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Power generation from the interaction of a liquid droplet and a liquid membrane

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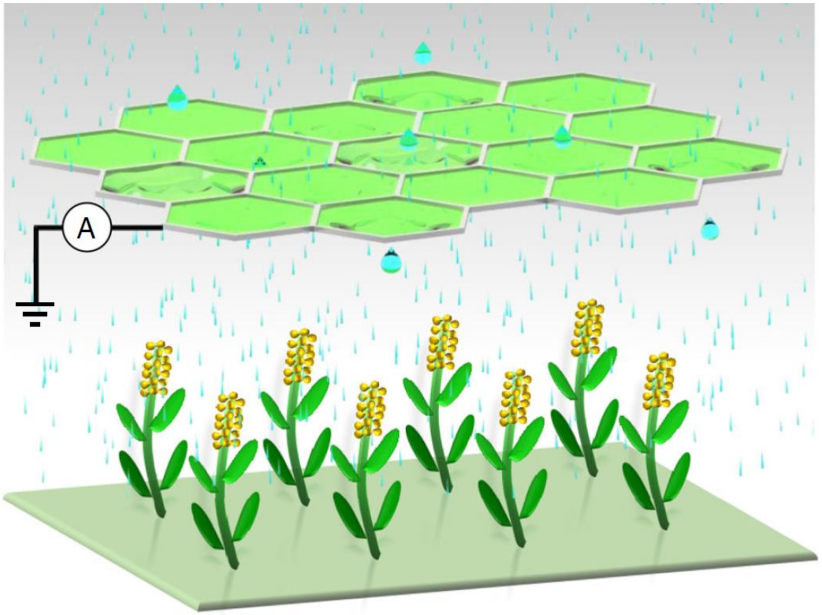

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Why am I presenting this paper?

1) First report on L-L contact electrification.
2) Utilized very simple physics of charge transfer to understand their phenomenon.
3) Way to static electricity generated during rain

Relevance to the group

1) Directly related to my work where I use to transfer charge created by solid–solid contact to transfer the charge to microdroplet to mimic rainy environment.
2) This work also shows charge filtration from the solid objects.
3) Dust carries a lot of charges, and this is one of the reason for dust to deposited on surfaces such as glass window.
4) It will help to quantify amount of charge carried by dust for better understanding of dust free surfaces.

