Energy Harvesting

Nature of Power Generation and Output Optimization Criteria for Triboelectric Nanogenerators

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Triboelectric nanogenerators (TENGs) are in the forefront of next-generation energy harvesting technologies, having been demonstrated as a leading candidate for numerous applications in energy harvesting and self-powered sensing. However, critical parameters affecting TENG output behavior and their optimization are not well understood. Herein, for the first time, the power output characteristics of TENGs are fully unveiled by rigorously analyzing their impedance behavior as a function of excitation source and device parameters. In this paper, Norton’s theorem, first presented in 1926 for two terminal linear electrical networks, is extended to represent TENGs, allowing accurate visualization of their dynamic power output behavior via small signal analysis. TENG impedance plots are introduced to accurately determine the peak power point of a given design, which holds paramount importance in understanding and improving TENGs. The knowledge with empirical understanding for these variations results in the design and construction of more efficient TENG devices for future applications.

1. Introduction

Scavenging energy from ambient sources such as sunlight,[1–3] heat,[4] and mechanical motion[5] is a key research area, targeted at powering next-generation mobile and portable electronic devices. Triboelectric nanogenerators (TENGs) are an emerging mechanical energy harvesting technology,[6–15] with potential applications in the areas of energy harvesting and self-powered active sensing.[8–11,16] TENGs contain many advantages over other energy harvesting technologies including simple construction, low cost, high power output, and flexible and wearable properties, among others. Achieving efficient conversion of mechanical input into electrical output is critical in designing these energy harvesters,[8,17,18] which depends on the electric field behavior of constituent TENG layers.[14,15] However, the power transmitted from the TENG to an external load depends largely on its internal impedance characteristics.[18–20]

A TENG is composed of at least one nonconductive triboelectric surface; hence, its internal impedance is significantly high.[14,21,22] This impedance can further increase during the movement of triboelectric layers due to the gap formed between contact surfaces.[14] Consequently, the optimum power extraction from a TENG via an external load can only be obtained through high load resistances,[14,19,22–27] which complicates the requirements of a majority of practical applications.[21] Therefore, a large proportion of potentially usable power may be wasted due to impedance mismatch, or sacrificed in power management circuits and transformer components, which are arguably the main drawbacks of triboelectric energy harvesting.[10,21,28,29] Gaining a better understanding of the energy conversion and power transmission characteristics based on the impedance behavior is hence a key challenge in designing optimized TENGs.

Herein, we present a comprehensive analysis by modeling and verifying the power generation characteristics of a vertical charge polarization TENG (VCPTENG), based on the distance-dependent electric field (DDEF) concept.[14,15] Electronic network theorems[30,31] are used to accurately describe the transfer of power from the TENG to an external load. A systematic study is carried out on optimization strategies for the structural and motion parameters of TENGs, to maximize their output power.

2. Theory

2.1. Energy Generation of TENG

The working mechanism of TENG is based on the triboelectric effect; separation of static charges between two contacting surfaces,[12–15] coupled with electrostatic induction resulting from the movement of such charged layers, to convert mechanical motion into electricity.[14,19] The origin of the triboelectric effect is attributed to electron,[14,15] ion,[33] or
charged materials[32], transfer, or a combination of these factors.[36] Triboelectric surface charge density ($\sigma_T$) increases and saturates after several contact–separation cycles of TENG layers,[36,37] and remains unchanged for long periods of time.[23,32,36] Compared to the applications of a practical TENG, this initial charging period is considered negligible.[14,19,23,24,27] Therefore, similar to previous theoretical models, we assume triboelectric charges at their saturated stage (after initial dynamic period), evenly distributed with a charge density of $\sigma_T$ (with opposite polarities on the two contact surfaces), which remain unchanged during TENG operation.[14,15,19,23,24,27]

Triboelectrically charged layers are finite in size; therefore, the magnitude of the electric fields generated by these layers decays with the distance from the charged surface, as suggested by the DDEF model.[14,15] Considering a charged layer with length ($L$), width ($W$), and surface charge density ($\sigma$), the average electric field along an axis perpendicular to its surface ($E_x$) is given by

$$E_x = \frac{\sigma}{\pi \epsilon} \arctan \left( \frac{L/W}{2(x/W)^2 + (L/W)^2 + 1} \right)$$

where $x$ is the distance from the charged layer and $\epsilon$ is the permittivity of the medium in which the electric field propagates.[14,15] Magnitude of $E_x$ drops rapidly as $x$ increases (Figure 1a).

