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ABSTRACT

We show that a solid-state apparatus with no moving parts can harvest electrical power from the wind. This apparatus, a Solid-state Wind-Energy Transformer (SWET), uses coronal discharge to create negative air ions, which the wind carries away from the SWET. The SWET harnesses the wind-induced currents and voltages to produce electrical power. We report on the operation of a low-power, proof-of-concept SWET. This device consists of a number of parallel electrical wires: "emitter wires," which have numerous, sharp coronal emitters attached to it, and bare "attractor wires." When a negative bias voltage is applied to the emitter wires relative to the attractor wires, the coronal emitters generate negative ions. The wind carries off these ions, which eventually settle to ground. The power imparted to the ions by the wind is extracted from the current returning to the SWET from the ground. This proof-of-concept SWET demonstrates that it is possible to generate net electrical power from the wind using only air ions. We estimate that SWET can be scaled up to commercially interesting powers by increasing the number and length of emitter and attractor wires and by controlling the bias voltage. SWETs have the potential to produce large amounts of electrical power at low costs with little negative environmental impact.

The generation of airflows by ionic currents, "electrohydrodynamics," is well studied and has numerous applications,[1] even including airplane flight.[2] The reverse process, using airflows to create ionic currents, has received much less attention. Until now, no one has generated net electrical power with wind-driven ionic currents. The barrier for producing electrical power by this process is the high mobility of air ions: "the mobility problem." Electric fields pull the ions through the neutral air, creating drift currents that tend to short-out the voltages generated by the wind-driven currents. This mobility problem can be overcome if the apparatus is designed such that the electric fields are sufficiently weak so that the wind largely controls the ion motion.

The traditional approach for producing electrical power from the wind via mechanical turbines has well-known shortcomings: wind turbines require massive supporting structures and regular maintenance. Additionally, they are highly visible, generate noise, and negatively impact some wildlife. This letter shows that the harvesting of wind energy through wind-driven ionic currents has the potential to be a cost-effective and environmentally benign technology that avoids these problems.

The Solid-state Wind-Energy Transformer (SWET) described here is a type of electrostatic wind energy converter (EWEC). EWECs generate electrical power when the wind moves charges.[3] Recent efforts in EWECs have concentrated on using aerosols (typically water droplets) to carry the electrical charge.[4–6] Aerosol-based EWECs have the advantage that the charged droplets couple strongly with the air and are readily transported by the wind,[7] mitigating the mobility problem. However, aerosol-based devices require continuous sprays of droplets or particles, and this extra complexity adds to their costs and limits their usefulness. For example, a system based on water droplets would be problematic in freezing conditions.

An EWEC that uses only charged air molecules or air ions can be less complicated and more reliable. However, early suggestions for ion-based EWECs[8] had not led to any demonstration of net electrical power generation. Here, we report on the performance of an ion-based EWEC, a SWET, which produces net electric power. This unit demonstrates that there are no physics barriers to using negative air ions to produce electrical power from the wind. The simplicity of this low-power apparatus suggests that SWETs could be scalable to commercially interesting powers.

The general principles of a SWET are illustrated in Fig. 1. The oval in the center of the figure represents the ion-generator portion of the SWET. The ions are produced by coronal discharges, which require some input power, as indicated. To produce net power, the wind-generated power has to exceed that expended in producing the air ions. The negative air ions (indicated by green circles with the minus sign) are transported by the wind, eventually settling to ground. The removal of negative charge from the SWET hardware leaves behind a positive charge and hence a positive voltage V_{load} relative to ground. The returning (negative) ground current passes through the "output load," generating the useful electrical power.

Ion leakage, indicated in the lower left of the figure, decreases the energy generation in SWETs. When V_{load} becomes large, various points or irregularities on the ground (represented by the triangles on the lower-left of the figure) produce negative air ions by coronal emission. These ions drift toward the SWET, creating "leakage currents" that partially short-out V_{load} and limit the generation of useful power.

