The Current Development and Future Outlook of Triboelectric Nanogenerators: A Survey of Literature

*Tinghai Cheng, Qi Gao, and Zhong Lin Wang**

Triboelectric nanogenerators are devices that effectively convert ambient mechanical energy into electricity, which can be used as a power source or a sensor signal. Since first proposed by Dr. Zhong Lin Wang in 2012, the development of triboelectric nanogenerators has grown rapidly. Herein, the development of the triboelectric nanogenerator and its global impact is investigated by analyzing the statistical publication numbers and the geographic distribution of the publications. In addition, this article also features the main applications of triboelectric nanogenerators such as blue energy, self-powered sensor/systems, and micro-/nanoenergy, and points out its future outlook. Several challenges and fundamental physical questions are also discussed to provide a more comprehensive view of this revolutionary technology.

1. Introduction

With the speedy development of sensor network, along with the increasing demand or wearable and ubiquitous "smart" devices, a tremendous quantity of small electronic devices has been widely applied all over the world. These small electronics include sensors, wireless transmitters, and/or actuators, etc. Generally, the power requirement for each of these small electronics is around milliwatt (mW) or microwatt (μW) range, with features such as low cost, mobility, light-weight, and sustainability. A conventional and most commonly used approach to provide the power for these electronics is installing batteries. Nevertheless, batteries have limited life spans. As the amount of the electronics increases dramatically, it has become much more difficult for the replacement, management, and/or recycling of the gigantic amount of batteries.

To address these issues, the concept of "self-powered" has been proposed and attracted much attention. Another critical alternative is to harvest energy from the ambient environment to serve as power sources. The invention of the nanogenerator opens up new area for both energy harvesting and self-powered sensors applications. Therefore, in this article, we focus on discussing the current development and future of nanogenerator, specifically triboelectric nanogenerator. The concept of "nanogenerator" was introduced in 2006 for using piezoelectric nanowires for converting tiny mechanical triggering into electric output in order to realize the self-powering proposed by Wang.[1,2]

In the January of 2012, another type of nanogenerator, triboelectric nanogenerator (TENG), that can also harvest ambient mechanical energy by combining contact-electrification and electrostatic induction was invented by our research group as well.[3–5] TENG has four basic modes: **Figure 1**a vertical contact-separation mode, Figure 1b in-plane contact-sliding mode, Figure 1c single-electrode mode, and Figure 1d freestanding triboelectric-layer mode.[6] Since then, the development of TENG technologies grows and expands rapidly. Moreover, the power density of a TENG, which depends on the device structure and active materials, has been reported to be up to 500 W m^{-2}.[7] In this article, we focus on and discuss the current development and future prospect of TENG. By now, nanogenerators represent a technology that use Maxwell's displacement current for energy harvesting.[8]

Dr. T. H. Cheng, Prof. Z. L. Wang
School of Materials Science and Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0245, USA
E-mail: zlwang@gatech.edu

Dr. T. H. Cheng, Q. Gao
School of Mechatronic Engineering
Changchun University of Technology
Changchun, Jilin 130012, P. R. China

Prof. Z. L. Wang
Beijing Institute of Nanoenergy and Nanosystems
Chinese Academy of Sciences
Beijing 100083, P. R. China

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/admt.201800588.

DOI: 10.1002/admt.201800588

2. Data Collection and Analysis

To demonstrate the growing tendency of the TENG field, herein, we run search queries using common keywords that related to the TENG research in the Web of Science database, with AND operator(s) between keywords. The keywords include triboelectric nanogenerator; TENG; triboelectric generator; triboelectric (AND) triboelectrification (AND) electrostatic induction; triboelectric (AND) nanogenerator; triboelectric (AND) generator; triboelectric (AND) sensor; triboelectric (AND) energy harvesting; triboelectric (AND) energy harvester; triboelectric (AND) self (AND) power; and triboelectric (AND) self-powered. The retrieval results were obtained on October 10th, 2018, with the keywords appearing in the titles, abstracts, or keywords of the publications. As can be seen from **Figure 2**, the number of publications (including research and review articles) each year grows from single-digit (6, in 2012) to more than 400 this year (in October). As the retrieval data was obtained around the end of this year (October), it is expected that the number of articles may exceed 500 this year. The total amount of publications reaches more than 1400 (1464) by this year (in October).

