Nanogenerators: A new paradigm in blue energy-harvesting

Arpita Adhikari¹, Joydip Sengupta²*

¹Department of Electronics and Communication Engineering, Techno Main Salt Lake, Kolkata-700091

²Department of Electronic Science, Jogesh Chandra Chaudhuri College, Kolkata-700033

* Corresponding author, E-mail: joydipdhruba@gmail.com

The depletion of natural energy sources demands non-conventional efficient alternatives with sustainable utility. The outstanding performance of nanomaterials resolves the energy scarcity issue through the introduction of small-scale, energy-harvesting devices, called nanogenerators. A nanogenerator is an ambient energy-harvester with exotic features of being a lightweight, sustainable and stand-alone device which promises efficient utilization of energy. Conversion of mechanical/thermal energy into electricity is the basic working principle of a nanogenerator. The nanogenerators employ piezoelectric or triboelectric properties of a material to harvest electrical energy from mechanical energy whereas for the generation of electrical energy from thermal energy the pyroelectric or thermoelectric properties are utilized. The unique and variant range of applicability of nanogenerators makes them increasingly popular among the scientific communities having interdisciplinary research interests. Nanogenerators are employed successfully in different energy sectors such as solar energy, water (blue) energy, wind energy and many more. The present chapter will summarize the fundamentals of different types of nanogenerators along with their applicability in harvesting blue energy.
Keywords: piezoelectric nanogenerator (PENG); triboelectric nanogenerator (TENG); pyroelectric nanogenerator (PyENG); thermoelectric nanogenerator (ThENG); self-powered systems; blue energy.

1. Introduction

The progress of civilization has undoubtedly reached its unprecedented peak with the commencement of the fourth industrial revolution in the 21st century. The present age of industrial advancement quite expectedly is facing an elevated demand for energy resources. Limited storage of natural energy resources is making the situation more critical day by day. Consequently, modern industries are confronting enormous energy challenges. Moreover, the modern time of industrialization threatens the near future of the mankind with the rising level of carbon pollution that paved the path of unpredictable changes of Earth’s climate possibly resulting in even scary extinction of life. The only way out of the critical situation may be the search for alternative and sustainable energy resources\(^1\). In the perspective of climate change, the added feature that a sustainable energy resource should have is that the energy utilization needs to be pollution-free. Thus the futuristic growth of science and technology is confronting the dual challenge of energy crisis and carbon pollution (Fig 1).
Fig.1. The global energy system faces a dual challenge: the need for ‘more energy and less carbon’.

2. Origin of Nanogenerators:

The search for alternative energy resources particularly in terms of the non-conventional and sustainable form is the essential prerequisite of modern society to maintain the futuristic scientific, technological and industrial drive towards a new era of automation. The novel advancement of mankind would not be possible without the revolutionary concept of the Internet of Things (IoT). All of this technological progress is the phenomenal consequence of the technological achievement of miniaturization science. Nanotechnology is the utmost discovery of miniaturization science which even outperformed the projection of technological growth that had been foreseen by Moore, decades before in 1975. Nanotechnology gives birth to nanodevices that need the power to operate. However, in general, the market-available battery size is much larger than the nanodevices, thus in turn governing the size of the entire system. Consequently, the practical realisation of a nano battery is highly desirable, preferably employing alternative energy resources. The nano-size battery usually has
a small lifetime posing a great hurdle to scientists. The desirable alternative is to develop a nano-sized battery that can harvest energy from the environment to become a self-sufficient green power resource for driving nanodevices. Nanogenerators are just fit in this scope. Firstly, they are of nano-size order and secondly, they are capable of converting naturally available mechanical energy into electrical energy. Moreover, this energy suffices to drive the nanodevice in self-power mode. The term nanogenerator was first coined in 1993 while the seed to the invention of nanogenerators is sowed long before in 1861 with the postulation of Maxwell’s equation (Fig 2).