To understand how the "mobility problem" affects the design of a SWET, consider the electric field just outside the ion generator, the oval in Fig. 1. If the ion generator is at voltage V_{load}, the electric field at the edge of the generator that opposes the removal of the ions has magnitude $E \approx 2V_{\mathrm{load}}/H$; here, H is the characteristic linear scale of the ion-generator. The drift velocity $\boldsymbol{v}_{drift}$ of the ions toward the SWET is $\boldsymbol{v}_{drift} = \mu \boldsymbol{E}$, where μ is the mobility for negative air ions; $\mu = 2.7 \times 10^{-4}\,\mathrm{m}^2\,\mathrm{s}^{-1}\,\mathrm{V}^{-1}$.[9] In order for the SWET to generate power, the wind velocity $\boldsymbol{v}_{wind}$ must be strong enough to overpower this drift of the ions through the air; that is, the wind velocity must be greater than the drift velocity. The condition $\boldsymbol{v}_{wind} > \boldsymbol{v}_{drift}$ gives an upper limit on the voltage induced by the wind

$$V_{\mathrm{load,max}} = \frac{H v_{\mathrm{wind}}}{2\mu} = 1.9 H v_{\mathrm{wind}}\,\mathrm{kV}, \tag{1}$$

where H is in meters and v_{wind} is in m/s.

We tested the basic concepts of SWETs, by building and characterizing a low-power, proof-of-concept unit that produces negative ions through coronal emission. The ion-generator portion of the unit consists of 55 parallel, 17-gauge, aluminum wires strung between two 8.5-m tall wooden masts, separated by about 8 m on a flat roof. All the wires are electrically isolated from the masts. Twenty of the wires, the emitter wires, have small tufts of 7-micrometer diameter carbon fibers (Torayca T700G) attached about every 15 cm. These small diameter fibers act as coronal emitters. The other 35 wires, the "attractor wires," are bare. To produce negative ions, we bias the emitter wires with a negative voltage V_{bias} relative to the attractor wires. When V_{bias} is large enough, the strong electric fields form at the tips of the carbon fibers, producing coronal emission and generating negative air ions.[9–11]

The upper right of Fig. 2 shows the wiring for one emission wire and two adjacent attractor wires. A battery-powered *UltraVolt* 40A12-N4 power supply (1-W maximum power) biases the emitter wires relative to the attractor wires. The case of this power supply floats at the voltage of the attractor wires and is electrically isolated from ground. The resistance R_{load} is a proxy for the output load; the power dissipated in R_{load} represents the output power. The resistance R_{leak}(shown by the dotted line) represents the path of the unavoidable leakage current.

The left side of Fig. 2 shows the arrangement of the 55 wires of the SWET unit. We found that having two attractor wires between each pair of emitter wires, rather than one, produced more power. However, we have not evaluated the many possible wire arrangements, and the one shown here is not optimized. The physical characteristics of the proof-of-concept SWET unit are summarized in Table I.

To characterize the expected performance of the proof-of-concept SWET, we measured the leakage current I_{leak} by applying positive voltages V_{load} to the attractor wires, while the load circuit was open ($R_{load} = \infty$). Figure 3 shows a plot of $I_{leak}{}^{1/2}$ vs V_{load}. The straight dashed line shows that the leakage current increases approximately quadratically with V_{load} above a threshold of around 10 kV; this quadratic dependence suggests that the leakage current is due to coronal emission[11] rather than some conductive path. The solid curve shows the load current that flows through the 5 G Ω resistor that is used for R_{load} vs V_{load}. We see that for $V_{load} < 20$ kV, the leakage current is relatively small compared to the load current. At higher load voltages, the leakage current would be larger and thus impair the power generation of the SWET. In a

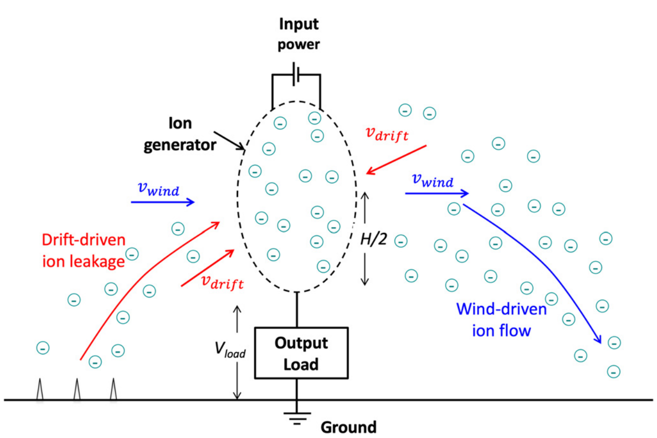

FIG. 1. Schematic of a solid-state wind-energy transformer.

