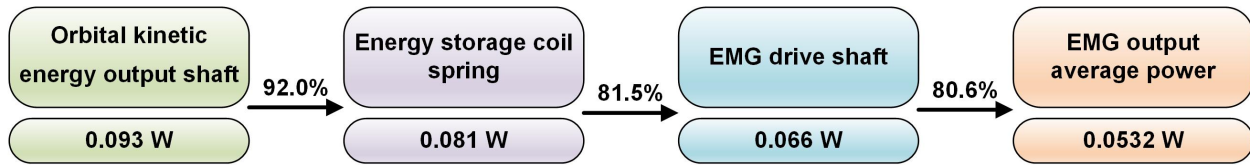


Figure S16. Average power and efficiencies of each component during the energy storage-release cycle.

Therefore, the efficiencies of spring energy storage, spring release, and EMG energy conversion are 92.0%, 81.5%, and 80.6%, respectively.

Note S6

Table S4. comprehensive comparison of the performance of CWT-TEHG with recent research on triboelectric-electromagnetic hybrid power generation.

Refs	Working wind speed range (m s ⁻¹)	Peak power and average power at highest wind speed (mW)		Peak power density		Maximum conversion efficiency
		TENG	EMG	TENG (W m ⁻²)	Overall (W m ⁻³) [#]	
[R1]	4-11	0.53, NA	2.12, NA	0.03	0.16	NA
[R2]	4-7	0.15, NA	34.8, NA	NA	NA	NA
[R3]	2.5-6.0	NA, 3.12	NA, 174.14	0.36	2.02	14.87%
[R4]	1-5	9.8, 2.6	1.5, 0.5	0.196	19.6	12%
[R5]	2.5-11.0	3.2, NA	85.2, NA	0.4	16.25	17.4% [*]
This work	2-10	27.2, 26.1	665.6, 211.5	0.9	27.3	24.3%

[#] Overall power density refers to the ratio of hybrid generator power to the overall volume of the prototype.

^{*} The conversion efficiency of [R5] is from mechanical energy to electrical energy.

[R1] Z. Wang, C. Huang, J. Cao, et al., “Mechanical-electrical conversion performance of electromagnetic-triboelectric hybrid generator for wind energy harvesting,” *iScience* **29** (2026): 114728. <https://doi.org/10.1016/j.isci.2026.114728>.

[R2] W. Li, K. Han, G. Shen, et al., “Triboelectric-electromagnetic metamaterial systems for self-powered multiparameter wireless monitoring,” *Nano Energy* **147** (2026): 111586. <https://doi.org/10.1016/j.nanoen.2025.111586>.

[R3] T. Xiong, Z. Xu, Q. He, et al., “Direction-adaptive triboelectric-electromagnetic hybrid nanogenerator for harvesting omnidirectional breeze wind energy,” *Nano Energy* **143** (2025): 111323. <https://doi.org/10.1016/j.nanoen.2025.111323>.

[R4] G. Yu, P. Ji, X. Gao, et al., “Efficient pedestrian-level wind energy harvesting using a hybridized technology,” *Energy & Environmental Science* **18** (2025): 8280. <https://doi.org/10.1039/d5ee03460d>.

[R5] J. Zhu, K. Fan, W. Wang, et al., “A robust hybrid nanogenerator strategy achieved by regenerative motion transmission toward wind energy harvesting and self-powered sensing,” *Nano Energy* **135** (2025): 110679. <https://doi.org/10.1016/j.nanoen.2025.110679>.

Note S7

During the outdoor application demonstration test, the wind speed range was 0-8 m s⁻¹, and the CWT-TEHG was installed 0.5 m above the ground and 3 m away from the moving vehicle. A complete charge-to-power cycle took approximately 55 s, and this was repeated 3 times under the same conditions.