According to Maxwell’s equation, the displacement current has two components. The first term of Maxwell’s equation, $\varepsilon_0 \frac{\partial E}{\partial t}$, postulates the origin of magnetic induction from the electric field. The term thus forms the basis of electromagnetic wave generation, the application of which extends to modern wireless communication technology. The second term $\frac{\partial P}{\partial t}$ defines the polarisation of medium and from this key term, the fundamental features of nanogenerator were originated. In nanogenerators, Maxwell’s displacement current serves as the driving force for converting mechanical energy into electrical energy.
Fig 2: A tree idea to illustrate the newly revised Maxwell’s displacement current: the first term $\varepsilon_0 \frac{\partial E}{\partial t}$ is responsible for the electromagnetic waves theory; and the newly added term due to $\frac{\partial P}{\partial t}$ is the applications of Maxwell’s equations in energy and sensors, which are the nanogenerators.\(^5\)

Presently, four primary effects, namely, piezoelectric, triboelectric, pyroelectric, and thermoelectric, are employed to develop nanogenerators which are widely utilized in different potential application sectors (Fig 3).
Fig 3a. Schematic illustration of nanogenerators based on (i) the piezoelectric effect, (ii) the triboelectric effect, (iii) the thermoelectric effect, (iv) the pyroelectric effect.
3. Piezoelectric nanogenerator (PENG)

In some materials, if stress is applied then their atomic structure alters which prompts the formation of dipole moment and leads to the generation of a voltage difference across the material. This type of material is called piezoelectric material and the said effect is known as the direct piezoelectric effect. However, if electrical polarisation occurs within piezoelectric material, then material deformation takes place. This is known as a converse piezoelectric effect (Fig 4).
A PENG is an energy harvesting nanodevice that can convert external mechanical energy into electrical energy employing the piezoelectric effect within a nanostructure piezoelectric material. PENG was first developed in 2006 by Wang’s group.

The basic working principle of a PENG relies on the piezo potential, which is produced within the piezoelectric material. In general, two electrodes are connected at the opposite sides of the piezoelectric material. Initially, the Fermi levels of the two electrodes are balanced electrostatically. When strain is employed to the material by external means, the piezo potential is developed within the material producing a difference in-between the internal and external Fermi levels at the contacts. To nullify the differences in-between the Fermi levels, the electrons start to flow through external circuits in-between two electrodes till two electrodes are electrostatically rebalanced. External mechanical forces can trigger strain within PENG in such a way that the strain undergoes periodical variations. This will give rise to an alternating current (AC) at the PENG output and establishes the PENG as a promising power source for the nanosystems.

The external mechanical force can be applied in two directions: one is perpendicular to the nanowire and the other is parallel to the nanowire (Fig 5a). However, in both cases, the top
contact behaves as Schottky contact and the bottom contact behaves like an ohmic contact. To boost the output power of the PENG, several nanowires should be integrated in such a way that the deformation of each nanowire is perfectly synchronized. Till now, there are two types of structures of PENG, namely, lateral-nanowire integrated NG (LING) and vertical-nanowire integrated NG (VING) (Fig 5b). In LING, the nanowires are grown parallel to a flexible substrate and during bending deformation all the nanowires are deformed synchronously with the substrate, resulting in elevated output power. While in VING, the device is fabricated directly on vertically grown nanowire arrays and it can produce energy from synchronous compression deformation of the NG.

Fig 5a. Different mechanism of operation of PENG: (left) Force exerted perpendicular to the growth of the nanowire and (right) Force exerted parallel to the growth of the nanowire.
Different piezoelectric materials such as lead zirconate titanate, barium titanate, zinc oxide, polyvinylidene fluoride, cadmium sulphide, molybdenum disulfide were used for the fabrication of PENG.

4. Triboelectric nanogenerator (TENG)

Some materials get electrically charged when they make frictional contact with another dissimilar material. This kind of contact-induced electrification is known as the triboelectric effect (Fig 6). After physical contact, the materials become oppositely charged, while, the strength of the charges is different for different materials.
Based on triboelectrification and electrostatic induction effects, Wang’s group first put forward the idea of TENG in 2012. There are four basic modes for TENG, namely vertical contact-separation (CS) mode, lateral-sliding (LS) mode, single-electrode (SE) mode, and freestanding triboelectric-layer (FT) mode. In all the four kinds of TENGs, there is a minimum of one pair of triboelectric surfaces with at least two electrodes (For SE mode, the ground is the other electrode). In the triboelectric effect, transport of electrostatic charges occurs from one surface to the other. Upon displacement of one of the triboelectric surfaces, the electrostatic status of the system changes resulting in the generation of the potential difference in-between the two electrodes. Subsequently, the generated potential difference causes a current to flow via the external circuit to balance the electrostatic status. Displacement of the triboelectric layers in the opposite direction creates a reverse potential difference in-between the electrodes, and therefore the current flows in the opposite direction. Thus, an AC output is generated from the TENG via periodical displacement of triboelectric layers.