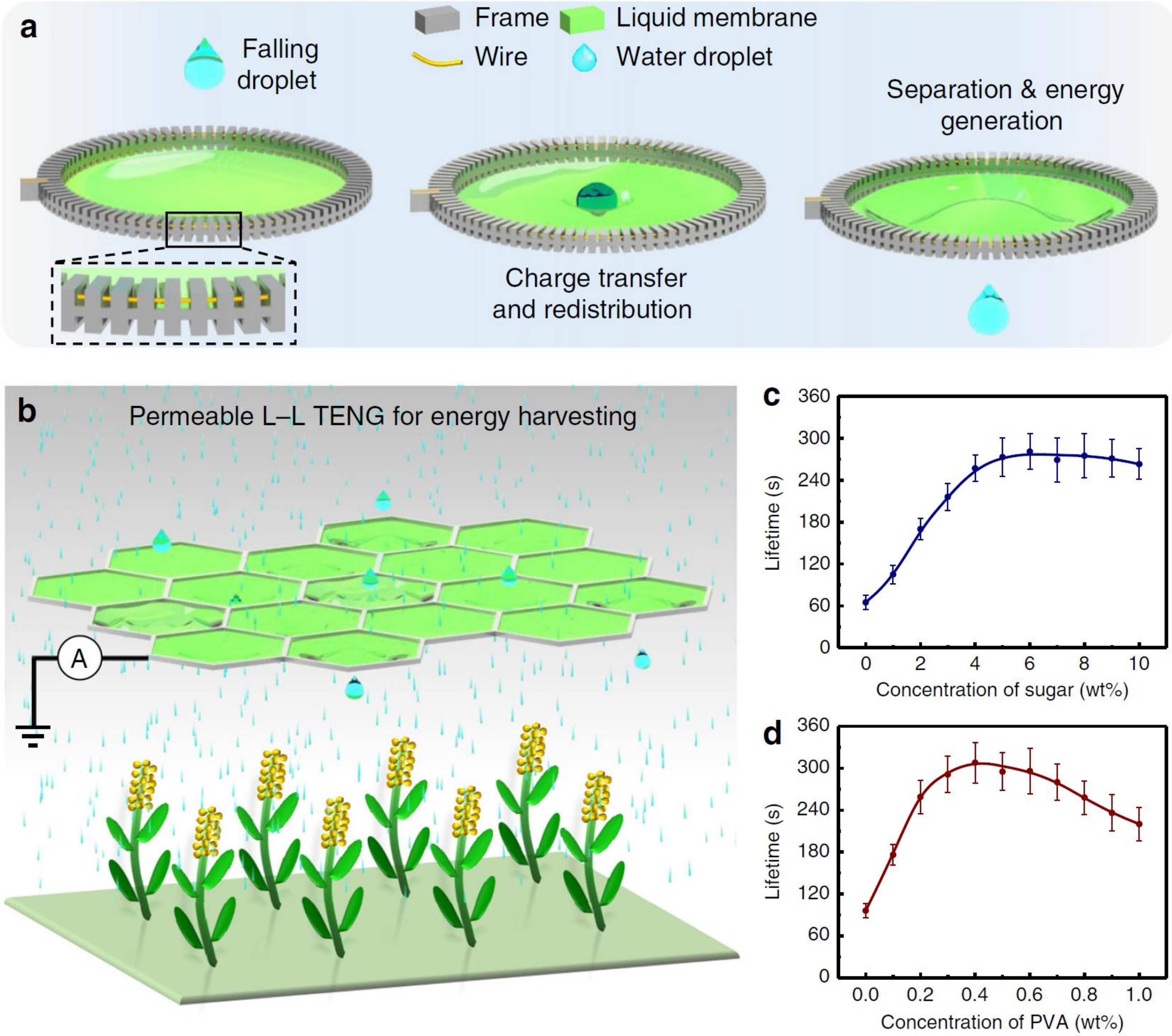


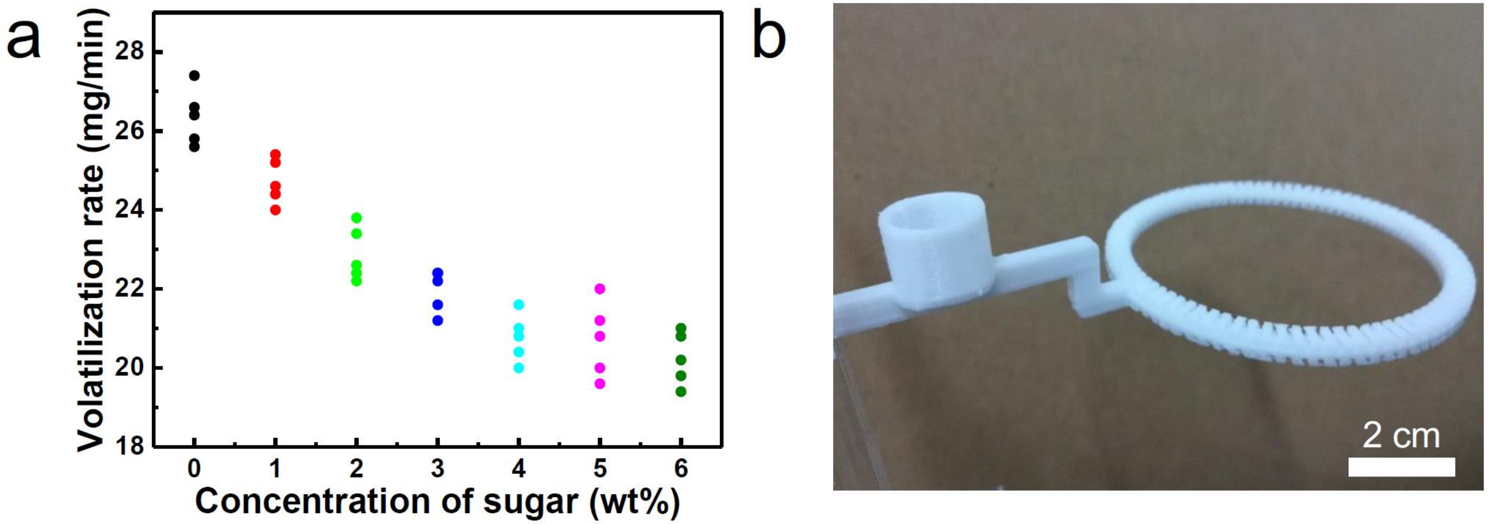
Fig. 1 Concept of the liquid membrane for harvesting ambient electrostatic energy. **a** Schematics showing the working principle of the liquid membrane for collecting electrostatic energy from charged droplets. The inset shows structure design of the frame for holding liquid membrane. **b** Schematic diagram of L–L TENG collects energy from raindrops in an irrigation system, while the motion behavior of raindrop is unaffected. **c, d** The effect of different sugar concentrations (**c**) and different PVA concentrations (**d**) on the lifetime of the liquid membrane. Error bars represent standard deviation based on five replicate data. Test conditions: temperature 25 ± 0.5 °C, humidity 30 ± 2%, five drops of water per second through the liquid membrane.

Supplementary Table 1. Lifetime of the liquid membrane with different surfactants and differen concentrations of sugar. The average lifetime (with standard deviations) were calculated from : independent measurements. (Test conditions: temperature 25 ± 0.5 °C, humidity 30 ± 2 %, five drops o water per second through the liquid membrane)

Concentration of sugar (wt%)	Lifetime of the liquid membrane (s)		
	2.1 wt% AES + 0.5 wt% PVA	0.3 wt% SDS + 0.5 wt% PVA	6 wt% Walch + 0.5 wt% PVA
0	72 ± 11	65 ± 8	179 ± 21
1	94 ± 18	105 ± 16	173 ± 27
2	90 ± 13	170 ± 24	186 ± 30
3	82 ± 15	216 ± 19	189 ± 29
4	84 ± 20	257 ± 18	195 ± 27
5	86 ± 16	273 ± 28	179 ± 35
6	78 ± 18	281 ± 24	195 ± 32
8	74 ± 21	275 ± 30	169 ± 20
10	68 ± 18	265 ± 31	196 ± 24
15	60 ± 19	251 ± 27	195 ± 32
20	58 ± 14	233 ± 18	177 ± 28

Supplementary Table 2. Lifetime of the liquid membrane with different surfactants and different concentrations of PVA. The average lifetime (with standard deviations) were calculated from 3 independen measurements. (Test conditions: temperature 25 ± 0.5 °C, humidity 30 ± 2 %, five drops of water per second through the liquid membrane)

Concentration of PVA (wt%)	Lifetime of liquid membrane (s)		
	2.1 wt% AES + 3 wt% sugar	0.3 wt% SDS + 5 wt% sugar	6 wt% Walch + 4 wt% sugar
0	56 ± 13	96 ± 9	77 ± 12
0.1	68 ± 18	176 ± 18	107 ± 18
0.2	74 ± 24	259 ± 25	159 ± 25
0.3	72 ± 25	291 ± 28	151 ± 26
0.4	76 ± 19	308 ± 34	182 ± 28
0.5	84 ± 16	294 ± 36	186 ± 20
0.6	82 ± 21	296 ± 33	192 ± 35
0.8	90 ± 28	258 ± 27	229 ± 34
1.0	80 ± 23	220 ± 31	195 ± 27
1.5	96 ± 26	236 ± 28	243 ± 37
2.0	82 ± 16	231 ± 33	241 ± 41



Supplementary Figure 1. a The evaporation rate of the liquid membrane at different sugar concentrations. The diameter of the tested liquid membrane is 60 mm, and the volatilization rate was tested for 5times.**b**The structure of the reservoir is designed to extend the lifetime of the liquid membrane.

Supplementary Table 3. The viscosity and density of membrane solution with different concentrations of PVA. (Test environment: temperature 25.0 ± 0.3 °C)

Concentration of PVA (wt%)	Viscosity (cP)	Density (kg/m^3)
0	1.079	1020.1 ± 1.5
0.1	1.276	1018.3 ± 0.8
0.2	1.326	1017.3 ± 1.2
0.3	1.356	1017.6 ± 0.6
0.4	1.417	1018.5 ± 2.2
0.5	1.478	1018.7 ± 1.8
0.6	1.554	1018.3 ± 1.4