The distance-dependent electric field equation (Equation (1)) can be used to accurately model the output characteristics of a multilayer VCPTENG with $m$ being triboelectrically charged surfaces (Figure 1b), as discussed in our previous work[15] (Note S1, Supporting Information). When a load with an impedance $Z_L$ is connected, the output behaviour of the TENG is described using

$$LWZ_L \frac{d\sigma_u(t)}{dt} + \frac{\sigma_u(t)}{\pi} \left( \frac{1}{\epsilon_a} + \frac{1}{\epsilon_b} \right) \int_{0}^{\infty} f(x) \, dx - \frac{\sigma_T}{\epsilon_a} \int_{x_a}^{\infty} f(x) \, dx - \frac{\sigma_T}{\epsilon_b} \int_{x_b}^{\infty} f(x) \, dx = 0$$

where $\sigma_u(t)$ is the output charge density at time $t$, $\epsilon_a$ and $\epsilon_b$ are dielectric constants, $y$ is the separation between the electrodes, $x_{a,i}$ and $x_{b,i}$ are distances from the $i$th charged surface to respective electrodes. $\sigma_T$ is the triboelectric charge density of the $i$th triboelectrically charged surface.

To simplify the discussion, we define

$$G(t) = \frac{1}{\pi} \left( \frac{1}{\epsilon_a} + \frac{1}{\epsilon_b} \right) \int_{0}^{\infty} f(x) \, dx$$

$$F_i(t) = \frac{1}{\pi} \sum_{i=1}^{m} \left( \frac{\sigma_T}{\epsilon_a} \int_{x_{a,i}}^{\infty} f(x) \, dx \right)$$

$$F_i(t) = -\frac{1}{\pi} \sum_{i=1}^{m} \left( \frac{\sigma_T}{\epsilon_b} \int_{x_{b,i}}^{\infty} f(x) \, dx \right)$$

Moreover, $LW\sigma_u(t) = Q_u(t)$, where $Q_u(t)$ is the output charge at time $t$. Hence, Equation (2) can be represented as

$$Z_L \frac{dQ_u(t)}{dt} + L W Q_u(t) = G(t) = F(t) + F_i(t)$$

The DDEF model power output equation (Equation (3)) is used to estimate the impedance characteristics of the TENG, by comparing with circuit-element-based previous TENG models.

![Figure 1](image-url)

**Figure 1.** a) The distance-dependent variation of the electric field against the increasing distance from its surface for a finite sheet (indicated by Equation (1)), where $L = W = 50$ mm, $\epsilon = \epsilon_0$, $\sigma = 40.7 \mu$C m$^{-2}$. b) Schematic illustration of a VCPTENG with $m$ triboelectrically charged surfaces. c) Previously accepted circuit representation[19] of TENG power generation. d) Circuit model representation of TENG power generation using Norton’s equivalent circuit.
presented in the literature. The previous theoretical models suggest a structure similar to Equation (3), stating

\[ K \frac{dQ(t)}{dt} + \frac{Q(t)}{C(t)} = V(t) \tag{4} \]

where each term of Equation (4) represents a unique circuit element, including a time-varying voltage source \( V(t) \), time-varying capacitor \( C(t) \), and external load \( R \) (Figure 1c). Considering Equations (3) and (4), the second term of Equation (3) is comparable to the capacitive element of the previous model. However, we note that Equation (3) deviates from the parallel-plate capacitor behavior due to the distance-dependent nature of its electric fields; therefore, we define the term effective capacitance \( K(t)_{\text{eff}} \) such that

\[ K(t)_{\text{eff}} = \frac{LW}{G(t)} = \left[ \frac{1}{LW} \left( \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} \right) \int_0^L f(x) \, dx \right]^{-1} \tag{5} \]

\( K(t)_{\text{eff}} \) is used to estimate the impedance behavior of the TENG under following assumptions. Considering the commonly used motion profile for TENG characterization and ease of calculations, a sinusoidal input motion is approximated with a frequency \( \omega \) for a given motion profile (see the Experimental Section). Similar to previous work, considering the magnitude of impedance at given time \( t \), and for relatively low frequencies (<1000 Hz), the internal impedance of the VCPTENG at time \( t \) \( (Z_i(t)) \) is defined as:

\[ Z_i(t) = \frac{1}{2\pi n K(t)_{\text{eff}}} = \left( \frac{1}{2\pi n L W} \left( \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} \right) \int_0^L f(x) \, dx \right) \tag{6} \]

A detailed comparison of this derivation is provided in Note S2 (Supporting Information).