The triggering process is different in all four modes of TENG (Fig 7). Contact and separation process of the two triboelectric layers causes triggering of CS mode while relative sliding between triboelectric layers is responsible for the triggering of LS mode. In both CS and LS
mode TENG, the external load is connected between the back electrodes of moving triboelectric layers and thereby imposing a limitation in the movement of the triboelectric layers. However, this limitation is waived off in the SE and FT mode of operation. In SE mode a triboelectric layer moves freely with respect to one static electrode, while in FT mode a triboelectric layer moves freely between the two static electrodes to trigger the NG. To increase the output power of TENG via structural optimization, different structures like the multi-layer integrations and grating structures have been fabricated.

![Diagram of working modes of TENG](image)

*Figure 7. Four working modes of TENG. a) Vertical CS mode. b) LS mode. c) SE mode. d) FT mode.*

Different natural and eco-friendly materials that can be used to fabricate TENG are described in recent reviews by Slabov et al. and Kim et al.

5. Pyroelectric nanogenerator (PyENG)

The time-dependent temperature fluctuation often causes spontaneous polarization in certain anisotropic solids, which is known as the pyroelectric effect. The key parameter of the pyroelectric effect is the pyroelectric coefficient which can be described as the differential
change in spontaneous polarization owing to an alteration in temperature. The pyroelectric coefficient is the attribute of two phenomena, namely primary pyroelectric effect and secondary pyroelectric effect. If all the dimensions of material remain constant (strain-free case), then the primary pyroelectric coefficient is employed to express the amount of charges generated due to an alteration in temperature. On the other hand, if the dimensions of a material are altered due to the temperature variation, then such anisotropic deformation of the material will produce a strain causing an additional contribution of piezoelectrically induced charges. This process is called secondary pyroelectric effect. In lead zirconate titanate, potassium niobate, barium titanate and some other ferroelectric materials the primary pyroelectric effect dominates while in zinc oxide, cadmium sulfide and some other wurtzite-type materials the secondary pyroelectric effect will predominate.

Based on the pyroelectric effect, Wang’s group devised the first pyroelectric nanogenerator (PyENG) in 2012. The principle of generation of current via primary pyroelectric coefficient can be explained through the example of potassium niobate nanowire PyENG. In potassium niobate dipole moments readily exist along with the spontaneous polarization density (Fig 8(a)-top). With increasing temperature, the random oscillations of the ions will intensify with a greater magnitude of spread around their corresponding aligning axes. This causes a reduction in effective dipole moments and consequently, the polarization density is decreased. To regain the previous electrostatic status, charge carriers flow through the external circuit (Fig 8(a)-middle). Even if the PyENG is cooled down from ambient temperature, the oscillations of the ions are reduced with a smaller amplitude of spread across their respective aligning axes and thereby causing an enhancement in effective dipole moments. The resulting increase in polarization density prompts the flow of charge in the reverse direction (Fig 8(a)-bottom).
The principle of generation of current via secondary pyroelectric coefficient can be explained via the example of zinc oxide nanowire. PyENG were vertically grown zinc oxide nanowires are sandwiched between two electrodes (Fig 8b). With the increase in temperature, a pyroelectric potential is created along zinc oxide nanowire, thus one electrode becomes electrically positive and the other electrode becomes electrically negative. As the Fermi level of the electrically negative electrode is enhanced, it will drive the electrons to flow from the negative electrode to the electrically positive electrode. After the temperature goes down to the initial value, the electrons accumulated at the positive electrode are released and flow back to the negative electrode as the pyroelectric electrical potential is faded away. Here, a difference in piezoelectric potential is created across the material by the anisotropic thermal deformation and because of the emerged potential difference, the electrons flow through the external circuit. Thus the output of secondary pyroelectric effect based nanogenerator is the combined effect of the piezoelectric coefficient and the anisotropic thermal deformation of the material.

*Fig 8a. Primary pyroelectric effect*. 

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Fig 8b. Secondary pyroelectric effect (Where D denotes electrical displacement, S denotes constant strain, E denotes electric field, T denotes elastic stress, σ denotes entropy, θ denotes temperature). 

Different materials like triglycine sulfate, gallium nitride, zinc oxide, perovskite-based pyroelectrics were used to fabricate PyENG.