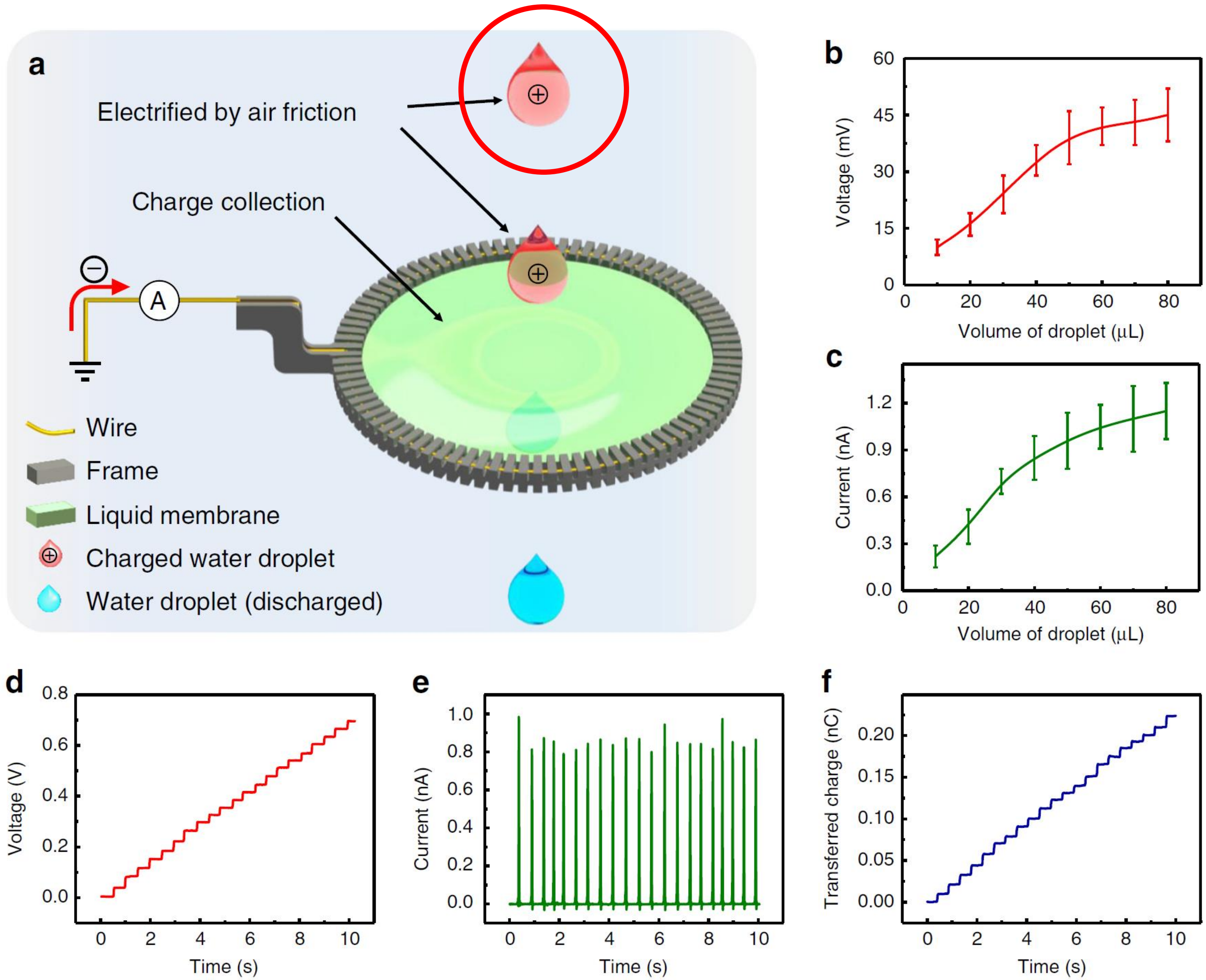
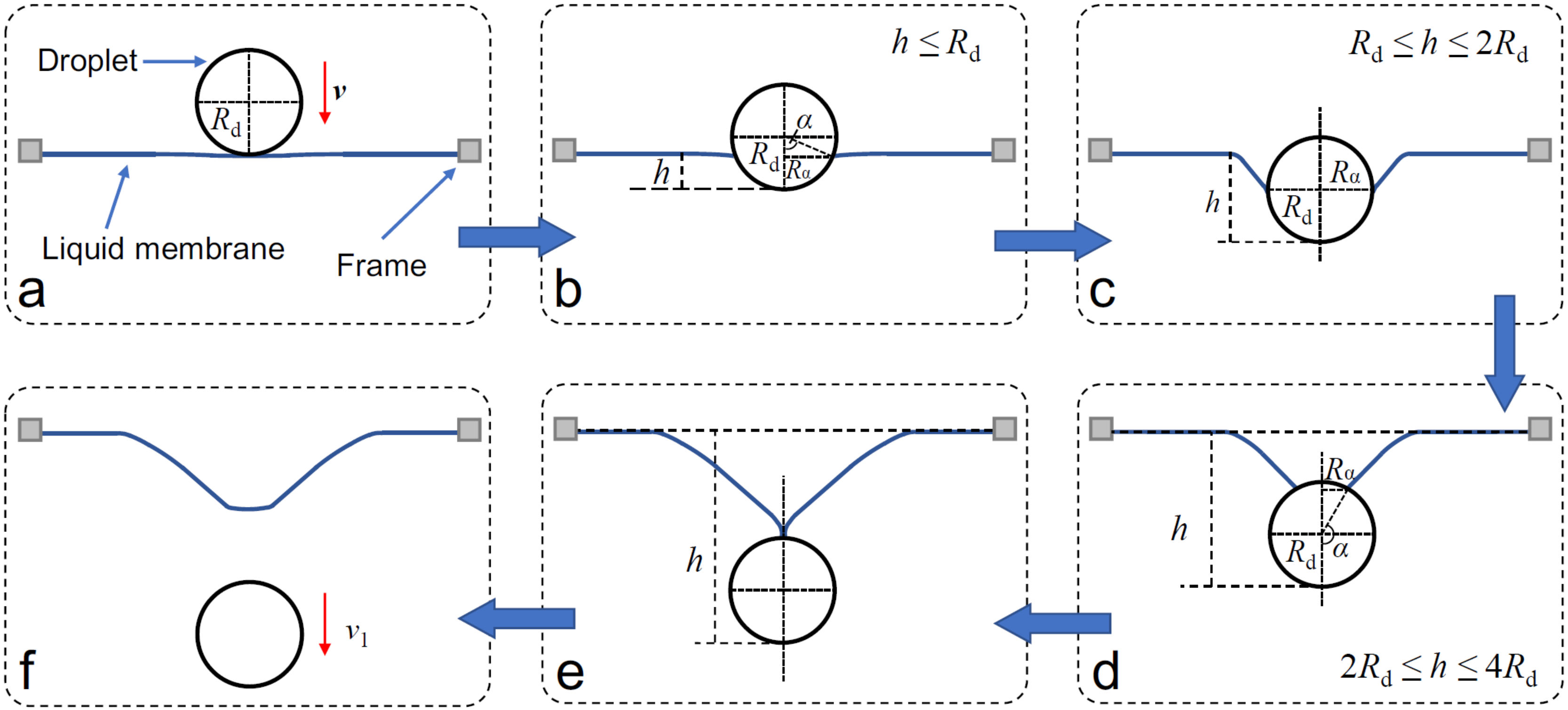


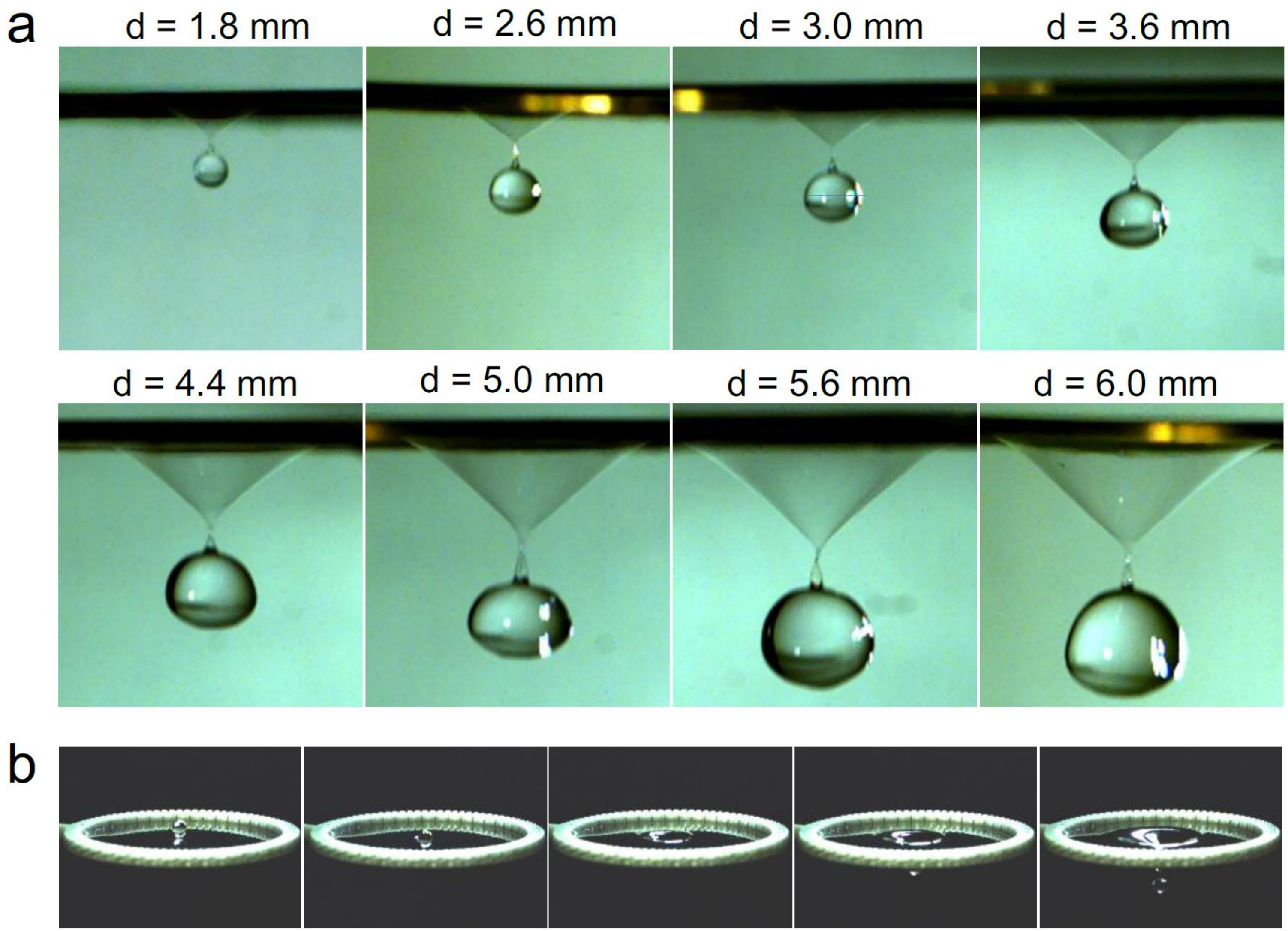
Fig. 2 Falling droplets contacting with a grounded liquid membrane without pre-charging. **a** Schematic diagram of liquid membrane collects energy from falling droplets, while droplets carry positive tribo-charges due to the friction with air. **b, c** Open-circuit voltage (V_{OC}) (**b**) and short-circuit current (I_{SC}) (**c**) of droplets passing through the liquid membrane with different size. **d−f** V_{OC} (**d**), I_{SC} (**e**), and transferred charge (**f**) of droplets passing through the liquid membrane. Error bars represent standard deviation based on five replicate data. (All tests were performed with a drop height of 3 meters).