### 2.2. Power Transmission of a VCPTENG

Considering the equivalence of Norton's theorem for a linear two-terminal system, the TENG (Figure 1b) is represented as a combination of a time-varying current source \( I_s(t) \) and TENG impedance \( Z_i(t) \), as both depend on the movement of TENG layers. The external load is represented as an impedance element \( Z_L \) connected in parallel with \( I_s(t) \) and \( Z_i(t) \). The current generated by the TENG is split between \( Z_i(t) \) and \( Z_L \), such that

\[ I_L(t) = \frac{I_s(t)}{Z_L} Z_i(t) \tag{7} \]

where \( I_L(t) \) represents the output current through \( Z_L \) at time \( t \). Considering the practical applications of TENGs and ease of calculations, \( Z_L \) is treated as purely resistive for the scope of this paper.

As per Equation (7), \( I_L(t) \) depends on \( I_s(t) \), and the characteristic impedance ratio (referred to as \( r \)-ratio) given by \( Z_i(t)/(Z_s(t) + Z_i) \), both of which are unique for a TENG. The power output at time \( t \) \( (P_{\text{out}}(t)) \) is estimated using

\[ P_{\text{out}}(t) = I_L(t)^2 Z_L \tag{8} \]

In this paper, the DDEF model is used to predict the power output of TENGs while Norton's equivalent TENG representation (Equation (7)) is used as a tool to decouple the TENG output into current and impedance elements, to easily understand the reasoning behind the time-varying output trends. While Equation (7) represents an unconventional expansion of the TENG impedance concepts, there is a significant match between the predictions made using Equation (7), with DDEF model predictions and experimental outputs, as evident from the Results and Discussion section. Therefore, the DDEF model and Equation (7) are used simultaneously to assess the output characteristics of VCPTENGs.

Furthermore, a comprehensive analysis on the derivation of the Norton's equivalent circuit and its comparison with the conventional circuit model is presented in Note S2 (Supporting Information).

### 3. Results and Discussion

#### 3.1. Evaluation of the TENG Power Transfer Equation

TENG power transfer equation (Equation (7)) was used to predict the output behavior of the TENG (the Experimental Section), under a sinusoidal contact–separation movement. Considering Norton's equivalent circuit (Figure 1d), the source current \( I_s(t) \) is assumed to be represented by the short-circuit current \( I_{sc}(t) \) of the TENG. Hence, from Note S1 (Supporting Information)

\[ I_s(t) = I_{sc}(t) = LW \int \frac{\sigma(t)}{\varepsilon_1} \frac{1}{\varepsilon_1} \int_{x_1}^{x_2(t)} f(x) \, dx + \frac{1}{\varepsilon_2} \int_{x_1}^{x_2(t)} f(x) \, dx \tag{9} \]

For a given contact or separation motion half-cycle, the magnitude of \( I_s(t) \) increases, peaks, and decreases, and the output power follows a similar trend. The maximum output power during a half-cycle movement of the TENG for a given \( Z_i \) is termed as “peak power” in this work, whereas the overall maximum power obtained by comparing the peak power across the relevant range of \( Z_i \) is termed as the “overall global peak power.” A similar convention is followed for other output parameters.

Analysis of the peak output power is commonly used to assess the power generation capability of TENGs and to optimize the impedance matching. However, the average output power is a critical parameter, which represents the power generation capability in real-life applications. An analysis was carried out to compare the trends of peak power and average power outputs of the TENG (Note S4, Supporting Information). The peak power output trends are comparable to average power trends, as discussed in Note S4 (Supporting Information). As evident from Figure S3 (Supporting Information), the load corresponding to overall global peak power results in maximizing the overall global average power. Hence, we note that the analysis conducted in this work using the peak power is representative of the general power output characteristics of the TENG.
The accuracy of the TENG power transfer equation was evaluated by comparing its output power predictions with the corresponding DDEF model\textsuperscript{[14]} outcomes (Figure 2a), where the latter were obtained by directly solving the characteristic power equation (Equation (3)). The predicted peak power from the DDEF model and the TENG power transfer equation show excellent agreement across the range of frequencies ($n = 0.1–1000$ Hz, $H = 1$ mm). Furthermore, the corresponding experimental results ($n = 0.1–10$ Hz, $H = 1$ mm) closely follow the theoretical predictions from both the models (Figure 2b), verifying the accuracy of the TENG power transfer equation and accompanying assumptions. Therefore, considering the simplicity and accuracy of output predictions, Equation (7) is used as a visualization tool to understand and assess the variation of TENG power generation, against different parameters.