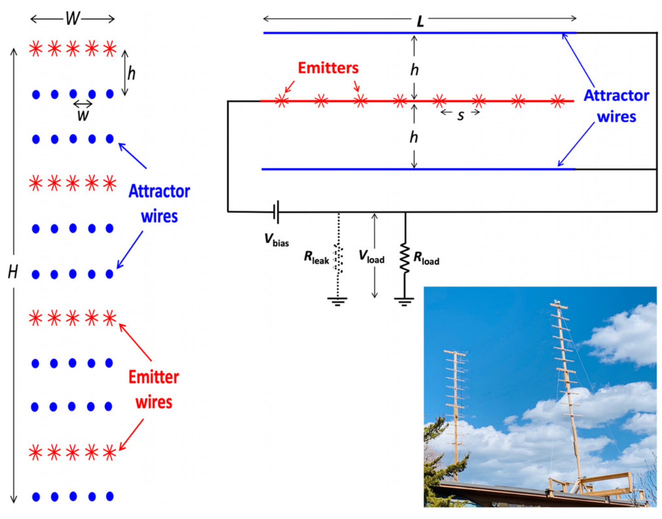

FIG. 2. The wiring of the emitter and attractor wires. The upper right panel shows spacing s of emitters on the emitter wires and the separation h between adjacent emitter and attractor wires. The left panel shows the edge-view of the emitter and attractor wires displaying how they are spaced relative to each other. The photo of the rig on the lower right shows the supporting masts; the thin emitter and attractor electrode wires that run between the masts are faint and may not be visible.

TABLE I. Physical characteristics of the proof-of-concept SWET unit.

Height of masts	8.5 m
Length of emitter and attractor electrodes, L	7 m
Height of the electrode array, *H*	5 m
Depth of the electrode array, *W*	1 m
Distance between emitter and attractor electrodes, *h*	50 cm
Distance between the same-voltage electrodes, *w*	25 cm
Average separation between emitters, *s*	15 cm
Number of emitter electrodes	20
Number of attractor electrodes	35

high-power SWET, the load current would be much larger, and the leakage current is expected to be relatively less important.

The bias voltage $V_{\rm bias}$ has to be large enough to generate coronal emission, but small enough so that the ions are not trapped by the electric field between the emitter and attractor wires. The average electric field between the emitter and attractor wires is $\langle E_{bias}\rangle = V_{bias}/h$. The wind can pull the ions away from the SWET electrodes if $v_{\rm wind} > \mu\langle E_{bias}\rangle$ or

$$v_{\rm wind} > \frac{\mu V_{\rm bias}}{h} = 3.8\left(\frac{V_{\rm bias}}{7\,{\rm kV}}\right)\left(\frac{h}{0.5\,{\rm m}}\right)^{-1}\frac{\rm m}{\rm s}. \qquad (2)$$

This condition sets a threshold wind velocity for the operation of the proof-of-concept SWET.

To characterize the performance of the low-power SWET, we measured the current emitted in negative ions $I_{\rm emit}$ and the return current $I_{\rm load}$ through a 5 GΩ load resistor for various wind speeds. We set the bias voltage at $V_{\rm bias} = 7$ kV and used an AcuRite 02064 Wireless Weather Station to measure the wind velocity.

The net voltage generated by the SWET is the load voltage minus the bias: $V_{\rm net} = V_{\rm load} - V_{\rm bias}$. The top of Fig. 4 shows measurements of $V_{\rm net}$ against the wind velocity perpendicular to the SWET wires. The proof-of-concept SWET device readily produced load voltages several times the bias voltage for perpendicular wind velocities above 6 m/s.

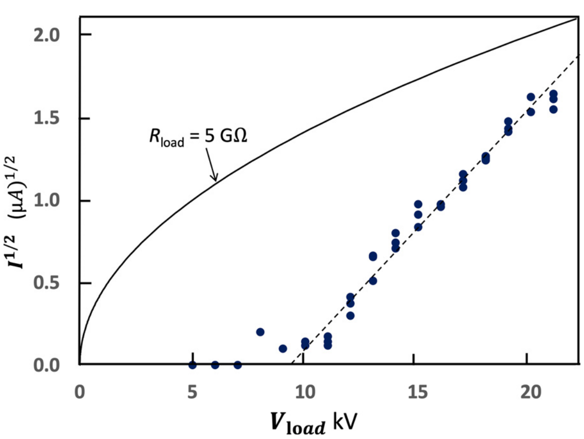

FIG. 3. The square root of leakage current is shown vs the load voltage. The smooth curve is the current through the 5 GΩ load resistor.