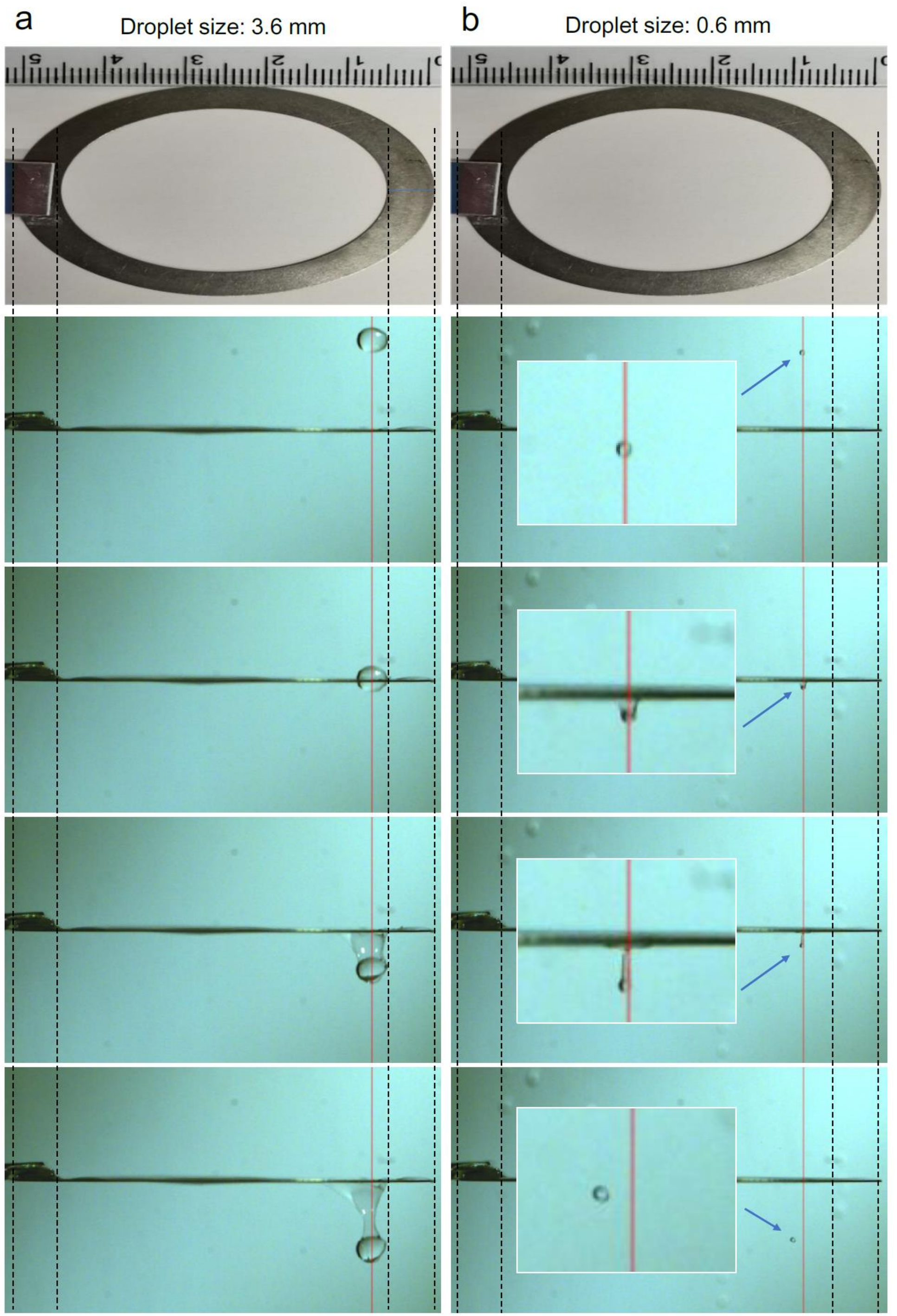
Supplementary Figure 2. Schematic diagram of a droplet passing through a liquid membrane.

$$G - F_s - F_a = ma \tag{1}$$

$$mg - \frac{4\pi\gamma}{R_d} R_\alpha{}^2 - \frac{1}{2} c \left(\frac{dh}{dt} \right)^2 \cdot \pi R_d{}^2 = m \frac{d^2 h}{dt^2} \tag{2}$$