6. Thermoelectric nanogenerator (ThENG)

If two interconnected dissimilar conductors are maintained at different temperatures, then a potential difference is created between the conductors that are directly proportional to the
temperature difference and such potential difference results in the flow of current in the loop. This thermoelectric phenomenon is called the Seebeck effect (Fig 9).

![Diagram of energy generation mechanism using the thermoelectric effect](image)

**Fig 9 Diagram of energy generation mechanism using the thermoelectric effect**.

The Seebeck effect is utilized to fabricate ThENG. If a thermal gradient exists in the environment, then a ThENG can convert the heat into electrical energy. In 2012 Wang’s group first fabricated ThENG using single Sb-Doped ZnO Micro/Nanobelts \(^{38}\) (Fig 10a). They had placed the ZnO belt on a glass substrate and used silver paste to fix the two ends, which eventually acted as electrodes with a separation of 3 mm. They found that 30 K temperature difference between two electrodes of ThENG can produce output current and voltage of about 194 nA and 10 mV, respectively.

To explain this phenomenon, a \(\pi\)-type model can be employed. In the \(\pi\)-type model, the structure is made up of one p-type and one n-type semiconductor, which is connected via a conducting wire/strip to complete the electrical circuit (Fig 10b). When one side of p-type and n-type material is heated and another one is cooled, the majority charge carriers (holes) of p-type materials and that (electrons) of n-type materials will diffuse from the hot side to
the cold side. This diffusion process results in building-up charge carriers at the cold end. Such build-up of charge carriers at one end produces a potential difference across the semiconductor, proportional to the temperature difference across the semiconductor. If the cold ends of both the semiconductors are electrically connected, then a current flows from the p-type material to the n-type material.

Fig 10a. A Zno ThENG based on the Seebeck effect (top left) Schematic diagram of a single Sb-doped ZnO micro belt NG. (bottom left) Calculated temperature distribution along a glass substrate. (right) I-V characteristic of a fabricated NG. 39.
7. Blue Energy and its harvesting using NG

As the futuristic growth of science and technology is confronting the dual challenge of energy crisis and carbon-pollution so renewable energy sources must be extensively explored and the use of fossil fuels should be restricted to a minimum.

Among the different renewable energy resources ocean energy is one of the least explored renewable energy sources on the earth. The total blue energy content of the Ocean was estimated to be $7.66 \times 10^{13}$ W$^4$. Both the thermal and mechanical energy can be harvested from the ocean. The temperature gradient that exists across the warm surface waters and the cool deeper waters can be utilized to generate thermal energy and mechanical energy can be harvested from the tides, waves and currents of the ocean. Blue energy has several advantages over the other available renewable energy resources. Firstly, blue energy is invariant to weather, time of the day, or temperature$^4$. Secondly, tides, waves and currents are predictable globally and more reliable than wind and solar energy. Finally, harvesting blue energy requires minimal use of land and small environmental interaction, thereby offering one of the most lenient techniques for large-scale, eco-friendly and sustainable electricity generation$^4$.

Among different NGs, TENG has a huge potential for harvesting blue energy$^4$. TENG can effectively harvest blue energy even at frequencies $< 5$ Hz which is perfectly suitable to harvest energy from a low-frequency ocean wave$^4$. Since the invention of TENG, much effort has been made to harvest blue energy via various designs of prototypes.