These research articles were published in 147 different scientific journals indexed in the Web of Science database, the related results are depicted in **Figure 3**. Among those articles, almost 15% (21 out of 147, 14.29%) were published in journals with impact factors higher than 10 (according to impact factor 2017 from Journal Citation Reports), including (in alphabetical order) *ACS Nano, Advanced Energy Materials, Advanced Functional Materials*, *Advanced Materials*, *Nano Energy, Nature Communication*, *Nature Energy*, *Nature Nanotechnology*, *Materials Today*, and *Science Advances*.

According to the retrieval results from Web of Science database, to date, the TENG research was conducted by research institutes and universities in 49 states and regions across six continents, Africa, Asia, Australia, Europe, North America, and South America (in alphabetical order), as shown in **Figure 4**, which suggests the global impact of the TENG research. **Figure 5** demonstrates the number of articles of TENG research conducted in different places and regions globally. The top five ones (in order) are People's Republic of China, the United States of America, Republic of Korea, Singapore, and Taiwan. **Figure 6** shows the top research institutes and universities with the most triboelectric nanogenerator publications, including Chinese Academy of Sciences, Georgia Institute of Technology, and Chongqing University, etc. Research institutes from the private sector such as Samsung Advanced Institute Technology also participate in TENG research (Figure 6), suggesting the great potential to bring this emerging technology to practical applications.

The number of citing articles is an important factor to evaluate research articles. To demonstrate the impact of the TENG research articles, we further investigate the number of articles citing those articles. As can be seen from **Figure 7**, the citation numbers increase dramatically from 23 (in 2012) to 11765 (in October 2018). As the citation numbers were collected on October, 2018, the number this year (11 765) has already surpassed the number from last year, with around 16% of increment. The result suggests it is highly possible that the citation number of TENG articles in 2018 will significantly exceed the total number in 2017, implying that the TENG research field is still expanding.

Tinghai Cheng received the B.Sc., M.Sc., and Ph.D. degrees from Harbin Institute of Technology in 2006, 2008, and 2013, respectively. He was a visiting scholar in School of Materials Science and Engineering at Georgia Institute of Technology under the supervision of Prof. Zhong Lin Wang from 2017 to 2018. Currently, he is an associate professor in the school of mechatronic engineering, Changchun University of Technology. His research interests are triboelectric nanogenerators, piezoelectric energy harvester, and piezoelectric actuators.

Qi Gao was born in 1995 in Jilin province, majored in mechanical engineering and achieved the B. Eng. degree from Changchun University of Technology in 2017. He continues pursuing a Master of Engineering degree in the same school. His research interests are triboelectric nanogenerators.

Zhong Lin Wang is the Hightower Chair in Materials Science and Engineering and Regents' Professor at Georgia Tech, and the chief scientist and director of the Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences. His discovery and breakthroughs in developing nanogenerators and self-powered nanosystems establish the principle and technological road map for harvesting mechanical energy from environmental and biological systems for powering personal electronics and future sensor networks. He coined and pioneered the field of piezotronics and piezophototronics.

3. Future Outlook of TENG Development

Through the analysis of published articles, the growing trend and global impact of TENG have been discussed in the previous sections. Herein, we would like to further discuss the major applications of TENG in the previous articles, along with the future prospect of TENG development.

Figure 8 shows the collection of major applications of TENGs previously published articles. There are three major

