Environmental life cycle assessment of CO_2-filled triboelectric nanogenerator toward Carbon Neutrality

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Supporting information Note 1

Figure S1 shows the breakdown strength of CO_2 at different gap distance based on the Paschen's law.[9] It can be observed that the breakdown strength of CO_2 at 10 atm is higher than the breakdown strength of CO_2 at 1 atm, indicating the breakdown is more difficult to take place. So, in the manuscript, our idea is to suppress breakdown effect by increasing gas pressure of TENG based on the above mentioned principles, thereby increasing the electric output to offset more carbon emissions.

It is not the voltage but the electric field strength that causes air breakdown, and the breakdown strength of air is approximately 3×10^6 V/m under atmospheric pressure.[1] Figure R4 shows the potential and electric field distribution of TENG under open-circuit with the surface charge density of 10 nC/cm^2. It can be seen that the voltage of TENG can reach thousand volts (Figure S2A-S2C). During the moving process, TENG is easily to form a very high local electric field of 10^7 V/m level. (Figure SDd-2F), which far exceeded the breakdown strength of air. Therefore, TENG can easily induce air breakdown under atmospheric pressure. More discussion about breakdown of TENG also can be obtained from those papers. [2-4]

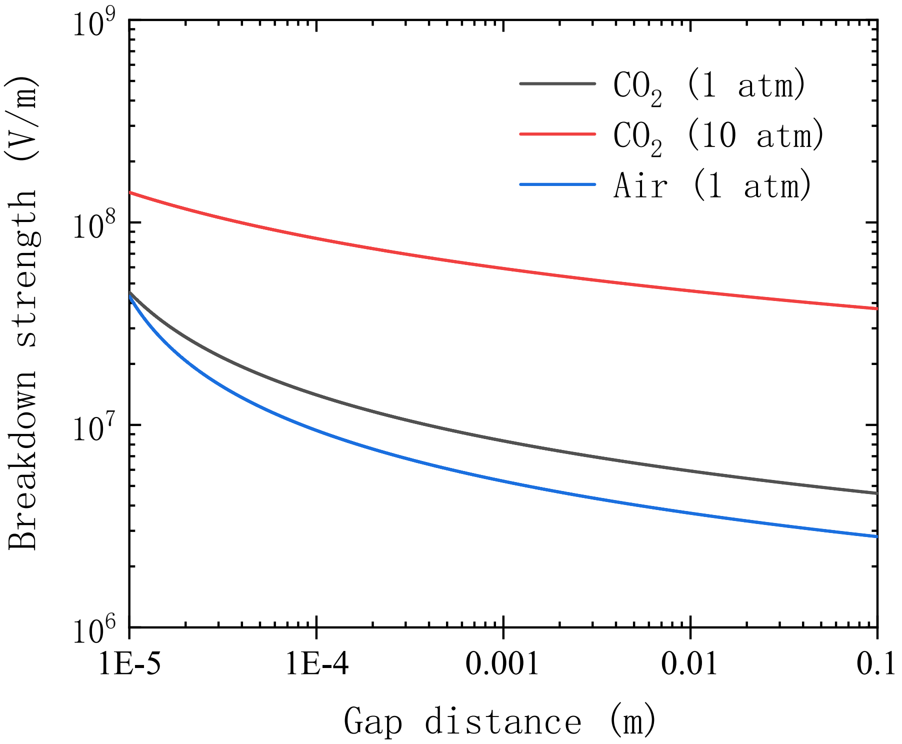


Figure S1. Paschen curves obtained from air and CO_2 under different gap distance.

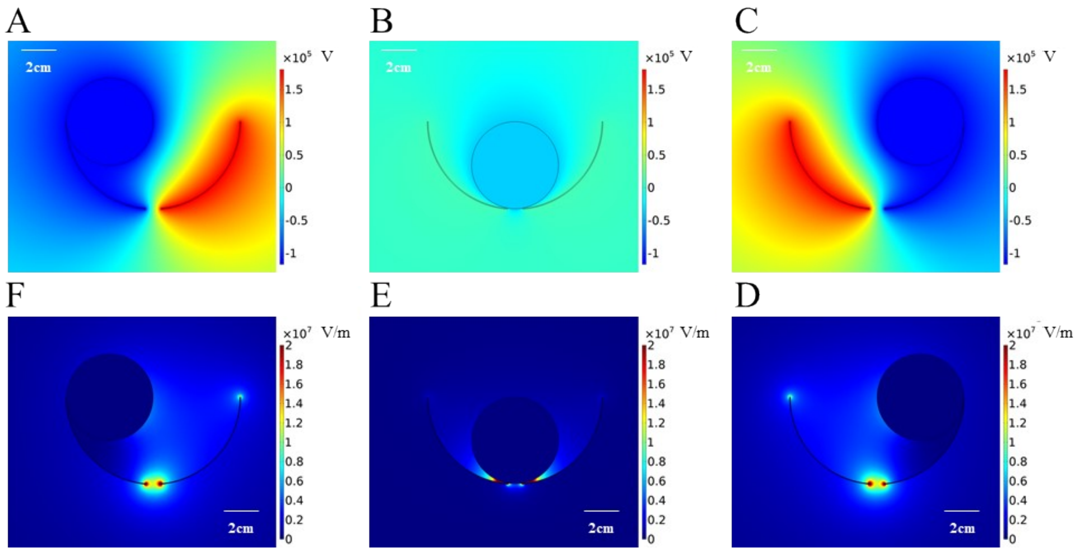
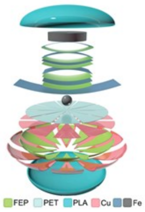
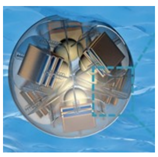
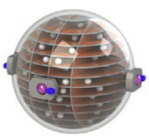
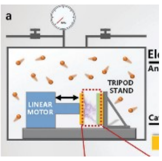
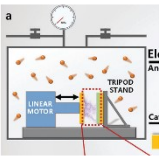