7.1 Water-involved TENG
In this type of TENG, water is used as one of the triboelectric materials and liquid-solid contact electrification harvests the output energy (Fig 11). The first water-involved TENG was reported by Lin et al.\(^46\) in 2013, where periodic contact and separation between water and polydimethylsiloxane (PDMS) pyramid array give rise to the output energy. The frequency response test revealed that the optimized power density is 50 mW/m\(^2\) at 5 Hz while the peak power density is nearly 0.13 W/m\(^2\). Here, the water remaining on the PDMS array will affect the output power. To overcome this hurdle, Lin et al.\(^46\) modified their design and used superhydrophobic polytetrafluoroethylene (PTFE) in place of PDMS and could achieve an output power of 20 mW/cm\(^2\). Later different kinds of polymer material with varied structures were employed by Zhu et al.\(^48\) and Zhao et al.\(^49\) for the fabrication of water involved TENG. By modification of the structures, they were able to achieve the output power up to 1.1 mW while initially; it was only 0.12 mW. When water flows through the air or an insulating tube, because of the contact with the air/solid surface, triboelectric charges will be induced on its surface and the water will contain the mechanical energy as well as the electrostatic energy. For harvesting the mechanical and electrostatic energies of flowing water, simultaneously, a dual-mode TENG was fabricated by Lin et al.\(^50\) employing a superhydrophobic TiO\(_2\) layer with hierarchical micro/nanostructures. Cheng et al.\(^51\) developed a dual-mode TENG consisting of a disk-TENG part and a water-TENG part. The water-TENG was composed of 8 wheel blades covered by PTFE film to harvest the electrostatic energy from flowing water. Kinetic energy can be harvested through the rotational movement of disk-TENG caused by the flowing water. A hybrid TENG comprising interfacial electrification enabled TENG and an impact-TENG was developed by Su et al.\(^52\) with an internal wavy-electrode structure to harvest mechanical energy and electrostatic energy from water. A novel cylinder-shaped structure TENG, based on contact electrification in-between water and PTFE filtration membranes, was proposed by Zhang et al.\(^53\). The
The recommended device can achieve a short-circuit current of 1.5 μA and an open-circuit voltage of 12 V. Fluorinated ethylene propylene (FEP) nanowire-based TENG was proposed by Li et al. Due to the presence of nanowires the contact area had been significantly increased and thus more friction between polymer and water took place which in turn had produced an output current of 10 μA and an output voltage of 200 V. Shi et al. proposed a buoy ball type symmetric spherical-shaped water-based TENG employing Al electrodes wrapped by Polytetrafluoroethylene (PTFE) thin film to produce the arbitrary directional and irregular water wave energy. A U-tube shaped TENG based on FEP was fabricated by Pan et al. to harvest blue energy. A further modified structure with sandwich-like water-FEP U-tube TENG was developed to harvest blue energy with a power density of 2.04 W/m³. Xu et al. developed a tower-shaped TENG which was composed of multiple units, made of PETF balls and nylon film-coated arc surface, connected in parallel. The tower-shaped TENG containing 10 units in parallel can harvest blue energy from random directions with a power density of 10.6 W/m³. Blue energy harvesting by regular fabric using a nontoxic and low-cost hydrophobic coating of Hydrophobic Cellulose Oleoyl Ester Nanoparticles (HCOENPs) was demonstrated by Xiong et al. Li et al. designed and fabricated a buoy-like liquid-solid contact-based TENG which magnifies the output energy via increased friction by 48.7 times, in comparison to the solid-solid contact-based TENG having an identical area. Nie et al. developed a novel liquid-liquid TENG that can harvest blue energy with a peak power of 137.4 nW by passing a liquid droplet through a freely suspended liquid membrane.
Fig. 11. Structure of a networked integrated triboelectric nanogenerator (NI-TENG). (a) Schematic diagram of a NI-TENG. (b) Enlarged sketch of the arrayed bridge rectifiers; c) SEM image of the PTFE nanowires on the electrification layer. (d) Enlarged view of the nanowires, inset: contact angle on the nanostructured surface. (e) Picture of a bendable as-fabricated NI-TENG, inset: Enlarged view of the rectifying diodes. 

However, one major problem of water involved TENG is that the seawater can corrode polymer films via direct contact. Thus to overcome this problem researchers are intending to use fully enclosed TENG to harvest blue energy as discussed in the next subsection.