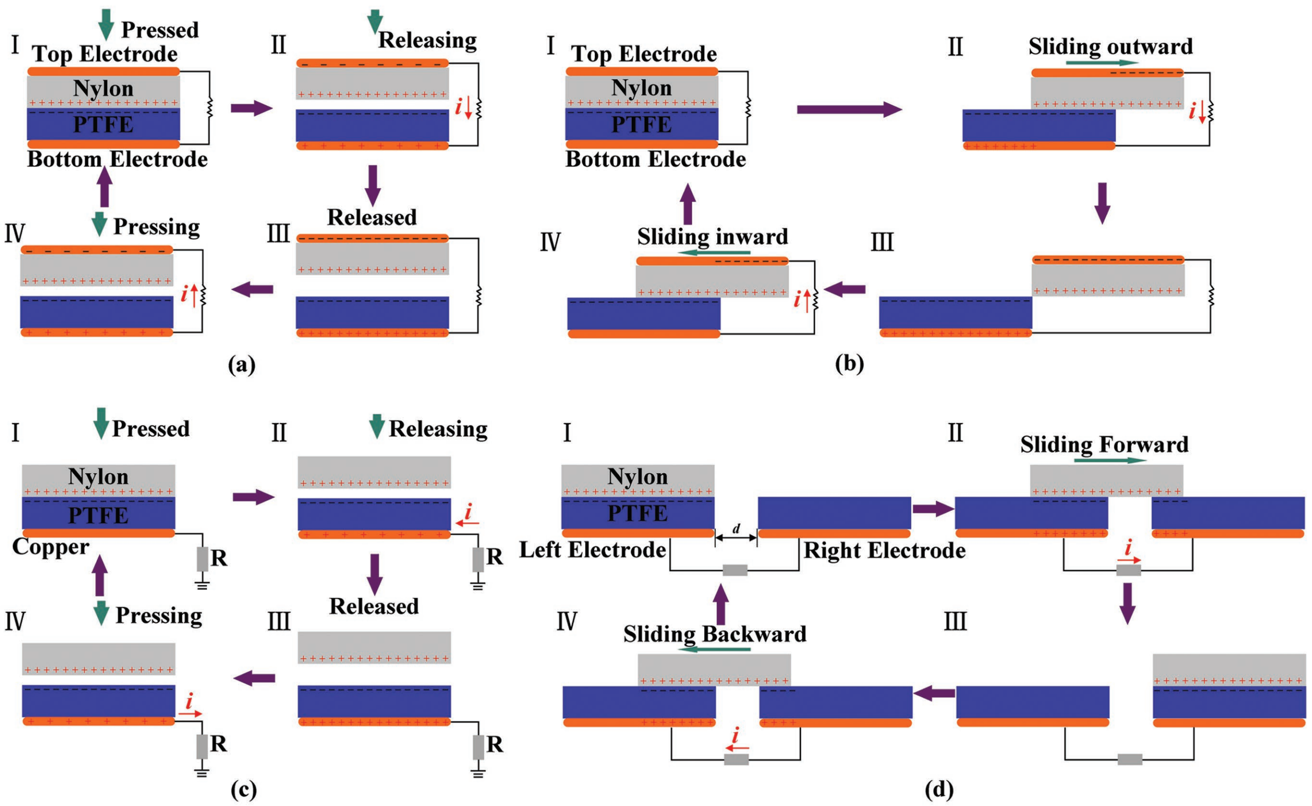

Figure 1. Four basic modes of TENG.

directions: using TENG as self-powered sensors/systems for biomedical monitoring, human-machine interface for security or identification, and robotics;[6,9–12] using TENG for harvesting water-wave energy to achieve the concept of blue energy;[13,14] using TENG as sustainable micro/nanopower sources for small electronic devices to achieve the idea of self-powering devices and so on.[7,15–17] The results suggest that TENGs are very promising with a wide range of applications in different

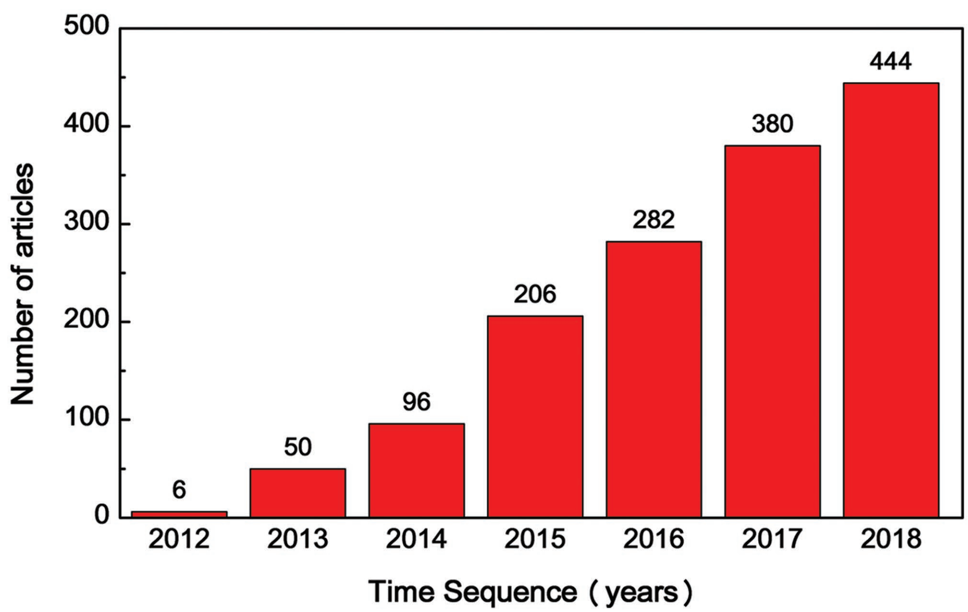

Figure 2. Number of articles on triboelectric nanogenerator published each year (by October 10th, 2018).