Figure S2. Potential and electric field distribution of TENG. (A-C) Potential difference of TENG when the inside ball is on the left. middle and right positions. (D-F) electric field distribution of TENG when the inside ball is on the left, middle and right positions.

Supporting information Note 2

Here, we summarize the output performance of some related works for harvesting ocean energy based on spherical TENG in Table R1.[5-11] There is still a certain difference between its output performance and our theoretical calculation results, but it also proves that TENG still has huge room for improvement in terms of output.

Demo	Voltage （V）	Current (μA)	Charge （nC）	Radious （cm）	Equivalent Average Power Density （W m^{-3}）	Reference
	350V	5	500	3.5	4.2	[5]
	281	76	270	6	0.085	[6]
	32.2	8.2	-	4	0.065	[7]
	7.6	0.74	27	65	0.012	[8]
	280	120	1000	7.5	2.4	[9]
	3000	5	550	3.3	8.69	[10]

 1 Atm	1000	4.6	100	Square type(2 cm × 2 cm)	39(theoretical)	[11] and this work
 10 Atm	8000	8	175	Square type(2 cm × 2 cm)	1021(theoretical)	[11] and this work

Supporting Information Note 3

Methods Section

1, effective maximized energy output E_{em}

In Figure 3S, we take SFT mode TENG as an example. Firstly, the red line represents the cycles for maximized energy(CMEO), which is the maximum energy TENG can theoretically output in each working cycle. However, due to the breakdown effect, voltage of TENG cannot go to very high without limitation. When the voltage of TENG is higher than the breakdown line, breakdown occurs, and some charge is released (yellow region). So the effective maximized effective energy output per cycle E_{em} can be defined as the area of CMEO subtracting the breakdown area in each figure. Then the volumetric energy density equals to the maximized energy divided by volume of TENG.

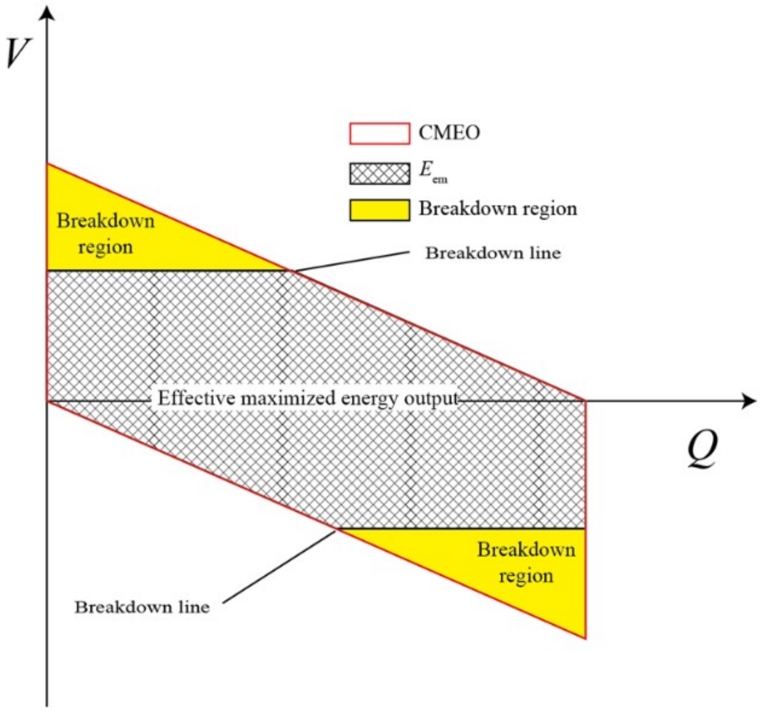


Figure S3. E_{em} and CEMO demonstrating in Q−V plots of SFT mode TENG

2, LCA analysis

In LCA, the environmental impacts of product are qualified through inventory of the energy and materials that required across the industry value chain，which is listed in Table 1. It is performed following the guidelines of the International Organization for Standardization (ISO) 1404053 and 14044 through GaBi Education software.

3, TENG Fabrication

Since the commercialization and industrialization of TENG is still at the beginning stage, so a roll-to-toll process is proposed to fabricate TENG. The process main consists of 4 steps: clean the acrylic sphere, paste copper tapes on the inside surface of sphere, solder the leads to two electrodes and put the PTFE ball into the sphere, and then package the whole structure and connect all the wires together at output terminal.

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