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NEWS

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Making use of water droplets as a sustainable green energy source

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In 2012, the first triboelectric nanogenerator (TENG) was invented to convert mechanical energy into electricity via the coupling effects of triboelectrification and electrostatic induction.[1] Since then, extensive efforts have been devoted into increasing the output power density of these energy harvesters, and the milestones have been summarized in Figure 1a with a maximum power density of 10 MW/m^2.[2] Among the exciting achievements in TENG field, the liquid–solid-based TENGs (L–S TENG) are paving their ways for harvesting water energy from oceans, raindrops, tides, and so on. As shown in Figure 1b, the first L–S TENG was reported in 2013, which utilized the liquid as one contact layer for a contact-and-separation mode TENG.[8] In the past few years, the investigations including liquid types, contact surface morphologies, and properties, as well as system architectures are reported in the liquid energy harvesting technology aiming for a better system design. Despite these optimizations, the maximum power density of L–S TENGs is still limited (11.7 W/m^2) because the charges are only generated and transferred by interfacial effect.[8–15] In addition to TENG technology, hydro-voltaic and reverse electrowetting are two of the representative technologies developed for water energy harvesting while their outputs are also restricted by the interfacial effect and complicated operations.[33,34]

To meet this challenge, Wang et al. have proposed a droplet-based electricity generator (DEG) with a novel transistor-like architecture for droplet energy harvesting in 2020.[16] This novel DEG was constructed by combining polytetrafluoroethylene (PTFE) film on an indium tin oxide substrate with a small aluminum electrode fabricated on the surface of the PTFE film. The instantaneous power density of this DEG was several orders of magnitude higher than its counterpart without the aluminum electrode on the surface. The boosted ultrahigh power density is attributed to the bulk effect where the spreading of an impinged water droplet on the PTFE surface enabled the formation of a close-loop electrical system between the droplet, two electrodes, and PTFE. Therefore, the charges flow directionally in the bulk close-loop electrical system rather than at the solid–liquid interface. Meanwhile, the outstanding performance of DEG also relied on the high surface charge density of the dielectric layer (PTFE), which is achieved by pre-charging the PTFE surface via continuous droplet impinging (1.6×10^4 s) so that further droplet energy harvesting could be more efficient with the saturated surface charge density. Following this significant work in L–S electricity generator, Wu et al have proposed a homogeneous electrowetting-assisted charge injection (h-EWCI) method to allow an ultrahigh negative charge density so as to enhance the power density up to 162 W/m^2.[17] After the invention of DEG, the dynamic working mechanisms and single electrode working modes have been investigated to enable comprehensive understanding and versatile applications of DEGs.[35,36] With the hydrophobic treatments and/or hydrophobic structures, the resulted dielectric materials have shown even higher output.[18,37] Except to that the long pre-charging time (1.6×10^4 s) remains as a hurdle on the road for commercialization, the DEG technology shows its promise in terms of output power densities. Now, writing in *Droplet*, Nan Zhang and colleagues show that boosted instantaneous power density and reduced charging time