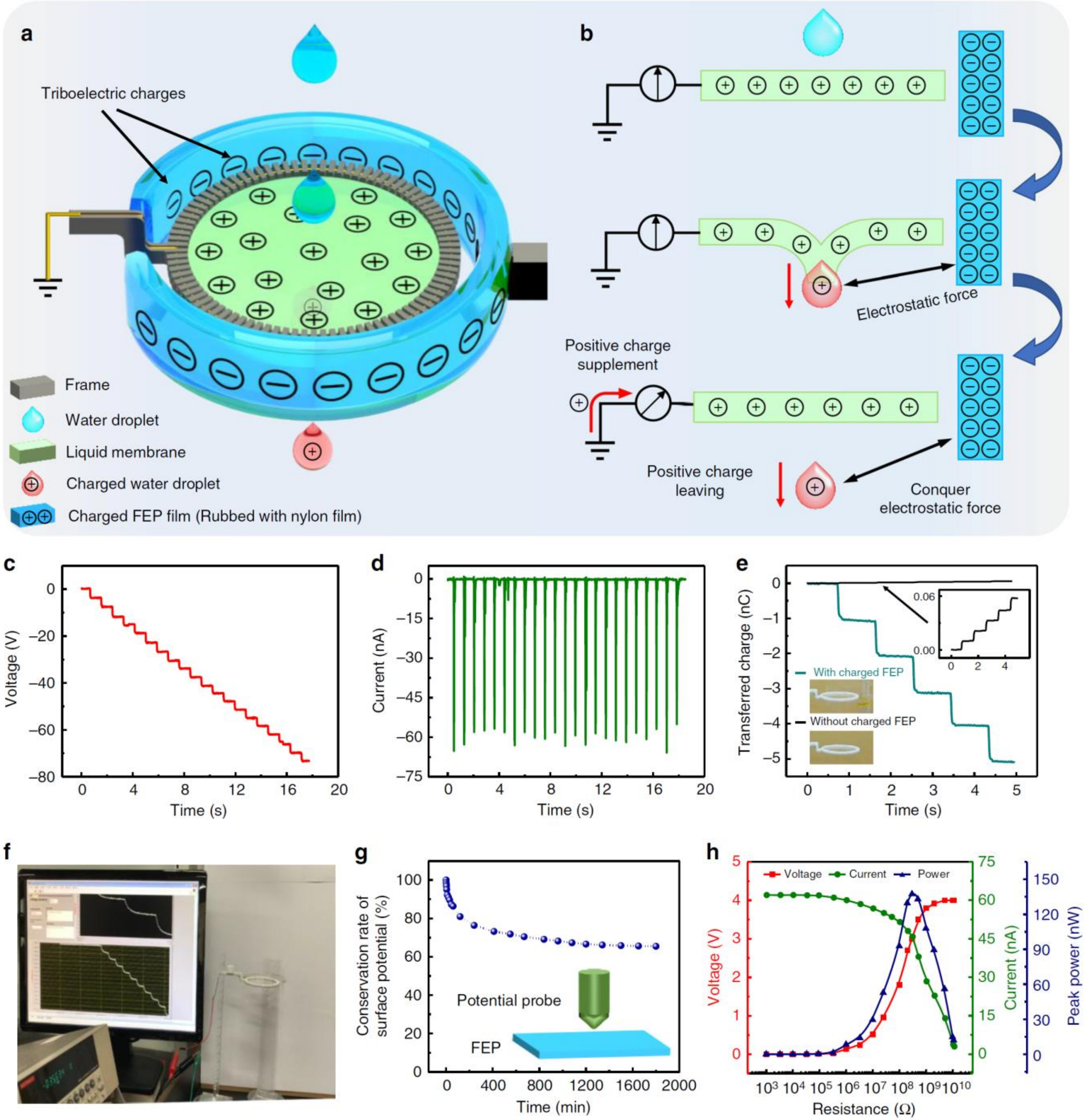


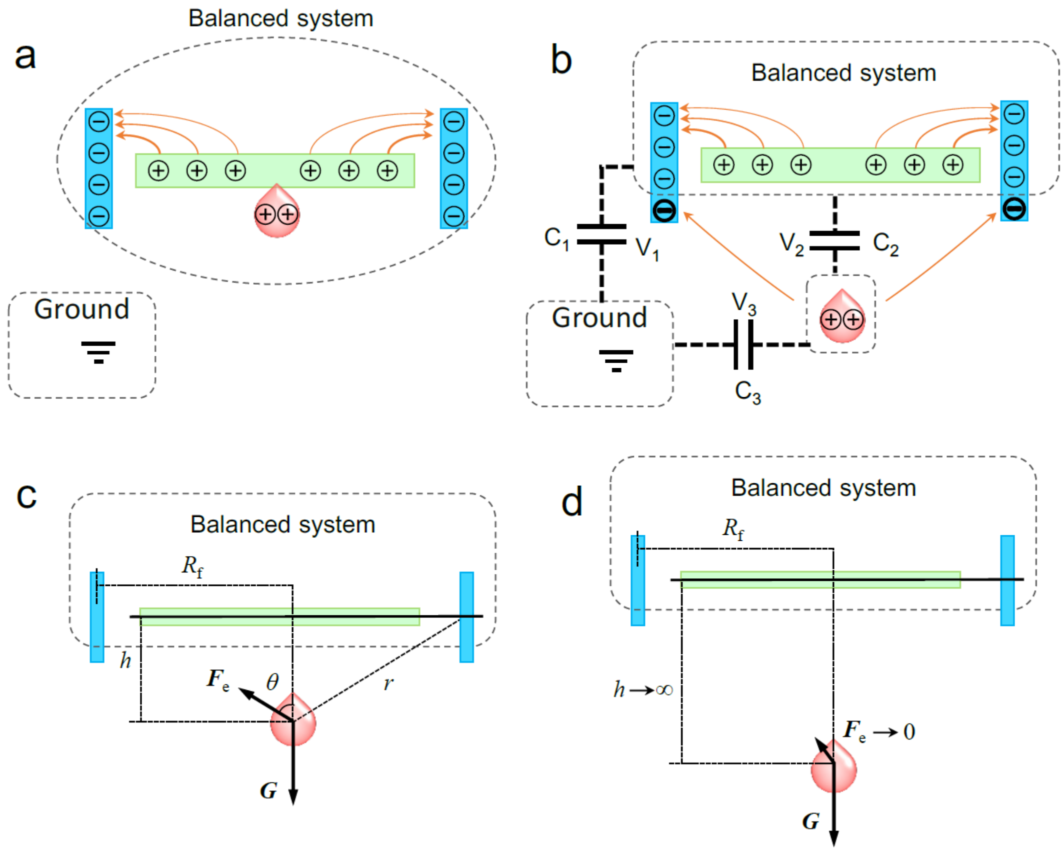
Supplementary Figure 3.a Photographs of different sizes of water droplets passing through the liquid membrane. **b** Images of a water droplet passes through the liquid membrane. The droplets fell from a height of 2 m.



Supplementary Figure 4. Motion behavior of droplets passing through the edge region of membrane with the size of 3.6 mm (**a**) and 0.6 mm (**b**).

Fig. 3 Falling droplets contacting with pre-charged liquid membrane. **a** Schematic diagram of energy generation by using a charged liquid membrane. The liquid membrane is charged by the electrostatic field on an FEP film. **b** Mechanism of energy generation of water droplets passing through the charged liquid membrane. **c, d** V_{OC} (c) and I_{SC} (d) of the droplets passing through the charged liquid membrane. e Transferred charge comparison of droplets passing liquid membrane with and without polarization. **f** Screenshot of the real-time output signals of the water droplets passing through the charged liquid membrane. **g** Stability of surface potential of the charged FEP film obtained by rubbing with nylon. **h** Dependence of the I_{SC} and power on the resistance.