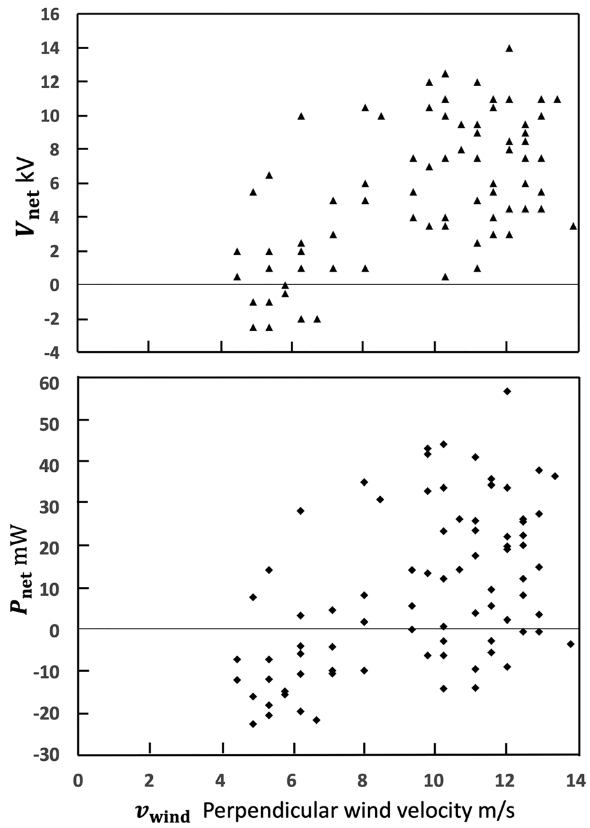

FIG. 4. Top: the net voltage $V_{\rm net}$ generated by the demonstration SWET vs the perpendicular wind velocities $v_{\rm wind}$ when the bias voltage is $V_{\rm load} = 7$ kV, and the load resistance is 5 GΩ. Bottom: the net power $P_{\rm net}$ for the same parameters.

The net power generated by the low-power SWET is the power deposited in the load resistor minus that required to produce the negative air ions

$$P_{\rm net} = \frac{V_{\rm load}^2}{R_{\rm load}} - I_{\rm emit}V_{\rm bias}, \qquad (3)$$

where $I_{\rm emit}$ is the total current emitted as negative ions. We ignore the inefficiencies in the power source since they could be mitigated by using highly efficient power electronics. The bottom of Fig. 4 shows $P_{\rm net}$ vs the perpendicular wind velocity. These data demonstrate net power generation by wind-driven air ions. The highest powers produced, around 50 mW, correspond to a power density of 50 mW/(LHW) = 1.4 mW m^{-3}.

We chose a load resistance of $R_{load} = 5$ GΩ to roughly optimize the output power. Since the voltage across the load is limited by the wind velocity [Eq. (1)], a much larger R_{load} would decrease the load power as $V_{\rm load}^2/R_{\rm load}$. On the other hand, coronal emitters are current limited,[11] and so load power is limited by $I_{\rm emit}{}^2R_{\rm load}$ and falls if R_{load} is too small.

In Fig. 4, the trends of the increase in $V_{\rm net}$ and $P_{\rm net}$ with wind velocity show considerable scatter for several reasons. Since the winds were generally gusty, the data are necessarily noisy. Additionally, the paucity of voltages above $V_{\rm net} = 13$ kV can be due to the large leakage currents, when $V_{load} = V_{\rm net} + V_{\rm bias}$ exceeds about 20 kV (see Fig. 3). The lack of positive values of $V_{\rm net}$ at low wind velocities is likely due to capture of the negative ions by the attractor wires near or below the threshold wind velocity, given by Eq. (2).

The low-power, proof-of-concept SWET shows that wind-driven air ions can generate electric power. Since the main components of the SWET are simply emitter and attractor wires, the SWET concept may be scalable to much higher powers by increasing the number and length of wires. A high-power SWET would have much lower load impedance, so that the leakage current could be relatively unimportant. Also, increasing the effective scale H creates larger net voltages; see Eq. (1).

The power that can be produced by the high-power SWET is roughly equal to the wind-induced voltage $V_{\rm load}$ times the total current produced by all the emitter wires; the input power for producing air ions would be relatively small and is neglected in the following power estimates. To assess the power that could be generated in large-scale SWET, we consider a large network of emitter and attractor wires similar to that indicated in Fig. 2, but with larger overall dimensions (H, W, and L) and smaller spacings, i.e., $s \ll h$ and $w \ll h$.

