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Piezoelectric and triboelectric nanogenerators: Trends and impacts

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ABSTRACT

Piezoelectric and triboelectric nanogenerators are the two recently developed technologies for effective harvesting of ambient mechanical energy for self-powered systems. The work herein briefly reports the trends and impacts of research based on piezoelectric and triboelectric nanogenerators. For the first time, a statistical study of publication trends in piezo- and triboelectric nanogenerators is used to investigate the current state of the research. We investigate the status of the research in these fields, based on their S-shaped history, as a description of their growth in size over time, considering the number of citations and published papers that use these two novel technologies. A brief discussion of the outlook for these technologies and their potential impact on everyday life is presented, particularly in the development of future 'smart' cities.

Introduction

Nanogenerators (NGs) have resulted in a revolution in the field of energy harvesting and sensing, and accordingly, a sharp growth of publications and research collaboration has emerged in these areas of research. The idea of nanogenerators was first proposed in 2006 embodied in the term "piezoelectric nanogenerators" (PENGs) [1]. Since then, PENGs have been used for many different applications and have prompted researchers to implement them for powering mobile devices and wearable electronics [2]. Six years later, a new method of energy harvesting, based on the triboelectrification effect, was proposed. This novel technology is called "triboelectric nanogenerators (TENGs)"[3]. Similar to PENGs, the new technology of energy harvesting has attracted many researchers to utilize it as a potent and viable approach in different self-powered sensing instruments. TENGs and PENGs have been used so far in different applications including wind [4] and water wave energy harvesting [5,6] traffic flow monitoring [7], tire condition monitoring [8,9] tactile sensing [10], biomedical energy harvesting [11], and safety systems [12]. In addition, researchers have provided a detailed techno-economic lifecycle assessment of two representative examples of TENG modules [13]. Nanogenerators, especially TENGs, have shown a high power density in comparison with other competitive technologies such as electromagnetic generators (EMGs). There are plenty of other advantages for nanogenerators in comparison with EMGs including high voltage, high efficiency at low frequency, low cost, low weight, multiple working modes and material choices.

In this work, we briefly study the the impact of nanogenerators on the field of energy harvesting and sensing. In addition, we relate the trends in publications to dynamic growth in nature, which is called S-shaped history [14].

S-shaped history and energy harvesting

Many common time-dependent growth phenomena in nature, such as population growth, follow an 'S-shaped' history, as shown in Fig. 1a [14]. The first part of the S-shaped curve, during time interval 0 to t_i is called the 'invasion' region, which shows two different phases, lag and positive acceleration. After time t_i the second phase starts, and ends at time $t_i + t_c$. This time interval is called the 'consolidation' region. The last part of the S-shaped curve is the 'plateau', which includes negative acceleration and stationary phases[14].

We look at the publication growth in the field of mechanical energy harvesting since 2000 in Fig. 1b. As the figure shows, the first six years from 2000 to 2006 represent the invasion part of the S-shaped curve. In 2006, discovery PENGs results in more researchers being attracted to the field of mechanical energy harvesting giving rise to 'consolidation' part of the S-shaped history. The discovery

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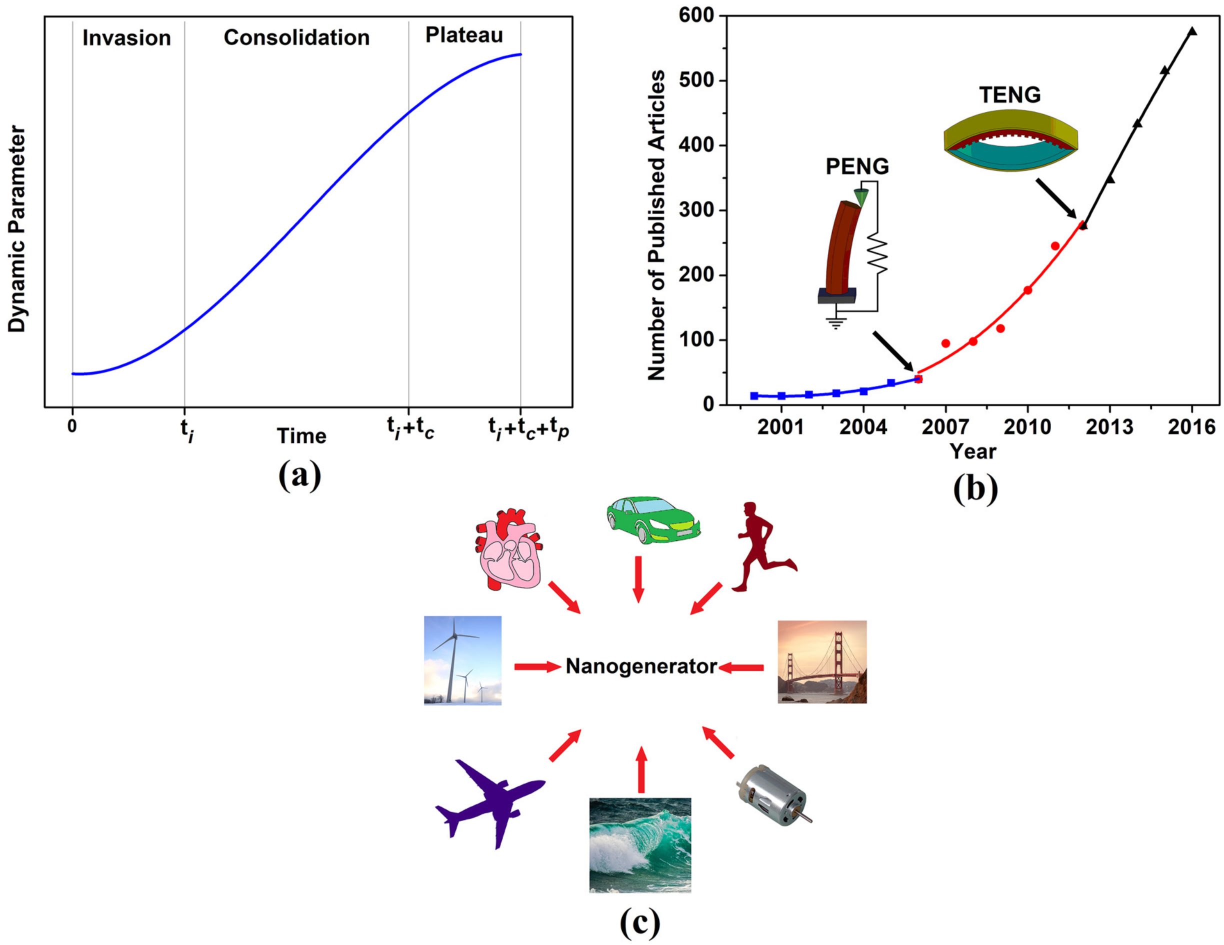