The maximum power transfer theorem\textsuperscript{[30,31]} states that the maximum power from an energy source to an external load is transferred when the impedance of the load is equal to the impedance of the source. In the context of a TENG, this suggests the overall global peak power occurs when $Z_L(t) = Z_s$, indicating the i-ratio reaching 0.5. However, since both source current ($I_s(t)$) and TENG impedance ($Z_s(t)$) are time-dependent variables, establishing the peak power transfer criteria becomes complicated. TENG power transfer equation (Equation (7)) is used to overcome this, via the introduction of TENG impedance plots (Figure 2f).

The parameters described in the TENG power transfer equation are plotted in Figure 2c–e, considering a sinusoidal half-cycle movement ($H = 1$ mm, $n = 1$ Hz), for different loading conditions. The source current ($I_s(t)$) remains the same for all three cases; however, changing the load ($Z_L$) causes the i-ratio to vary, and the output current ($I_L(t)$) changes accordingly (Figure 2c–e). As a result, the output power changes (Figure 2a,b). During the overall global peak power that occurs around $Z_L = 1$ GΩ, the peak $I_s(t)$ coincides with the i-ratio of $\approx 0.5$ (Figure 2d), depicting the relationship predicted by the maximum power transfer theorem. The i-ratio corresponding to peak $I_s(t)$ tends toward 1 at smaller $Z_L$ (Figure 2c) and toward 0 when $Z_L$ is large (Figure 2e). These deviations from optimum power transfer condition (i-ratio = 0.5) result in low output power (Figure 2a,b), forming the basis of characteristic three-working-region behavior\textsuperscript{[14,23,24,27]} of TENG power output. A closer analysis on the occurrence of overall global peak power transfer is provided in Note S5 (Supporting Information).

The impedance behavior can be used to devise a visualization method for TENG output power: The TENG impedance plot (Figure 2f), where $I_s(t)$ and the i-ratios (with corresponding $Z_L$ marked) are plotted against time, accurately maps the occurrence of overall global peak power, corresponding $Z_L$, and their variations under different structural and motion parameters.
3.1.1. Factors Affecting TENG Power Generation and Transmission

Generating an electrical output as well as its transmission through external loads is equally important in optimizing TENG output power, as evident from Figure 2. Therefore, optimizing TENG power output is a twofold process: first improving $I_S(t)$ and second enhancing the impedance matching. To achieve the latter for a desired application with impedance $Z_L$, the TENG impedance ($Z_S(t)$) has to be engineered, to move the i-ratio corresponding to peak $I_S(t)$ closer to 0.5. Since TENGs are high impedance devices, it is often desirable to reduce $Z_S(t)$ (without losing output power) to obtain a better matching with typically low impedance practical applications. Developing such optimization strategies warrants an in-depth understanding of the effect of motion and device parameters on TENG power output, which is achieved via the DDEF model, TENG impedance plots, and experimental results. The primary parameters directly affecting the output power (indicated in Equations (2)–(6)) are discussed in detail, along with the secondary factors that could influence these primary parameters.

3.2. Motion Parameters

3.2.1. Frequency

Increasing the frequency ($n$) of the TENG layer movement increases the power output (Figure 2a,b). The overall global peak power increases proportional to $n$ (Figure 3a), whereas $Z_L$ corresponding to overall global peak power shows an inverse proportionality (Figure 3b). This output behavior can be fully explained as follows.

In the DDEF model simulations presented in Figures 2a,b and 3a–d, $n$ is systematically increased while keeping the other parameters constant. Since $H = 1$ mm, the maximum potential difference of the TENG is constant, implying that the maximum output charge is relatively constant. When $n$ is increased, the rate of transfer of these charges increases proportionally as discussed in our previous work, resulting in a corresponding increase in $I_S(t)$. Therefore, according to Equation (9), $I_S(t) \propto n$ (Figure 3c), and hence from Equation (7), $I_L(t) \propto n$. Furthermore, $I_S(t)$ maximizes around $x(t) \approx 170 \mu m$ for different $n$ (Figure 3c). However, $Z_S(t) \propto \frac{1}{n}$ (Equation (6)), hence, $Z_S(t)$ corresponding to maximum $I_S(t)$ (referred to as $Z_{S,\text{optimum}}$) shows this inverse proportionality. The overall global peak power is obtained when $Z_L = Z_{S,\text{optimum}}$ (referred to as $Z_{L,\text{optimum}}$). Hence, $Z_{L,\text{optimum}} \propto \frac{1}{n}$ (Figure 3b). Therefore, from Equation (8), the resultant overall global peak power is proportional to $n$ (Figure 3a). These output trends can easily be visualized by using TENG impedance plots. As an example, the impedance plots for $n = 1$ Hz and $n = 1000$ Hz are represented by Figures 2f and 3d, respectively. Increasing $n$ from 1 Hz (Figure 2f) to 1000 Hz (Figure 3d) significantly increases $I_S(t)$, indicating a higher electrical signal generated at increased $n$. At
the same time, \( Z_{\text{optimum}} \) shows a proportional reduction, when \( n \) is increased. Therefore, TENG impedance plots accurately determine the variation of the impedance, source current, and, hence, the power output, providing guidance toward selecting optimum motion conditions. An analysis was conducted using the DDEF model, for TENG layers separating at a constant velocity from contact, which shows an equivalent output behavior (Note S6, Supporting Information).