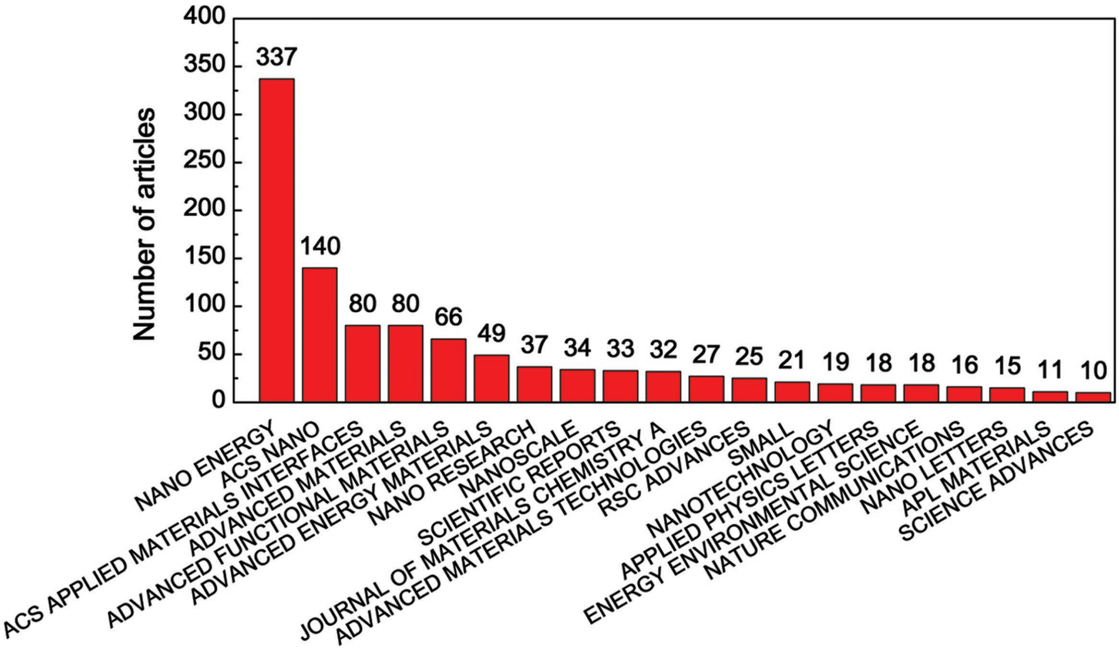

Figure 3. Number of articles of triboelectric nanogenerator published in top 20 scientific journals.

fields. However, we would like to point out some unsolved technical challenges.

First, as TENGs have been proved that they can efficiently harvest energy at low frequency, they can convert irregular mechanical energy from the ambient environment and human motions into electricity. However, one of the features of the electrical output is generally pulsed with high voltage, which is not suitable for direct use as a power source. To provide continuous electrical output to drive conventional electronics, a power management is urgently required. Second,