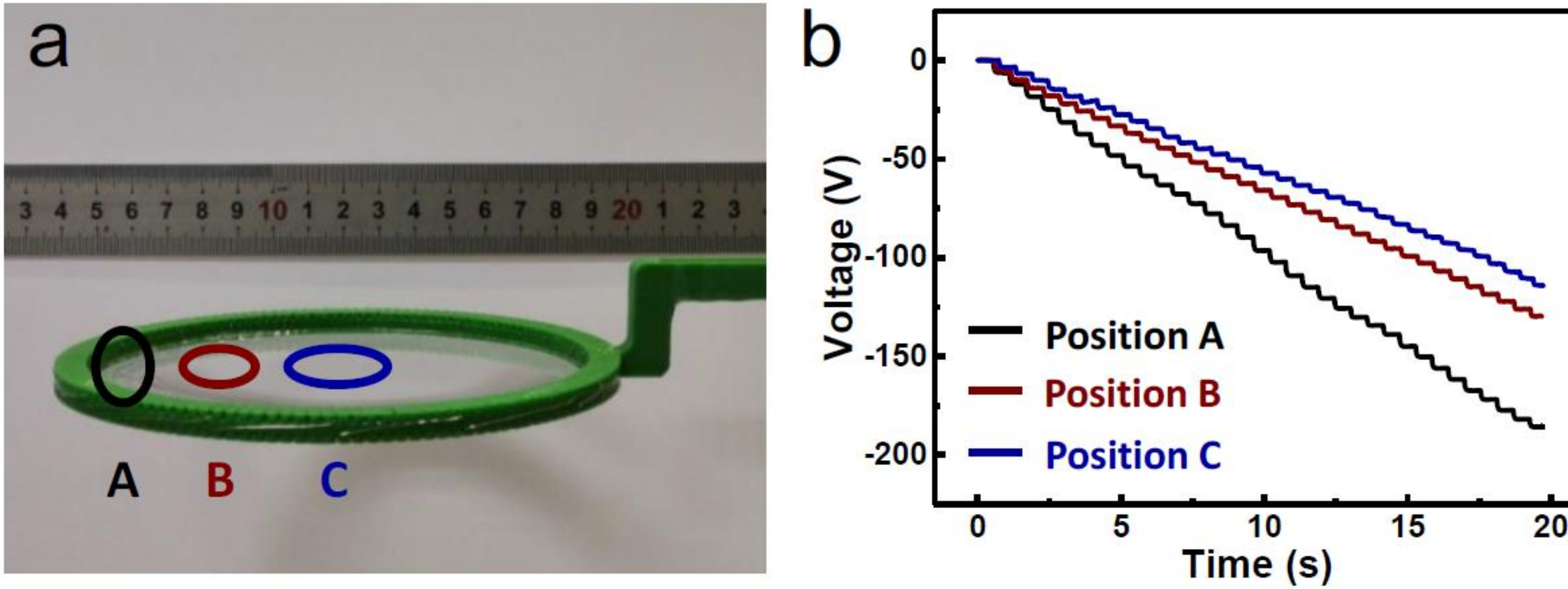


$$V_{OC} \approx \frac{q}{2C_1} \tag{3}$$

$$F_e = \frac{qQ(h)}{4\pi\varepsilon_0} \frac{h}{(h^2 + R_f{}^2)^{\frac{3}{2}}} \tag{4}$$

$$E_g - W_e = \Delta E_k \tag{5}$$

Supplementary Figure 5.The kinetic energy of droplet is converted into electrical energy. a Schematic diagram of electric field distribution with water droplet at different positions. **B** Circuit model with three capacitances for the liquid membrane-based nanogenerator at open-circuit condition. **c, d** The force analysis of the water droplet after passing through the liquid membrane.



Supplementary Figure 6. **A larger frame is prepared for studying the different output at different falling position of the membrane. a** A larger membrane for checking the charge transfer and three different positions on the liquid membrane for droplets to pass through. **b** V_{OC} of droplets passing through these positions.

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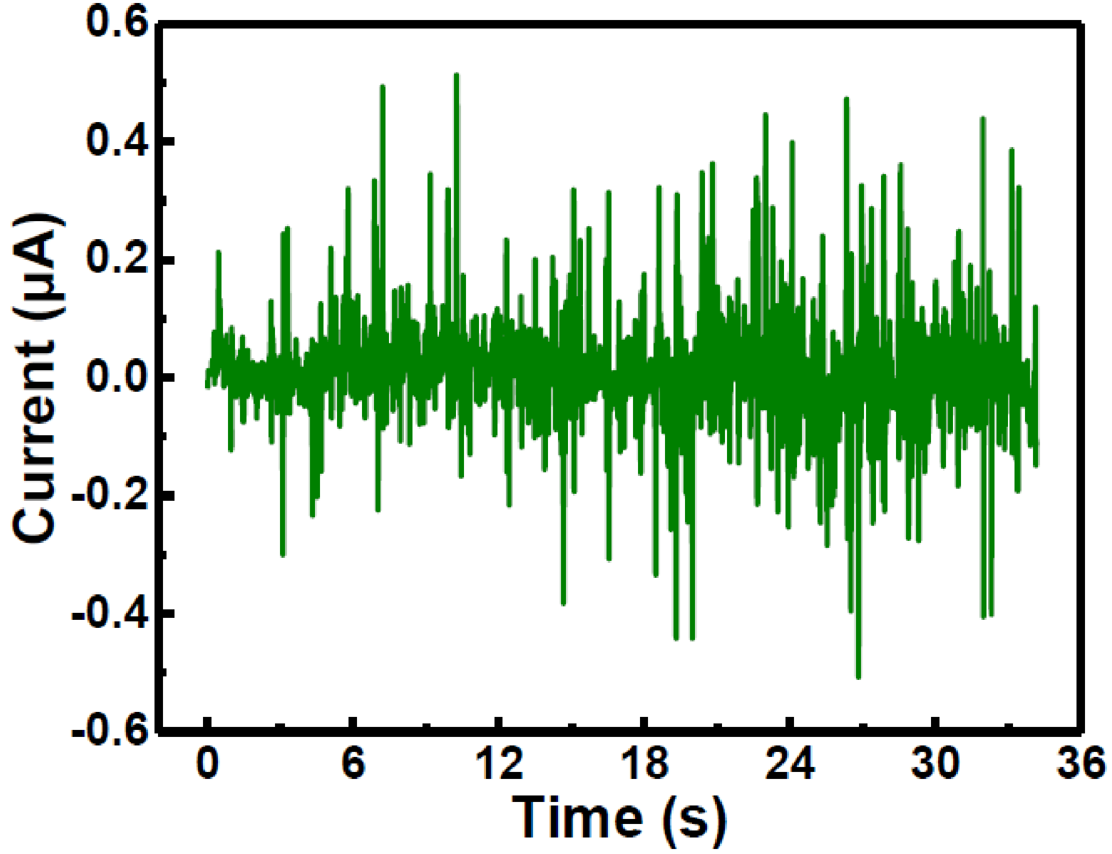


Supplementary Figure 7. I_{sc} **of the real raindrops passing through the grounded liquid membrane.**