As evident from Figure 3a,b, adjusting the input frequency can potentially be utilized to fine-tune the output power produced in the TENG, to suit different applications. Increasing \( n \) improves the power output (Figure 3a) and decreases \( Z_{\text{optimum}} \) (Figure 3b), both of which are desirable in powering practical devices, which are mostly low impedance applications with considerable power consumption.\(^{[21]}\)

In practical applications where the \( n \) of the ambient mechanical motion might be limited due to physical restrictions, frequency enhancement techniques can be suggested to convert low input frequencies into high frequencies, in order to obtain higher output power and to lower \( Z_{\text{optimum}} \). For example, Bhatia et al.\(^{[29]}\) proposed a mechanical system that converts low-frequency input energy into high-frequency (50 Hz) output signals, using a frequency regulator composed of a spiral spring, gear train, cam, and a fly wheel. Similarly, Kim et al.\(^{[44]}\) used a gear train to enhance the frequency of the TENG, obtaining a power output improvement of around seven times. Moreover, cantilever-type structures have been used to convert low-frequency plucking movements into high-frequency oscillations, and to harvest power effectively using other energy harvesting techniques, which we suggest can be adopted for TENGs.\(^{[45]}\) Therefore, appropriate frequency enhancement and regulation techniques can be used to improve the power output performance of the TENG, depending on the applications.

However, it should be noted that the maximum applicable \( n \) is limited by the dielectric losses that could occur at high frequencies (typically > 10 GHz).\(^{[46]}\)

### 3.2.2. Amplitude

The effect of amplitude \( (H) \) of the sinusoidal movement on TENG output power was observed using the DDEF predictions and experimental outputs at \( n = 1 \) Hz (Figure 3e–f). As a general trend, the peak power increases at a decreasing rate when \( H \) is increased. Furthermore, \( Z_{\text{optimum}} \) does not show a pronounced shift for the range of \( H \) used. This output behavior can be understood using the DDEF model and TENG power transfer equation. As reported in our previous work, \( I_H(t) \) increases with a decreasing rate and starts to saturate as \( H \) increases (around \( H = 1 \) mm for the TENG given in the Experimental Section).\(^{[14]}\) Therefore \( I_H(t) \) and the resultant \( I_H(t) \) follow a similar trend causing the peak power of the TENG to vary as depicted in Figure 3e–f. The rate of peak power increment decreases notably after \( H = 1 \) mm for the given TENG.

Determining the optimum \( H \) for a VCPTENG is challenging due to this nonlinear increment of the power output. In optimizing motion conditions for a TENG, or in designing a TENG for given motion conditions, concise guidance on design criteria has not yet been presented. Herein, we suggest that the saturation of peak power against \( H \), coupled with the understanding of TENG layer separations corresponding to the peak power, and the energy transmission related to TENG movement, can be used to define the criteria for selecting the optimum \( H \). A detailed analysis on these optimization criteria for sinusoidal (Section S7.1, Supporting information) and constant velocity (Section S7.2, Supporting information) TENG layer movements is provided in Note S7 (Supporting information).

#### 3.2.3. Contact and Noncontact Motion Regimes

Typically, triboelectric surfaces of a VCPTENG contact during movement cycles, however, some devices are designed to work in a noncontact regime (gap existing between triboelectric surfaces during minimum separation), once they are triboelectrically charged.\(^{[47]}\) The effect of the minimum separation \( (h) \) on triboelectrically charged VCPTENG was analyzed using the DDEF model, where the movement of TENG layers is described using \( x(t) = H \sin(2\pi nt) + (H + h) \) (by default, \( h = 0 \) is used for all the other experiments except for the ones as stated in this section). For the experiments and simulations in this section, \( H = 1 \) mm and \( n = 1 \) Hz were used.