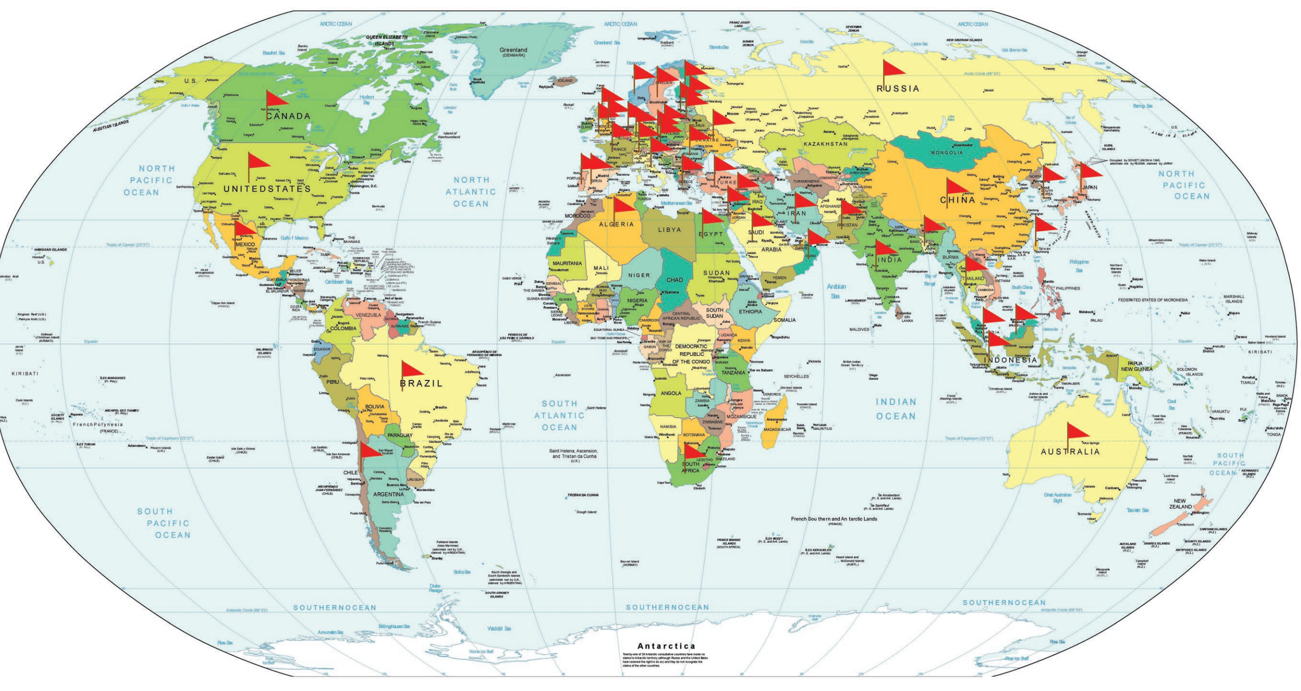

Figure 4. Triboelectric nanogenerator research conducted by research institutes and universities across six continents globally.

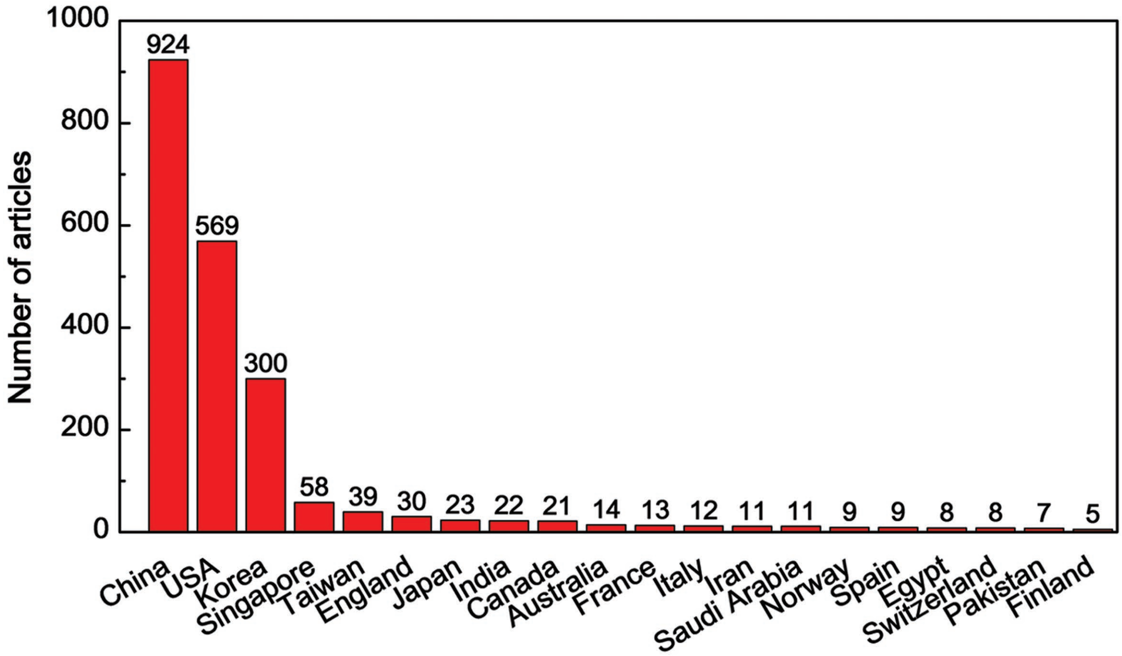

Figure 5. Number of articles of triboelectric nanogenerator published in different places.