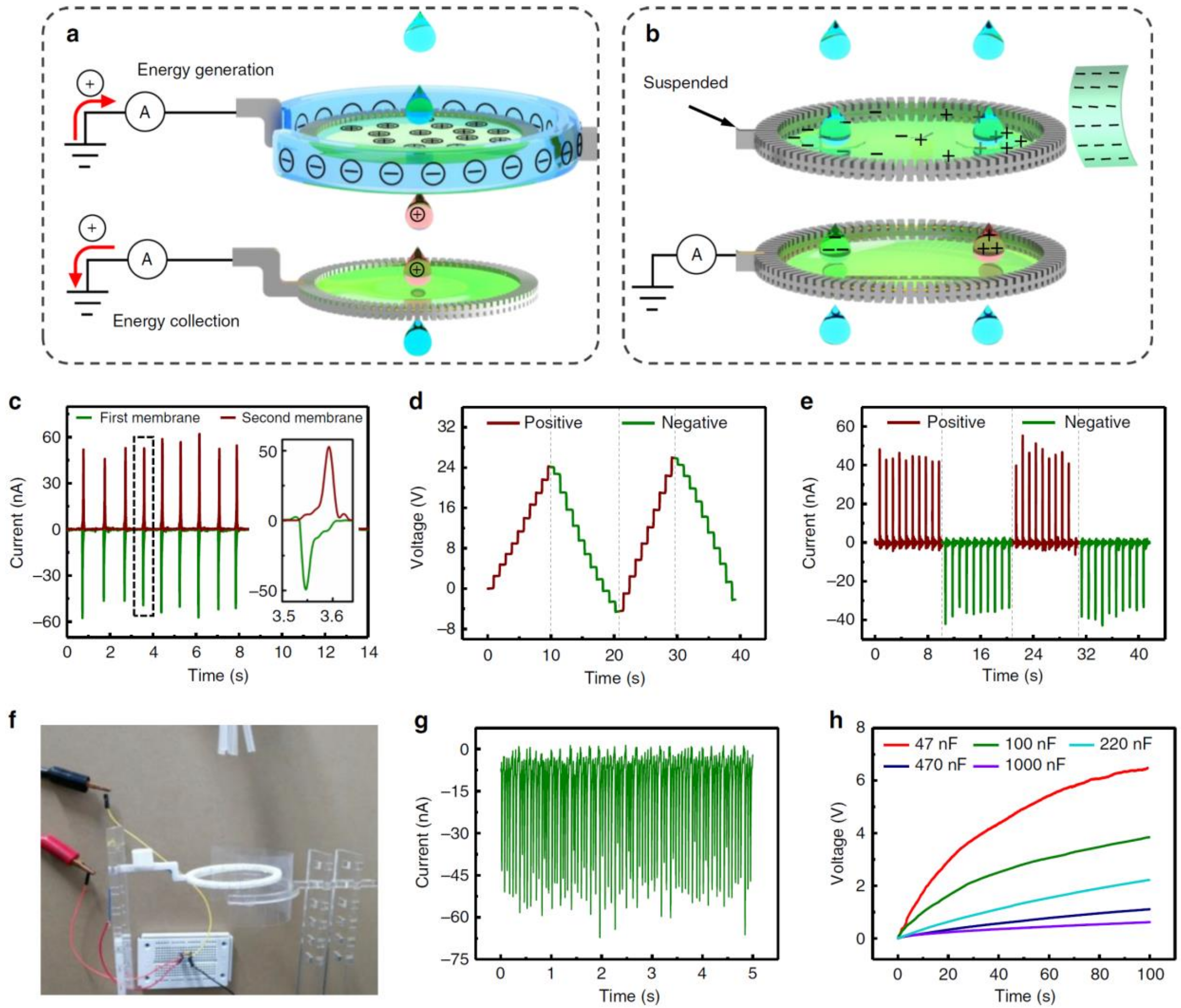
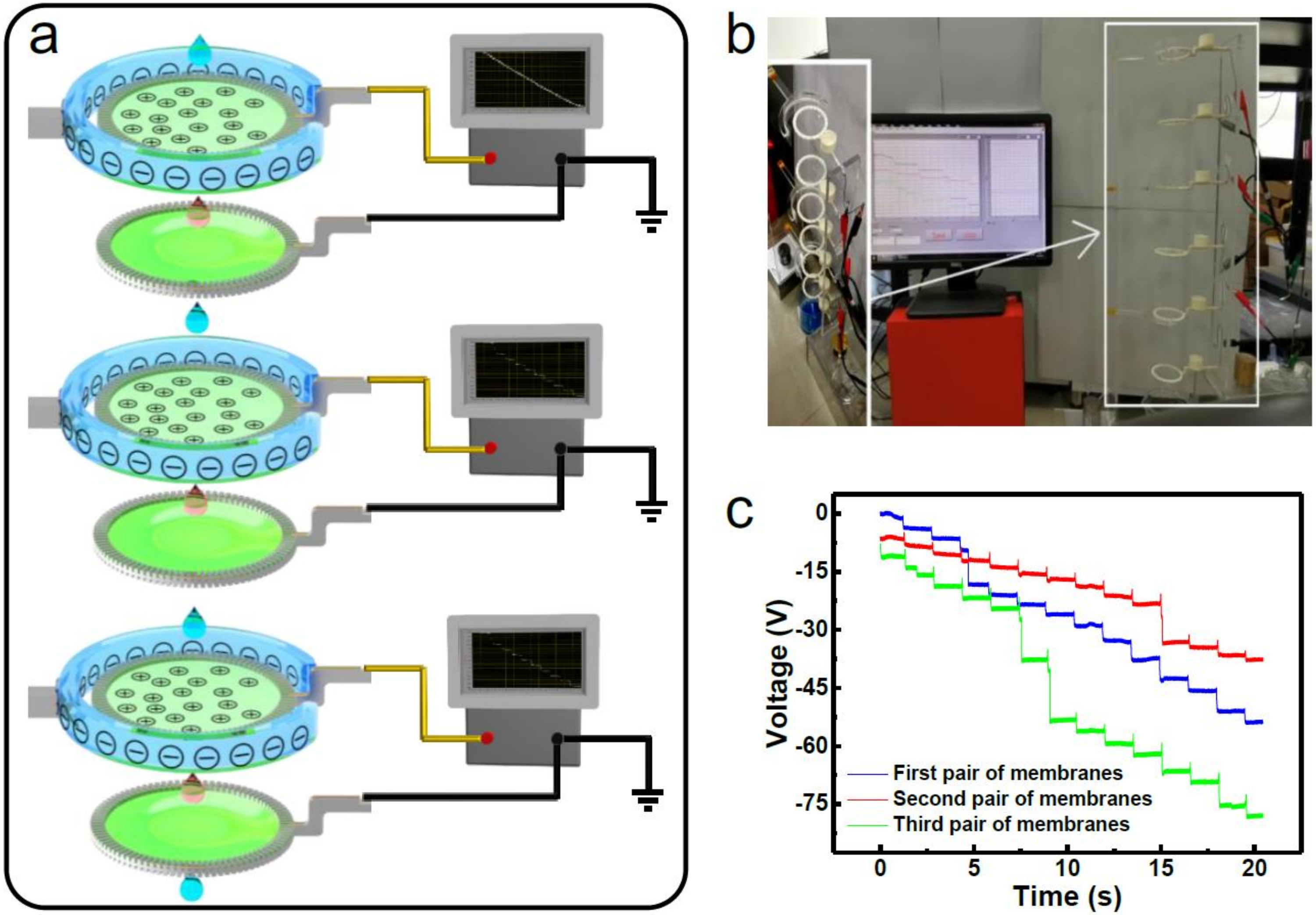
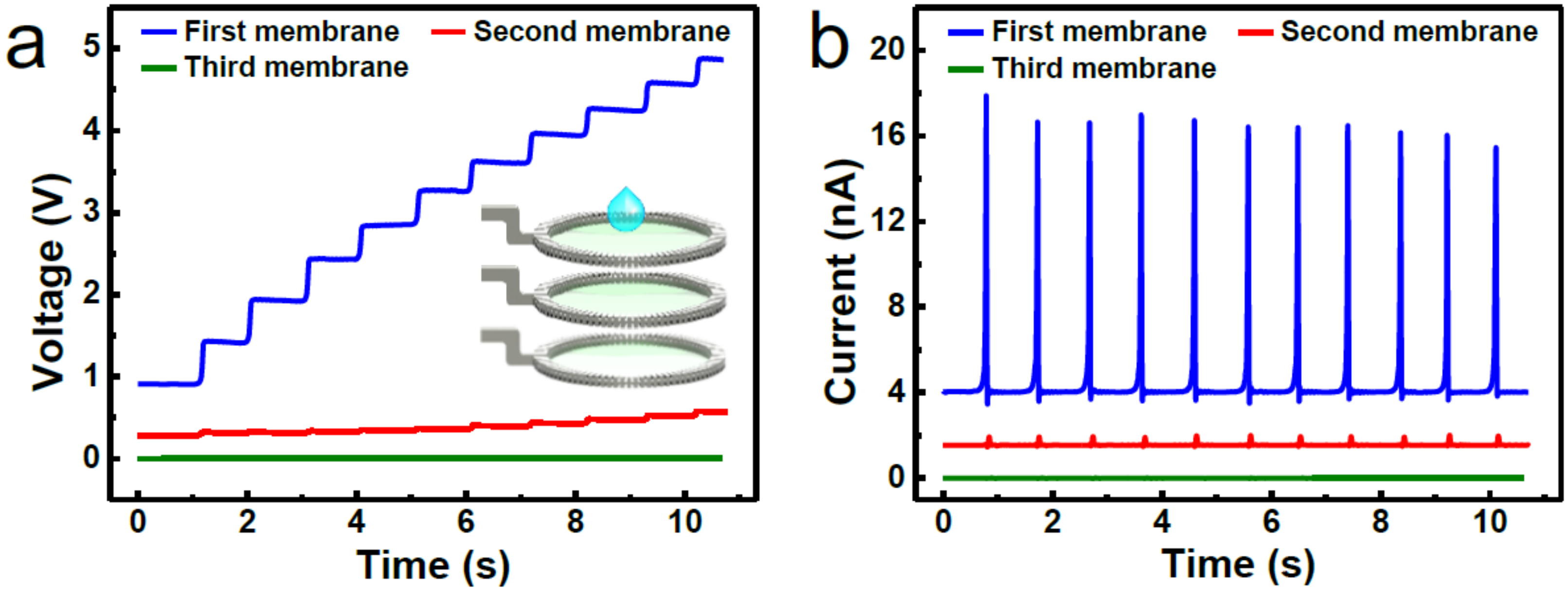