Fig. 1. a) Illustration of S-shaped history, b) Trends of publications in the area of energy harvesting c) Applications of TENGs and PENGs in different systems.

of TENGs six years later increased the growth in publications in the field.

As shown in Fig 1b, the discovery of both piezoelectric and triboelectric nanogenerators has resulted in two distinct increases in the growth of publications in the field of energy harvesting. A decade of working and performing research on 'nanogenerators' has now delivered several novel platforms for energy harvesting and self-powered sensing. 'Nanogenerators' have shown promising potential for different applications including transportation, healthcare and rehabilitation after surgery or injury, wind and wave energy generators, vibration monitoring, mobile electronics, wearable/flexible electronics and even environmental protection as shown in Fig. 1c.

Piezoelectric nanogenerators

The very first article in which the term "piezoelectric nanogenerator" was used is a paper by Z. L. Wang who is the inventor of this concept. Based on the Web of Science Database, this revolutionary article has been cited more than 3500 times in only one decade (2006–2016). Fig. 2a shows the trend in citations of this article, and the high impact this topic has had on the research community in the field of energy harvesting and sensing. Fig. 2a shows that research progress in the area of piezoelectric nanogenerators is at the 'consolidation' stage and we expect that it will achieve monotonic progress in coming years. Both extracted data from Google Scholar and Web of Science follow a similar trend as indicated with black and red lines in Fig. 2a. Based on this figure, we can see that this new field of research has matured rapidly, and has attracted the attention of many researchers and scientists in a span of only 10 years.

Triboelectric nanogenerators

The triboelectric nanogenerator was first proposed in 2012 as an effective means to harvest wasted kinetic energy to power portable electronic devices. Since then, this new approach has attracted researchers to try to implement TENGs in applications. In the last five years, hundreds of papers have been published, and a number of devices have been fabricated using this new technology. Fig. 2b indicates the number of citations for the first article, which proposed the triboelectric nanogenerator in 2012. After 5 years, this article has been cited more than 700 times. The rapid development of this new technology, in only a few years, demonstrates the high demand for TENGs in future electrical devices and mobile electronics.

As presented in Fig. 2c, about 195 patents have been registered based on triboelectric and piezoelectric nanogenerators.

World map of NGs

Fig. 2d indicates the contribution of different countries to the area of PENGs. Based on the Scopus database, more than twenty nine countries have at least one published paper based on the new concept of PENGs. The United States of America and China have presented the highest number of published papers in this field, respectively. After USA and China, South Korea, India, and Taiwan have shown significant contributions to the area of PENGs, respec-