The DDEF predictions (Figure 4a) and experimental results (Figure 4b) indicate that the peak output power decreases when

![Figure 4](https://www.advenergymat.de)
$h$ is increased, whereas $Z_{\text{L, optimum}}$ increases (Figure 4a,b). This output behavior can be understood by comparing TENG impedance plots for $h = 0$ (Figure 2f) and $h = 500$ µm (Figure 4c) scenarios. $I_{S}(t)$ decreases significantly from a peak value of $\approx 430$ to $\approx 150$ nA. The distance-dependent electric fields from the TENG layers decay rapidly at elevated $h$ (similar to Figure 1a); therefore, the induced output charge is relatively low, resulting in a low $I_{S}(t)$. Furthermore, increasing $h$ reduces $K_{\text{eff}}$, causing $Z_{\text{L, optimum}}$ to increase from $\approx 1$ GΩ for $h = 0$ to $\approx 5$ GΩ for $h = 500$ µm, as depicted by TENG impedance plots. Consequently, the output power depletes and $Z_{\text{L, optimum}}$ increases when $h$ is increased, both of which are undesirable in TENG applications. Hence, obtaining sufficient connection between TENG layers during the contact state of contact–separation movement without any air gaps is critical to achieve the highest power outputs and to minimize the internal impedance of TENGs. This observation can be used as one of the key reasons in explaining high output performances of some of the TENG architectures, which utilize conformal polymers such as polydimethylsiloxane (PDMS).[9,17]

Therefore, it is evident that enhancing $n$, improving $H$ up to a threshold, and obtaining proper contact and separation between TENG layers is critical to improve the output power as well as to engineer its impedance favorably.

### 3.3. Device Parameters

Material properties and dimensions of TENG layers play a key role in the output behavior of a TENG. Herein, evaluation of the effect of major device parameters along with their optimization methods is discussed, which is imperative in designing TENGs for different applications.

#### 3.3.1. Material Properties

Triboelectric charge density ($\sigma_T$) depends on the relative position of triboelectric pairs in the triboelectric series,[5-7] structuring of triboelectric surfaces,[40,48] contact area influenced by the applied force,[16,49] and the surrounding environmental factors.[50–52] The DDEF model was used to simulate the power output of the TENG at increasing $\sigma_T$ (Figure 5a-c) under a sinusoidal movement ($n = 1$ Hz, $H = 1$ mm), where device parameters are the same as described in the Experimental Section. Figure 5a depicts the DDEF predictions for peak power, suggesting that the power output increases with increasing $\sigma_T$. This relationship can be explained using the TENG impedance plots. As suggested by Equation (9), $I_{S}(t) \propto \sigma_T$ (Figure 5b). Consider the cases of TENG impedance plots for $\sigma_T = 40.7$ µC m$^{-2}$ (Figure 2f) and $\sigma_T = 407$ µC m$^{-2}$ (Figure 5c). $I_{S}(t)$ indicates a proportional increment when $\sigma_T$ is increased. At the same time, $Z_{S}(t)$ does not vary when $\sigma_T$ is increased, resulting in overall global peak power obtained through $Z_{\text{L}} = 1$ GΩ throughout the range of $\sigma_T$ (Figure 5a). Therefore, from Equations (7) and (8), $P_{\text{out}}(t) \propto \sigma_T^2$ (Figure 5a). This predicted output trend is consistent with the previously reported theoretical predictions[19,23,53] and experimental output trends,[50–52] which suggest that the output power density and triboelectric charge density are quadratically related.
The environmental factors such as humidity, pressure, temperature, and surrounding medium have been shown to affect triboelectric charge density and, therefore, could result in variations in the steady state $\sigma_T$ value. The mathematical quantification of triboelectric charging and the effect of such environmental parameters are still under research. However, under reasonably controlled surrounding, the (saturated) $\sigma_T$ could be assumed as an approximately constant value, which can be estimated by comparing experimental and predicted charge and current outputs, as evident from the experimental work presented in our previous work.

Permittivity of constituent materials affects the electric field propagation across TENG layers and the impedance behavior and, hence, affects TENG power output. The DDEF model was used to predict the output power when the dielectric constant of TENG layer 1 ($\varepsilon_{r,1}$) is increased (Figure 5d), while all other TENG parameters are kept similar to the TENG described in the Experimental Section. The peak power output trends show a notable variation when the dielectric constant is increased, especially at large $Z_l$ values (Figure 5d). The highest output is observed when $\varepsilon_{r,1} = 1$ (Figure 5d), which resembles a TENG in which an electrode placed in free space acts as one of the TENG layers. The peak output power reduces as $\varepsilon_{r,1}$ is increased until a threshold value, and the output trends remain unchanged thereafter (Figure 5d). Moreover, overall global peak power is observed between 1 and 5 GΩ when $\varepsilon_{r,1} = 1$ whereas this is observed between 100 MΩ and 1 GΩ when $\varepsilon_{r,1}$ further increases, indicating a minor shift in $Z_l$ at lower permittivity is significantly increased.