Fig. 4 Power generations by passing droplets through multiple liquid membranes. **a** Schematic diagram of the multiple generations by combining a charged liquid membrane. **b** Schematic diagram of a suspended charged liquid membrane causing the passed droplets to be positively and negatively charged, respectively. **c** I_{sc} of the droplets passing through the two liquid membranes in **a**. Insert is the output current of one droplet. **d, e** V_{oc} (d) and I_{sc} (e) of water droplets passing through different locations of the polarized liquid membrane. **f** Photograph of water droplets dripped simultaneously with five tubes for improving output power to charge capacitors. The drip rate of each tube is ~5 drops per second. **g** I_{sc} of the multi-tube droplets passing through a polarized liquid membrane. **h** Charging voltage curves for different capacitors with the device in **f**.


a
b
c
Voltage (V)
Time (s)
First pair of membranes
Second pair of membranes
Third pair of membranes



Supplementary Figure 10. **a,b** Open-circuit voltage (**a**) and short-circuit current (**b**) of droplets passing through three liquid membranes. Insert of (**a**) is the Schematic diagram of a droplet passing through three liquid membranes.

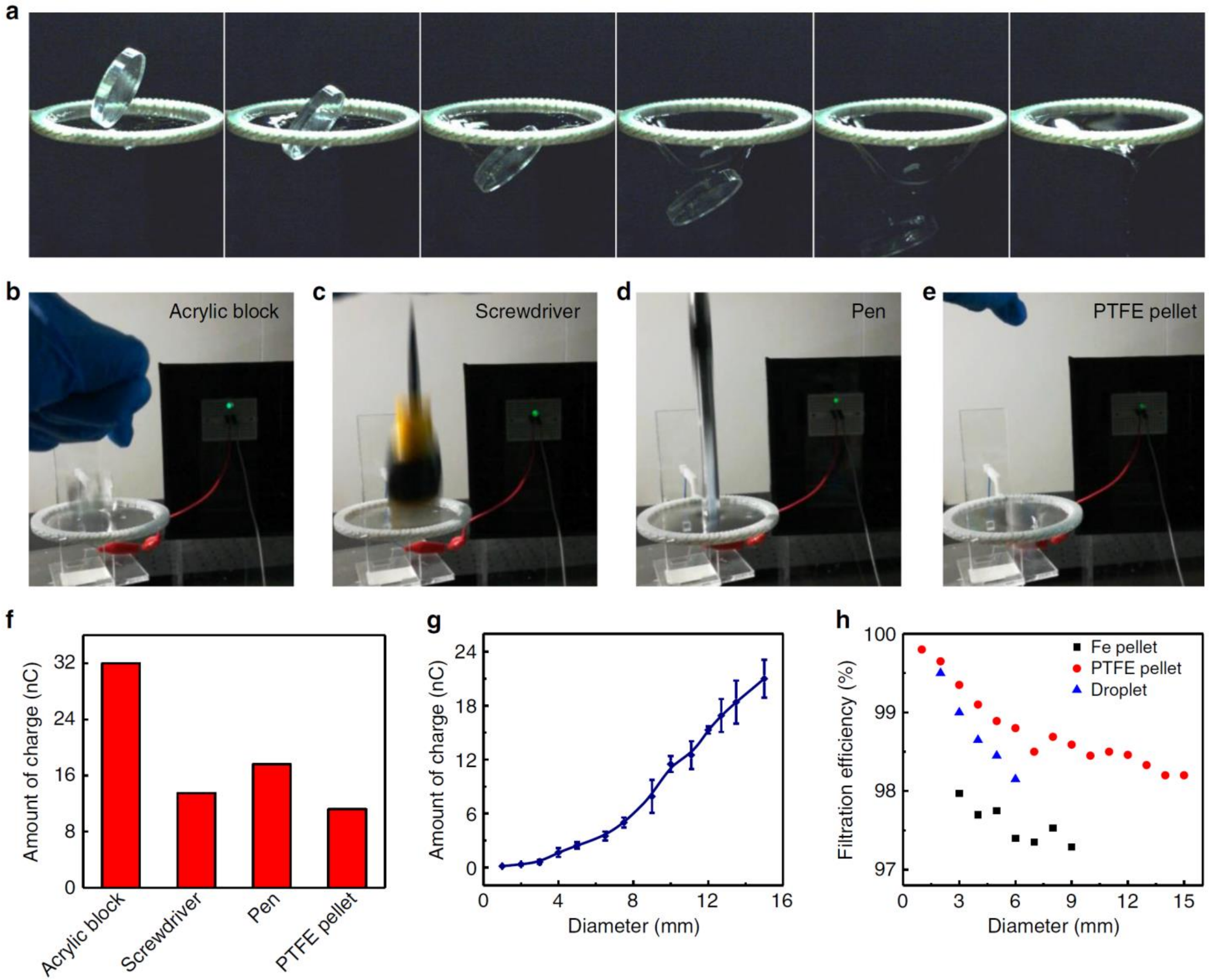


Fig. 5 Liquid membrane collecting electrostatic charges from solid objects. **a** Images of an acrylic block passing through the liquid membrane. **b–e** Photographs of the liquid membrane filtering the electrostatic charges from the acrylic block, screwdriver, pen, and PTFE pellet, respectively. **f** Amount of charge of different objects filtered by the liquid membrane. **g** Amount of charge of PTFE pellets with different diameter filtered by the liquid membrane. **h** Charge filtration efficiency of the liquid membrane for Fe pellets, PTFE pellets and water droplets of different sizes. Error bars represent standard deviation based on three replicate data in panel **c**.

THANK YOU FOR YOUR ATTENTION!

ANY QUESTIONS ?