7.2 Non-water-involved TENG

In general, a waterproof layer is employed in the non-water-involved TENG (Fig 12). In July 2013, the first non-water-involved TENG was fabricated in a fully enclosed spherical shell by Yang et al. using PTFE-polyamide (PA) film. A suspended three-dimensional spiral structured TENG was designed and fabricated by Hu et al. for harvesting blue energy with a power density of 2.76 W/m². Wen et al. developed a wavy-structured based TENG
comprised a Cu-Kapton-Cu film sandwiched in-between two flat nanostructured PTFE to collect blue energy with a power density of 0.4 W/m². Zhang et al. further modified the structure and designed a regular dodecahedron device containing 12 sets of wavy-structured TENGs. Each TENG consists of a wavy-structured Cu-Kapton-Cu film sandwiched between two flat nanostructured FEP thin films. This TENG can harvest 0.64 MW power from a 1 km² surface area of water. Chen et al. created a network of TENGs that can generate an average output power of 1.15 MW from a 1 km² surface area. A water treatment system was designed by Jiang et al. employing a TENG which will harvest energy from the water itself. Xu et al. designed an array of integrated TENG based on air-driven membrane structures with an optimized peak power density of 13.23 W/m³. Here air pressure was used to distribute and transfer harvested water wave energy and a spring-levitated oscillator helped it to achieve resonance in a short period. Jiang et al. developed a spring-assisted TENG comprising two Cu-PTFE-based TENGs connected through spring. They found that due to the presence of the spring, the energy conversion efficiency can be augmented by 150.3%. The spring-based structure was modified by Xiao et al. by employing silicone rubber/carbon black composite electrode which can provide better contact with the dielectric film. While triggered by the water waves it can generate output with a maximum power density of 2.40 W/m³. Later they fabricated a TENG array consisting of four spherical TENGs based on the spring-assisted multilayered structure to harvest power up to 15.97 mW. A box-shaped TENG consisting of wavy-structured Cu-Kapton-Cu and FEP films, with an enclosed metal ball, was designed and fabricated by Jiang et al. Later they optimised the charging behaviour under the enclosed ball collision and direct water wave impact. They reported that in case of the direct water wave impact, deformation depth governs the energy storage efficiency, whereas for the enclosed ball collision the size of the ball is responsible for energy storage efficiency. A ball-shell structured TENG network was developed by Xu et
al.\textsuperscript{74} with flexible connections. They found that the charge output of the coupled units is 10 times more in comparison to that without coupling. Cheng et al.\textsuperscript{75} devised a new methodology of soft-surface-contact based spherical TENG employing silicone rubber to maximize the transferred charge during the triboelectric effect by 10 folds in comparison to conventional PTFE based hard-contact TENG. A torus structured TENG enclosing a ball was fabricated by Liu et al.\textsuperscript{76} which can harvest blue energy with a power density of 0.21 W/m\textsuperscript{2}. Self-assembly of a self-healable and reconfigurable TENG network was developed by Yang et al.\textsuperscript{77} with an average power density of 8.69 W/m\textsuperscript{3}. A pendulum structured robust TENG was fabricated by Lin et al.\textsuperscript{78} which can deliver frequency multiplied output. Zhong et al.\textsuperscript{79} fabricated a TENG with an open book-like structure. Owing to its unique structure, many TENGs can be accommodated in a small area with a high packing density to harvest blue energy with a peak power density of 7.45 W/m\textsuperscript{3}. To harvest multidirectional blue energy, Lei et al.\textsuperscript{80} designed a butterfly-shaped TENG using spring-assisted four-bar linkage to achieve a maximum output power density of 9.559 W/m\textsuperscript{3}. A bimodal, highly stretchable, superhydrophobic TENG was developed by Chen et al.\textsuperscript{81} which was made of an ionic conductor and hierarchical micro-nano structures with self-cleaning properties. The proposed TENG can harvest blue energy with a power density of 0.36 mW. The principle of the pendulum was applied to fabricate a TENG with a compact disk-track structure to achieve a peak power density of 14.71 W/m\textsuperscript{3} via an area contact mechanism. An oblate spheroidal TENG was designed and fabricated by Liu et al.\textsuperscript{82} which is much superior compared to the traditional sphere shell and can harvest blue energy with a power density of 21.356 mW. The performance of spherical-shaped TENG was further improved by Liang et al.\textsuperscript{83} using a spring-assisted multilayered structure with an integrated power management module (PMM) to control the harvested energy.
8. Summary and perspective

Mankind moves towards modernization of every aspect of technology and modernization needs energy. However, the conventional energies are limited and thus the continuous proliferation of technological progress necessitates an alternative one. The process to harvest alternative energy should be inexpensive, self-powered, eco-friendly, sustainable and preferably maintenance free for a seamless growth of technology. The evolution of nanogenerator in 2006 created a revolution in harvesting alternative energy from the ambient environment by various means. The four physical processes, namely, piezoelectric effect, triboelectric effect, pyroelectric effect, thermoelectric effects were employed in the nanogenerators to harvest energy. The rapid growth in the development of the different nanogenerators has marked the foundation for self-powered modern electronic systems. However, to harvest ambient energy like blue energy on a large scale, a nanogenerator with
long durability, efficient energy conversion and enhanced output power density is desirable.

The futuristic research on nanogenerators should be focused on the efficient integration methodology and improved power management module.

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