researchers can investigate the more fundamental phenomena of triboelectrification under extreme environmental conditions, such as high temperature, high magnetic field, or vacuum environment, which could help answer the key physics questions (e.g., electron transfer) of contact electrification. Although previously published articles have unveiled some mechanisms,[18,19] more efforts should be put in to answer those fundamental physics questions. Third, although it has been proposed that there are four basic working models of TENGs, using the mechanical structural design to improve the performance is still lacking. As mechanical structural design can be used to improve the frequency of mechanical motions, or transform mechanical motions to different directions, etc., the integration of complex mechanical design is expected to improve the performance of

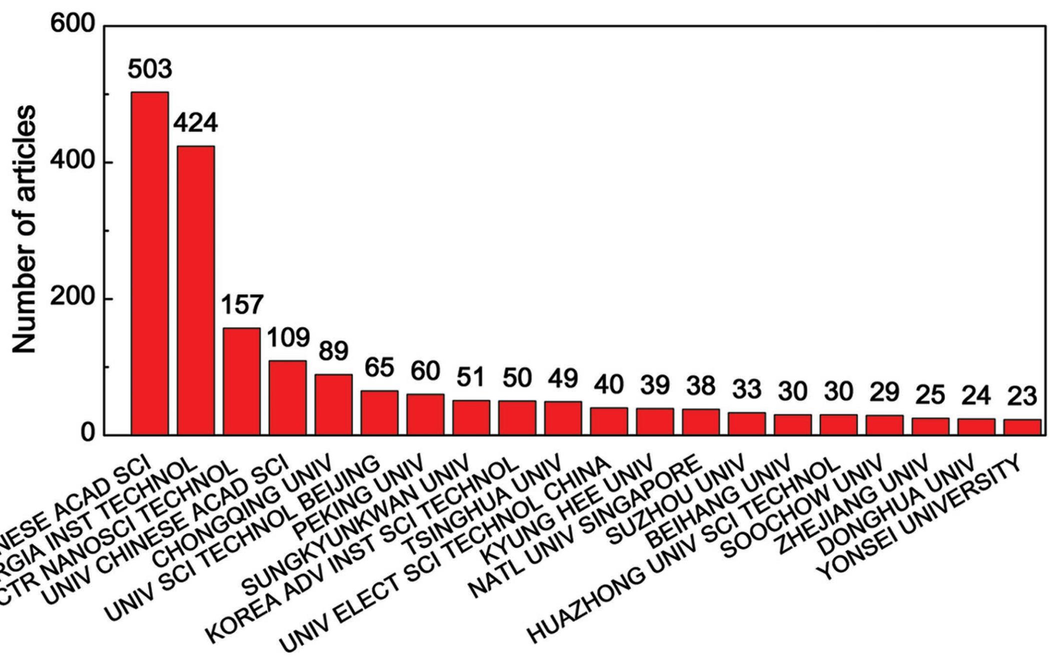

Figure 6. Number of articles of triboelectric nanogenerator from different research institutes.

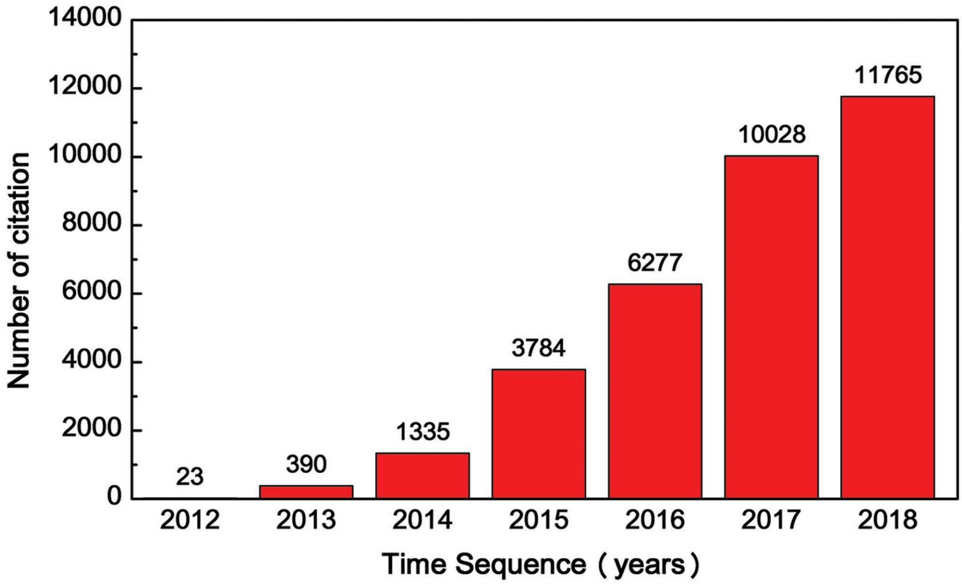

Figure 7. Number of articles citing triboelectric nanogenerator research articles.

