Supplementary Information (SI) for Sustainable Energy & Fuels.

Supplementary information

A symbiotic energy-sensing wind generator enabled AI for smart road

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S1. GRU Chart Supplement

Table S1

Main dimensional parameters of DW-TEHG

Classification	Parameter
Device dimension (length × width × height)	200 mm × 200 mm × 220 mm
Coil (diameter × thickness)	20 mm × 5 mm
Magnet (diameter × thickness)	20 mm × 5mm
PTFE (outer diameter × inner diameter × height)	8mm × 3 mm × 8 mm
Comb-like copper ring (thickness)	0.05 mm
Upper wind cup (cup diameter × rod length)	80 mm × 80 mm
Lower wind cup (cup diameter × rod length)	60 mm × 60 mm

S2. Theoretical of GRU

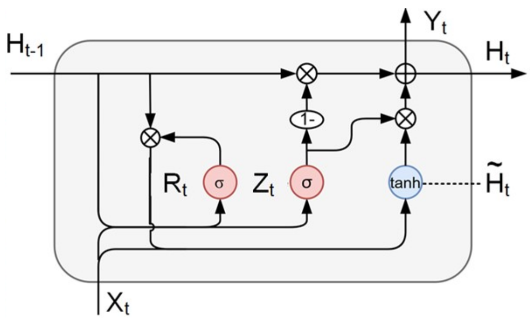

Figure S1. The structure of a GRU cell

Gated Recurrent Unit (GRU) is an implementation of recurrent neural networks and is also designed to solve the problem of calculating gradients and the problem of consecutive products of matrices leading to vanishing or exploding gradients that exists in recurrent neural networks. Compared to LSTM networks, GRU can achieve the same effect of LSTM and are faster to compute.

For a given time step t, assuming that the input is a small batch X_t, and the hidden state at the previous time step is H_{t-1}, then the reset gate R_t and the update gate Z_t can be expressed as follows.

$$R_t = \sigma(X_t W_{xr} + H_{t-1} W_{hr} + b_r) \tag{S1}$$

$$Z_t = \sigma(X_t W_{xz} + H_{t-1} W_{hz} + b_z) \tag{S2}$$

Where W_{xr}, W_{xz} are the weight parameters corresponding to the input variables, b_r, b_z are the bias parameters, and the sigmoid function is used to transform the input values to the interval (0,1).

$$\tilde{H} = tanh(X_t W_{xh} + (R_t \odot H_{h-1}) W_{hh} + b_h) \tag{S3}$$

where W_{xh}, W_{hh} are the weight parameters and b_h is the bias term, and the tanh nonlinear activation function is used to ensure that the values in the marquee hidden state remain in the interval (-1, 1). Finally, the new hidden state H_t, H_t can be expressed as:

$$H_t = Z_t \odot H_{t-1} + (1 - Z_t) \odot \tilde{H} \tag{S4}$$

The model retains the on state whenever Z_t approaches 1, and as Z_t approaches 0, the new H_t approaches $\tilde{H}_t$. These designs can handle the problem of gradient vanishing in recurrent neural networks and better capture sequence dependencies with long time-step distances.

S3. Theoretical analysis of DW-TEHG

a_i and b_i are the pressure coefficient and drag coefficient of the rotor, respectively, which can be expressed as:

$$a_i = C_n(\theta_i) + C_n(\theta_i + 120^\circ) + C_n(\theta_i + 120^\circ) \tag{S5}$$

$$b_i = C_n(\theta_i)\cos\theta_i + C_n(\theta_i + 120^\circ)\cos(\theta_i + 120^\circ) + C_n(\theta_i + 240^\circ)\cos(\theta_i + 240^\circ) \tag{S6}$$

where $C_n(\theta_i)$ is the aerodynamic coefficient of the wind cup at θ_i. This coefficient is generally related to the shape of the wind cup, the ambient temperature, and the Reynolds number, but not to the mass of the wind cup.