TENG impedance plots can be used to understand these output trends. $I_S(t)$ remains almost unchanged when $\varepsilon_{r,1}$ is increased (Figure 5e). Compare the TENG impedance plots for $\varepsilon_{r,1} = 1$ (Figure 5f) and $\varepsilon_{r,1} = 3.24$ (Figure 2f) as a typical example. Although $I_S(t)$ is constant, $Z_l(t)$ reduces from $\approx 5\, \Omega$ to $\approx 1\, \Omega$ when $\varepsilon_{r,1}$ is increased from $\varepsilon_{r,1} = 1$ (Figure 5f) to $\varepsilon_{r,1} = 3.24$ (Figure 2f), respectively, as evident from Equation (6). Consequently, the power output decreases as a result of increasing the dielectric constant.

Herein, we note that Figure 5d–f represents the impact of change in dielectric constant toward the distance-dependent electric field propagation, and how it affects the power output. In these simulations, the dielectric constant is systematically changed, while all other TENG parameters (such as triboelectric charge density, dimensions and surface properties) are kept constant. However, some of the previous experimental studies have reported relatively different trends for the relationship between the dielectric constant and output power, considering the overall change in triboelectric charge density, surface properties, etc., caused by the addition of high dielectric constant materials to a TENG contact surface. Therefore, a detailed comparison between the predictions shown in Figure 5d–f against previously reported theoretical and experimental results is provided in Note S8.

The material properties including the charge density and dielectric constant are investigated independently in this section, to study their effect on the power output. However, these parameters are interrelated in real-life TENGs. For example, changing $\varepsilon_{r,1}$ of a material might require changing the triboelectric material, which would change $\sigma_T$. Therefore, experimental realization of these predictions is complicated. However, the trends indicated in Section 3.3.1 together with the TENG impedance plots can be used as a guide in the selection of suitable materials for TENGs, while maintaining a balance between these parameters.

### 3.3.2. TENG Dimensions

Thickness of the constituent TENG layers directly affects their electric field propagation and polarization and, hence, influences the power output. PDMS thickness of the TENG (Experimental Section) was increased systematically to observe its effect on the power output (Figure 6a–c). The DDEF model suggests that the peak power decreases when the layer thickness is increased, whereas $Z_l$ decreases (Figure 6a). The experimental results confirm this trend (Figure 6b). When the thickness is further increased, the output power and $Z_l$ tend to saturate and remain almost unchanged afterward (Figure S9, Supporting Information).

This output behavior can be further verified by comparing the TENG impedance plots for PDMS layer thicknesses 20 µm (Figure 2f) and 20 000 µm (Figure 6c). $I_S(t)$ decreases significantly at higher thicknesses, whereas $Z_l$ increases. Consequently, the resultant output power decreases. As suggested by the DDEF model, the electric fields from charged TENG surfaces propagate longer distances at higher layer thickness, to reach respective electrode–dielectric interfaces, where the induction of output charges takes place. This results in reduction of the electric field strength due to their distance-dependent nature (Figure 1a), causing the output power to decrease and the device impedance to increase. However, when the layer thickness is further increased, both $Z_l$ (Equation (6)) and $I_S(t)$ (Equation (9)) tend to saturate (Figure S9, Supporting Information) as the power output becomes comparable to a nonparallel TENG layer scenario, as reported in our previous work. Therefore, lower dielectric layer thicknesses are typically beneficial for TENGs in terms of obtaining a higher power output and reducing their internal impedance. However, other important factors such as the durability of the TENG and the stability of triboelectric charges have to be considered in selecting the minimum thickness of the TENG layers.

The effect of the size of TENG layers was studied by changing the length ($L$) of the TENG (Experimental Section). The case of $L = W$ is selected for the ease of calculations; however, we note that the same methods can be applied for different shapes and nonplanar geometries.

Increasing $L$ increases the surface area of TENG layers, resulting in an increase in the peak output power and reduction of $Z_l$ as indicated by the DDEF simulations (Figure 6d) and the experimental results (Figure 6e). Comparing the TENG impedance plots for $L = 50\, \text{mm}$ (Figure 2f) and $L = 1000\, \text{mm}$ (Figure 6f), increasing $L$ results in a notable increase in $I_S(t)$, whereas $Z_l$ shows an inverse proportionality as described by Equation (6). Therefore, increasing the layer size and surface area not only increases the output power, but also helps to move the overall global peak power toward low $Z_l$ values, both of which are favorable for TENG energy harvesting applications.