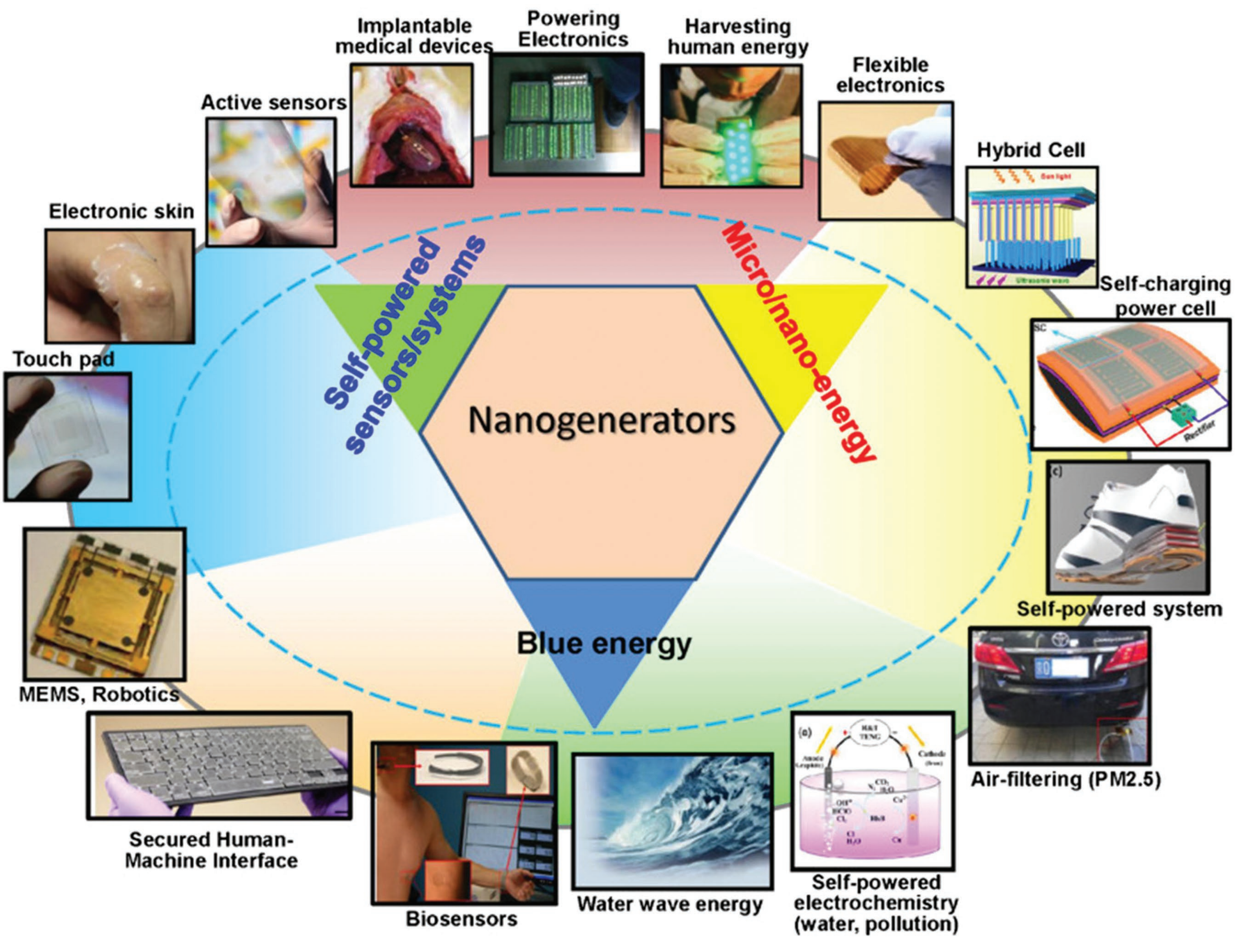

Figure 8. A summary of the three major fields of nanogenerators: serving as self-powered sensors, blue energy (water-wave energy harvesting), and micro-/nanoenergy source. Reproduced with permission.[8] Copyright 2017, the authors, published under CC BY-NC-ND 4.0.