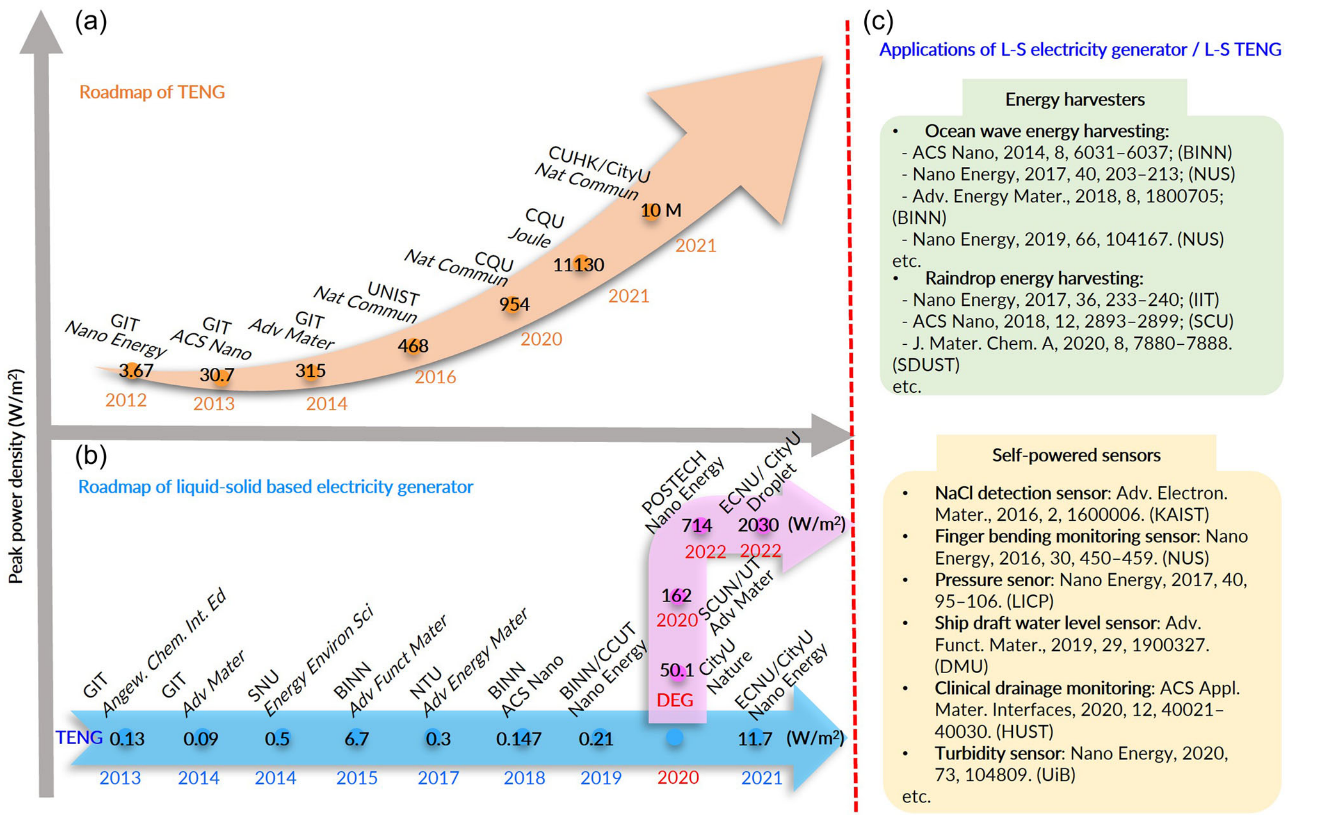

FIGURE 1 Historical milestones of the development of triboelectric nanogenerators (TENGs) and liquid–solid-based electricity generators. (a) The peak power density roadmap of TENG.[1–7] (b) The peak power density roadmap of liquid–solid-based electricity generators including TENG and the droplet-based electricity generators (DEGs).[8–19] (c) Versatile applications of liquid–solid-based TENG (including conventional TENG and DEG).[20–32]

can be realized via systematically modeling and optimizing the hydrodynamic and circuit system.[19]

The research team based at the East China Normal University (ECNU) and City University of Hong Kong (CityU) reports that the output performance of DEG is determined by the dielectric materials, the thickness of dielectric materials, the droplet ion concentration, and the external impedance. Even using the similar device structure and materials as reported in Xu et al.,[16] the authors in this study have investigated the optimal parameters of dielectric layer thickness and droplet ion concentration to enable ultrahigh output density as well as shorting charging time. A maximum instantaneous power density of 2.03 kW/m^2 was realized, accompanied with a shortened charging time of 6.36 s. This is the highest output performance achieved in DEGs and even in all water energy harvesters (Figure 1).

The important concern of high output is that the amount of generated charges in DEG should be sufficient and can be released rapidly when the spreading droplet contacts the upper electrode. The authors have proposed a similar circuit model for the DEG working mechanism where the DEG can be treated as the charge transfer between three capacitors, for example, water-PTFE (C_{PTFE}), water-PTFE interface (C_{EDL1}), and water-upper electrode interface (C_{EDL2}). The thickness of C_{EDL1} and C_{EDL2} are several orders of magnitude smaller than that of C_{PTFE}, thus the C_{PTFE} can be treated as a charge source, in which the charging time to reach a saturated surface charge density as well as the available charges to be released are modulated by the thickness of PTFE layer. This model provides a friendly approach to easily understanding the working mechanism of all DEGs.

There are three important parameters to evaluate output performance of DEG, for example, V_{oc}, I_{sc}, and P. They have been expressed as $V_{oc} = \frac{Q}{C_{PTFE}} = \frac{Qd}{\varepsilon_p A_{max}}$, $I_{sc} = \frac{Q}{\tau}$, where $\tau = \frac{R_w \varepsilon_p A_{max}}{d}$, and $P = I^2 R_L$, respectively. The authors have summarized the impacts of dielectric material thickness and droplet ion concentration to the output performance of DEG. Firstly, the thickness of dielectric materials not only influences the C_{PTFE} and time constant but also brings reduced surface charge Q on PTFE through the intermediate of the decreased electric field intensity when the thickness is larger enough. Secondly, the droplet concentration is highly related with the formation of EDL so that the surface charge Q could be influenced as well. The droplet concentration also determines the internal impedance R_w as well as the time constant τ. Thirdly, the power density could also be influenced by the external impedance besides dielectric material thickness and droplet ion concentration. Therefore, to obtain the optimal output performance of DEG, all the three parameters are required to consider. In this study, the maximum power density reported is about 2.03 kW/m^2 when the thickness of dielectric layer is 300 µm, the ion concentration is 200 mM, and the external impedance is 51 kΩ.

Furthermore, speaking of the charging time, it is reported that as the thickness increase, the amount of stored charge on PTFE from one impinging droplet is enlarged while the saturated charge on PTFE is reduced, contributing to reduced impinging times and a short charging time. Thus, a shortened charging time of 6.36 s is achieved in this study.

N. Zhang et al. provide an explicit direction for researchers to enhance the performance of DEG by controlling the dielectric materials, dielectric materials thickness, droplet concentrations, and external impedance. Besides the efforts of investigating optimal dielectric material thickness and droplet ion concentration in this study, it is promising to develop novel materials with high charge storage capability to further advance the output performance of DEG. Certainly, the working mechanism and circuit model reported in this study are crucial in the development of liquid–solid-based electricity generators towards higher power density and practicality. As indicated in Figure 1c, the applications of liquid–solid-based electricity generators have covered many fields, such as energy harvesters from oceans, tides, raindrops, and so on, as well as self-powered physical and chemical sensors.[20–32] Further advancements of high-power-density DEGs or other liquid–solid-based electricity generators could provide seamless solutions to keep these fields continuously blooming.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICS STATEMENT

The authors declare no ethical issues.

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