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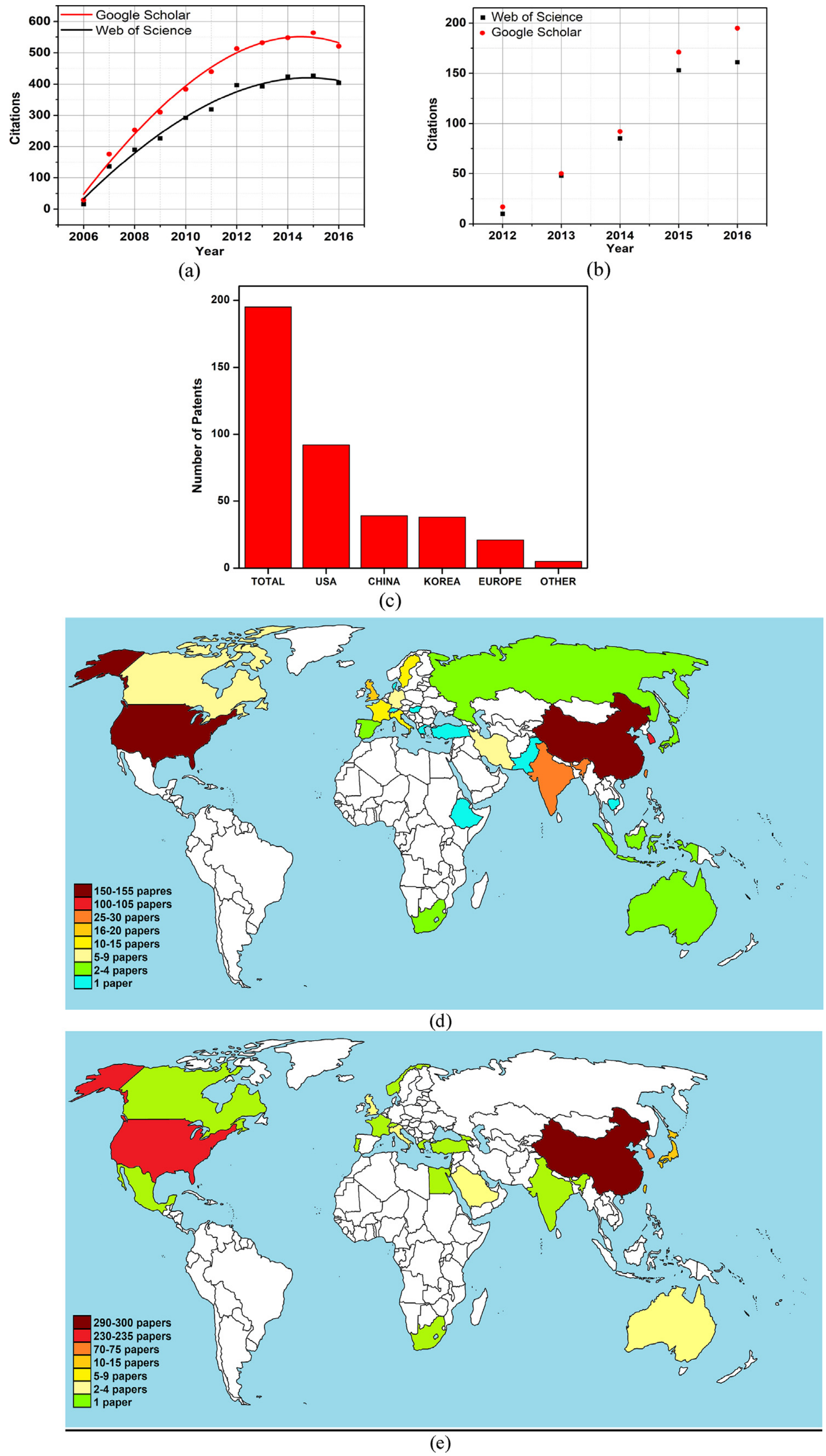

Fig. 2. a) Trends in citations of the first article [1], which proposed “piezoelectric nanogenerators”, b) Trends of citations of the first article [3], which proposed triboelectric nanogenerators, c) registered patents based on nanogenerators d) countries with publications about “piezoelectric nanogenerators” (2006–2016), e) countries with publications about “triboelectric nanogenerators” (2012–2016).

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tively. Georgia Institutes of Technology in USA, Chinese Academy of Sciences in China, and Sungkyunkwan University in South Korea stand out as centers of development in this field.

Fig. 2e represents the contribution of different countries to the field of TENGs. Based on the Scopus database, authors from more than twenty countries have published at least one paper in the area of TENGs. China, USA, South Korea, Taiwan and Japan have the highest number of published papers in this area, respectively. Georgia Institutes of Technology and Chinese Academy of Sciences have had significant contributions in development of this new technology.

Perspective

PENGs and TENGs have exhibited a significant impact on the field of energy harvesting and self-powered sensing. These two new technologies have shown promising potential for developing new systems for different applications such as kinetic energy harvesting, condition monitoring, biomedical systems, and also for powering portable devices. Researchers have shown that nanogenerators can be used in smart watches, self-powered keyboards, self-powered touch pads, safety devices, ocean wave based energy harvesters, and intelligent tires.

The high potential and capability of these two new technologies could lead to many new instruments in different systems. For example, nanogenerators can be used in biomedical and rehabilitation devices as smart sensors, or as a sustainable energy source. Thus, these devices could be effective for smart health monitoring and healthcare. In addition, these technologies can be utilized in different parts of automotive vehicles such as the tires, suspension, exhaust, and as self-powered sensors, accelerating the development of 'smart' vehicles. Smart homes could also benefit from NGs as a sustainable power source. Nanogenerators could even provide a reliable solution for the energy supply of smart cities of the future by effectively scavenging wasted kinetic energy from the environment.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.nantod.2018.08.001.

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