With the wind cup rotating continuously at 120°, we can calculate the average a_{ave} and b_{ave} of a_i and b_i over a cycle, which can be calculated as:

$$a_{ave} = \frac{3}{2\pi}\int_0^{\frac{2\pi}{3}} a_i d\theta = \frac{3}{2\pi}\int_0^{\frac{2\pi}{3}} (C_n(\theta_i) + C_n(\theta_i + 120^\circ) + C_n(\theta_i + 240^\circ)) d\theta \tag{S7}$$

$$b_{ave} = \frac{3}{2\pi}\int_0^{\frac{2\pi}{3}} b_i d\theta = \frac{3}{2\pi}\int_0^{\frac{2\pi}{3}} (C_n(\theta_i)\cos\theta_i + C_n(\theta_i + 120^\circ)\cos(\theta_i + 120^\circ) + C_n(\theta_i + 240^\circ)\cos(\theta_i + 240^\circ)) d\theta \tag{S8}$$

Accordingly, Eq. (2) can be simplified as:

$$F_{cup} = S_{cup}\rho v_{wind}(a_{ave} v_{wind} - 2\pi R b_{ave} n) \tag{S9}$$

With the constant change of wind speed, the rotational speed of the wind cup rotor does not change immediately and abruptly, but changes gradually according to the increase and decrease of wind speed. The dynamics of wind energy captured by the wind cup can be expressed as:

$$2\pi(J_r + J_{s1} + J_m)\frac{dn(\tau)}{d\tau} = M_w - T_m - T_e \tag{S10}$$

where J_r, J_{s1} and J_m are the rotational inertia of the rotor of the wind cup, the rotor shaft, and the turntable, respectively. $n(\tau)$ is the real-time rotational speed of the rotor of the wind cup.

In the road environment, there are two states of operation of the wind cup, acceleration and deceleration, because there are traffic winds generated by vehicles in addition to natural winds. The response of the wind cup rotor varies for different states of motion.

The dynamic equation of the rotor during the acceleration period can be expressed as:

$$(J_r + J_{s1} + J_m)\frac{dw}{dt} = \frac{1}{2}C_d\rho v_{wind}^2 N\pi r^2 R \tag{S11}$$

Where w, N, r, R are the angular velocity of the wind cup rotor, the number of wind cups, the radius of the circular cross section of the wind cups, and the radius of rotation of the wind cup rotor, respectively. C_d is the accelerating torque coefficient of the wind cup rotor, which can be expressed as：

$$C_d = C_{d0}[1 - \lambda_0^2 (wR / v_{wind})^2] \tag{S12}$$

where C_{d0} is the torque coefficient of the wind cup at rest and λ_0 is the constant of the wind cup rotor, which can be expressed as:

$$\lambda_0 = v_{wind} / w_s R \tag{S13}$$

where w_s is the angular velocity of the wind cup when it reaches steady state.

When the wind cup rotor decelerates and rotates, its dynamic equation is:

$$(J_r + J_{s1} + J_m)\frac{dw}{dt} = \frac{1}{2} k_d \rho w^2 N \pi^2 R^3 \tag{S14}$$

where k_d is the deceleration moment coefficient of the wind cup, which can be expressed as:

$$k_d = k_{d0}[\left(\frac{v_{wind}}{wR}\right)^2 - \lambda_0^2] \tag{S15}$$

Where k_{d0} is the static torque coefficient in the decelerated state of the wind cup.

In addition, regarding the relationship between wind speed and rotational speed, we can usually express it as:

$$n = k_r v_{wind}^{\tau} \tag{S16}$$

where k_r is a constant of proportionality, which depends on the design and calibration of the fan blades, and τ is the power number of the calibrated wind speed.

Regarding the power generation part, the power $P(t)$ of EMG can be expressed as follows:

$$P(t) = n\frac{V^2}{R_e + R_i} = n\frac{[N\frac{d\Phi}{dt}]^2}{R_e + R_i} \tag{S17}$$