The effect of major device and structural parameters on TENG output power is analyzed individually in the above
discussion, to fully understand their output behavior. Guided by the implications of the DDEF model and TENG impedance plots, multiple complementary parameters can be engineered to further enhance the TENG output performances. As an example, Note S9 (Supporting Information) shows simultaneous optimization of $L$ and $n$, aimed at increasing the output power and decreasing TENG internal impedance.

4. Conclusions

A comprehensive analysis on the power output characteristics of VCPTENG has been presented based on Maxwell's equations, supported by experimental results. This work, for the first time, extensively discusses the time-dependent impedance characteristics of TENGs, which are critical in designing and optimizing energy harvesters for different applications. The electronic network theorems are used to construct in-depth understanding of the power transfer from a TENG to an external load, allowing precise visualization of the fundamental output variations via the introduction of TENG impedance plots.

Enhancing frequency, improving amplitude (up to a threshold), and obtaining conformal contact and complete separation between TENG layers are important motion parameters to improve power output of TENGs and to engineer their impedance. On the other hand, increasing the triboelectric charge density and reducing the dielectric constant improves the output power. Furthermore, decreased TENG layer thickness and increased surface area have favorable effects on the output power as well as the impedance behavior. The optimization strategies and limitations for device and motion parameters of TENGs are discussed in detail, paving the roadmap for the design and development of better energy harvesters for future applications.

5. Experimental Section

A VCPTENG was fabricated using PDMS and polyethylene terephthalate (PET) as triboelectric contact surfaces, following methods similar to our previous work.[14] PET sheets with a single-sided conductive layer ($\text{In}_2\text{O}_3/\text{Ag}/\text{Au}$) were used (sheet resistance $<10 \ \Omega \ \text{sq}^{-1}$ and thickness 0.2 mm; Delta Technologies, USA) to fabricate the TENG, after cleaning with acetone, methanol, and isopropyl alcohol. The PET side of the sheet was used as the first triboelectric contact surface.

The second triboelectric surface was prepared by depositing a PDMS layer with the desired thickness, on the PET surface of a similar sheet. Sylgard 184 PDMS (Dow Corning, USA) elastomer and crosslinker were mixed at a ratio of 10:1, degassed under vacuum, and spin coated on the PET side of the sheet, which was then cured at 90 °C for 30 min. In general, a PDMS thickness of 20 $\mu$m was obtained by spin coating the mixture at 3000 rpm for 30 s (apart from the thickness variations described in Section 3.3.2, where multiple spin coating cycles were used to increase the thickness). The PDMS-coated layer consists of length ($L$) = 50 mm, width ($W$) = 50 mm, and thickness ($T$) = 0.22 mm, whereas for the PET contacting surface these values were $L$ = 50 mm, $W$ = 50 mm, and $T$ = 0.2 mm. A schematic representation of the device and the layer arrangement is summarized in Note S3 (Supporting Information). The material system and device architecture described above were targeted to obtain consistent outputs using a simple TENG structure, involving simple fabrication techniques, in order to test the accuracy of the predictions from the proposed theoretical models.

Figure 6. a) DDEF simulations and b) experimental results for the peak output power, at increasing PDMS layer thicknesses. c) TENG impedance plot for the PDMS layer thickness = 20 000 $\mu$m. d) DDEF simulations and e) experimental results for the peak output power at increasing $L$. f) TENG impedance plot for $L$ = 1000 mm. Sinusoidal motion profile with $n = 1 \ \text{Hz}$, $H = 1 \ \text{mm}$ was used for (a)–(f). Error bars indicate the standard deviation of ten readings.
The TENG layers were contacted and separated using a bespoke linear motor setup (Note S3, Supporting Information).[4–15] The charge and the voltage outputs were measured using a Keithley 6517B electrometer, whereas the current measurements were conducted using a Keithley 6487 picoammeter.[4–15] The test procedure was identical to that used in our previous work,[4–15] as described in Note S3 (Supporting Information).

The output simulations were conducted using the DDEF model[4–15] and further explained using the TENG power transfer equation (Equation (7)). The device parameters used for the simulations were identical to that described in Note S3 (Supporting Information), unless otherwise stated. Typically, the contact–separation movement of the TENG layers was achieved through sinusoidal motion profiles described by $x(t) = H \sin (2\pi t + (3\pi/2)) + H$, where $x(t)$ is the separation of TENG layers at time $t$, $H$ is the amplitude, and $n$ is the frequency of the movement, unless otherwise stated.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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