The emitted ion current density is the charge density times the ion velocity. As a first approximation, we neglect the effects of the wind, and so the currents drifting from the emitter wires to the attractor wires are largely one dimensional, except near the individual emitters, where the equipotential surfaces sharply curve around the tips of the emitters. In this approximation, the current density J_{emit} per unit area in most of the region between the emitter wires and the attractor wires is

$$J_{emit} = \rho\, v_{\rm drift,bias} = \rho \mu E_{\rm bias}, \tag{4}$$

where ρ is the charge density. The bias voltage is

$$V_{\rm bias} = \int_0^h E_{\rm bias}\, dz, \tag{5}$$

and the charge density of the air ions is given by Poisson's equation

$$\rho = \varepsilon_0 \frac{dE_{\rm bias}}{dz}, \tag{6}$$

where ε_0 is the vacuum permittivity. Since J_{emit} is independent of the distance z from the emitter wires, the solution to these equations is

$$E_{\rm bias} = \frac{3V_{\rm bias}}{2h}\left(\frac{z}{h}\right)^{\frac{1}{2}} \tag{7}$$

and

$$J_{\rm emit} = \frac{9\,\varepsilon_0\,\mu\, V_{\rm bias}^2}{8h^3}. \tag{8}$$

This estimate of the current density in the absence of wind gives a lower limit to the actual current density. If the wind velocity is comparable to or larger that the drift velocity $v_{\rm drift,bias}$ between the electrodes, the charged ions would escape more quickly than indicated in Eq. (4). The current density of Eq. (8) is thus a lower limit to the actual current density. To be conservative, we ignore this wind-induced current enhancement. The total current produced by a high-power SWET is the total effective area of emitters times current density J_{emit} [Eq. (8)]. For a high-power SWET of width W, height H, and length L, the total current-producing area of emitters is $A_{tot} = (2/3)WHL/h$, and the total current is $I_{\rm SWET} = A_{tot}J_{emit}$.

We take the load voltage to be $V_{\rm load} \equiv \alpha\, V_{\rm load,max}$, where α is a voltage efficiency factor. By comparing Eq. (1) with the upper panel of Fig. 4, we estimate that $\alpha \approx 0.2$ for the proof-of-concept SWET. In an optimized high-power SWET, the bias voltage $V_{\rm bias}$ would be as large as possible, to maximize the current density $J_{\rm emit}$, while still being small enough so that the negative air ions could escape the SWET, i.e., $V_{\rm bias} \approx v_{\rm wind} h/\mu$ [see Eq. (2)]. With this estimate for $V_{\rm bias}$, the power of a large-scale SWET is $P_{\rm SWET} = I_{\rm SWET}\, V_{\rm load}$,

$$P_{\rm SWET} = \frac{3\,\alpha\,\varepsilon_0\, v_{\rm wind}^3\, WH^2L}{8h^2\mu^2}$$
$$200\,\alpha\left(\frac{v_{\rm wind}}{10\,{\rm m/s}}\right)^3\left(\frac{h}{0.5{\rm m}}\right)^{-2}\left(\frac{W}{5{\rm m}}\right)\left(\frac{H}{15{\rm m}}\right)^2\left(\frac{L}{\rm km}\right)\,{\rm kW}. \tag{9}$$

The high-power SWET generates a moderate amount of power per km. If α was only 20%, the SWET would generate about 40 kW per km [for the fiducial values of Eq. (9)]. To produce MWs of power, a SWET system could stretch over many km or have many shorter segments. An extended power source would provide opportunities for balancing the power generation in response to local weather conditions or power requirements.

The estimate of $P_{\rm SWET}$ in Eq. (9) assumes that the SWET does not significantly impede the wind flow. This assumption is valid if the SWET extracts only a small fraction of the available wind power. The available power density in the wind is limited by conservation laws to the Betz limit:[12] $P_{\rm Betz} = (8/27)\,\rho v_{\rm wind}^3$. Comparing the Betz limit with Eq. (9) gives the constraint

$$\frac{P_{\rm SWET}}{P_{\rm Betz}} \approx 0.04\,\alpha\left(\frac{h}{0.5{\rm m}}\right)^{-2}\left(\frac{W}{5{\rm m}}\right)\left(\frac{H}{15{\rm m}}\right) \ll 1. \tag{10}$$

For dimensions near the fiducial values considered here, this inequality is well satisfied. Since the SWETs do not greatly disturb the wind flow, many SWET units can be located near each other, allowing for high-power-density SWET wind farms.

The low-power, proof-of-concept SWET described here proves that devices of this type can extract electrical power from the wind through ionic currents. There do not appear to be any fundamental obstacles to scaling up this technology to high powers. Large-scale SWETs hold the potential of being significant sources of low-cost electrical power with few environmental downsides.

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