TENGs, and open up more potential applications in mechanical structures and even robotics. Last, to take advantage of the self-powered sensing technologies and integrate them with artificial intelligence. Recently, TENGs have been introduced to the area of ubiquitous computation,[20] which shows the potential of using TENGs to build up an actual sensor network for further applications.

In conclusion, through this analysis, the emerging TENG technology has shown great potential in various fields globally and keeps expanding rapidly. It can be expected that the upward trend of the TENG development could potentially lead to more practical applications in the future.

Acknowledgements

Research was supported by the Hightower Chair foundation, the National Key R&D Project from Minister of Science and Technology (2016YFA0202704), and the National Science Foundation of China (51775130). T.H.C. also thanks the China Scholarship Council for supplying oversea scholarship.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

blue energy, self-powered systems, triboelectric nanogenerators

Received: November 2, 2018
Revised: December 12, 2018
Published online:

[1] Z. L. Wang, J. Song, *Science* **2006**, *312*, 242.
[2] Z. L. Wang, *Sci. Am.* **2008**, *298*, 82.
[3] F. R. Fan, Z. Q. Tian, Z. L. Wang, *Nano Energy* **2012**, *1*, 328.
[4] F. R. Fan, L. Lin, G. Zhu, W. Wu, R. Zhang, Z. L. Wang, *Nano Lett.* **2012**, *12*, 3109.
[5] S. Wang, L. Lin, Z. L. Wang, *Nano Lett.* **2012**, *12*, 6339.
[6] S. Wang, L. Lin, Z. L. Wang, *Nano Energy* **2015**, *11*, 436.
[7] Z. L. Wang, J. Chen, L. Lin, *Energy Environ. Sci.* **2015**, *8*, 2250.
[8] Z. L. Wang, *Mater. Today* **2017**, *20*, 74.
[9] K. Dong, J. Deng, Y. Zi, Y. C. Wang, C. Xu, H. Zou, W. Ding, Y. Dai, B. Gu, B. Sun, Z. L. Wang, *Adv. Mater.* **2017**, *29*, 1702648.
[10] Z. L. Wang, *ACS Nano* **2013**, *7*, 9533.
[11] R. Liu, X. Kuang, J. Deng, Y. C. Wang, A. C. Wang, W. Ding, Y. C. Lai, J. Chen, P. Wang, Z. Lin, H. J. Qi, B. Sun, Z. L. Wang, *Adv. Mater.* **2018**, *30*, 1705195.
[12] H. Guo, X. Pu, J. Chen, Y. Meng, M. H. Yeh, G. Liu, Q. Tang, B. Chen, D. Liu, S. Qi, C. Wu, C. Hu, J. Wang, Z. L. Wang, *Sci. Rob.* **2018**, *3*, eaat2516.
[13] S. L. Zhang, M. Xu, C. Zhang, Y. C. Wang, H. Zou, X. He, Z. Wang, Z. L. Wang, *Nano Energy* **2018**, *48*, 421.
[14] Z. L. Wang, T. Jiang, L. Xu, *Nano Energy* **2017**, *39*, 9.
[15] M. Xu, P. Wang, Y. C. Wang, S. L. Zhang, A. C. Wang, C. Zhang, Z. Wang, X. Pan, Z. L. Wang, *Adv. Energy Mater.* **2018**, *8*, 1702432.
[16] Y. Chen, Y. C. Wang, Y. Zhang, H. Zou, Z. Lin, G. Zhang, C. Zou, Z. L. Wang, *Adv. Energy Mater.* **2018**, *8*, 1802159.
[17] Z. L. Wang, *Faraday Discuss.* **2014**, *176*, 447.
[18] C. Xu, Y. Zi, A. C. Wang, H. Zou, Y. Dai, X. He, P. Wang, Y. C. Wang, P. Feng, D. Li, Z. L. Wang, *Adv. Mater.* **2018**, *30*, 1706790.
[19] J. Wang, C. Wu, Y. Dai, Z. Zhao, A. Wang, T. Zhang, Z. L. Wang, *Nat. Commun.* **2017**, *8*, 88.
[20] N. Arora, S. L. Zhang, F. Shahmiri, D. Osorio, Y. C. Wang, M. Gupta, Z. J. Wang, T. Starner, Z. L. Wang, G. D. Abowd, *Proc. ACM Interact., Mobile, Wearable Ubiquitous Technol.* **2018**, *2*, 1.