Nanogenerators for Green Energy Harvesting

Subjects: Energy & Fuels

Contributor: Enrique Delgado-Alvarado , Ernesto A. Elvira-Hernández , José Hernández-Hernández , Jesús Huerta-Chua , Héctor Vázquez-Leal , Jaime Martínez-Castillo , Pedro J. García-Ramírez , Agustín L. Herrera-May

Natural sources of green energy include sunshine, water, biomass, geothermal heat, and wind. These energies are alternate forms of electrical energy that do not rely on fossil fuels. Green energy is environmentally benign, as it avoids the generation of greenhouse gases and pollutants. Various systems and equipment have been utilized to gather natural energy. Nanogenerators have recently emerged as an alterna- tive technique for collecting energy from both natural and artificial sources, with significant benefits such as light weight, low-cost production, simple operation, easy signal processing, and low-cost materials.

energy harvesting green energy hybrid nanogenerators

1. Introduction

The internet of things (IoT) gadgets, smart sensors, internet of medical things (IoMT) for healthcare systems, and consumer electronics devices have seen significant expansion in recent years. These devices often employ traditional batteries, which have drawbacks owing to their huge size, finite lifetime, and harmful components that contaminate the environment [1][2][3]. This issue with traditional batteries may restrict the efficiency of future IoT gadgets, smart sensors, and wearable devices. Thus, new eco-friendly alternative technologies to power these gadgets are current and future research challenges. Recent studies [4][5][6][7][8] have described nanogenerators capable of harvesting green energy by several transduction methods such as the piezoelectric, triboelectric, electromagnetic, and thermoelectric effects. The nanogenerators can harvest green energy from natural and artificial sources from wind, water, thermal, solar, mechanical vibrations, and motions of the human body [9][10][11][12][13]. These nanogenerators have unique features such as light weight, low-cost fabrication, tiny size, simple performance and signal processing, high power density, and a longer lifetime when compared to conventional batteries. Thus, nanogenerators provide a cost-effective alternative for powering future IoT devices, smart sensors, and consumer electronics products based on green energy harvesting from the environment. Furthermore, nanogenerators may be used to drive self-powered sensors for applications ranging from telecommunications to health monitoring, the automotive and military industries, agriculture, aerospace, and smart cities [14][15][16][17][18][19].

Most commercial low-power electronic devices require rectifier circuits to convert the variable output current of nanogenerators into direct current (DC). In addition, several researchers have used rectifiers coupled with antennas to design rectennas, which can harvest radio frequency (RF) energy and convert it to direct current [20][21][22][23][24][25]. Supercapacitors can also be integrated into nanogenerators to store their output power [26][27]. Thus, rectifier circuits and supercapacitors can enable the nanogenerators to have a consistent output power. In addition, hybrid nanogenerators may gather multiple green energy sources using two or more acquisition processes [28][29][30][31]. Due to this performance characteristic, hybrid nanogenerators can increase their output power densities in comparison to a single nanogenerator. The hybrid nanogenerators can power electronic devices for longer periods of time by utilizing various green energy sources (e.g., wind, heat, rain, solar radiation, and mechanical vibrations). These hybrid nanogenerators may be capable of harvesting a mix of green energies to continuously power electronics and sensors. This might enable the conversion of accessible green energy sources into electricity both during the day and at night, as well as in both indoor and outdoor environments.

More research is needed to increase the performance, stability, and reliability of nanogenerators. For instance, optimization methods may be utilized in the design of nano-generators for each individual application to forecast the best electrical and structural configurations and material selection. This optimized nanogenerator design can increase output power density and service time. Another idea is to employ wearable and flexible materials to create nanogenerators that are adaptive to the human body and gather biomechanical energy [32][33]. Additionally, effective packaging solutions for nanogenerators are necessary to improve their wear resistance and resistance to high temperature and humidity fluctuations. Better packing materials and the usage of long-lasting materials for nanogenerators can improve their reliability. The sensitivity of rectification circuits used in nanogenerators can be improved in the electronic section to produce a higher output DC power. Furthermore, these circuits may be manufactured utilizing microelectronic technology to reduce their size [34][35].

2. Operation Principle

2.1. Vibration Energy

The vibration energy from the environment can be harvested using nanogenerators with transduction mechanisms such as piezoelectric, electromagnetic, triboelectric, and piezotronic effects. For instance, these nanogenerator types can convert mechanical vibrations caused by the wind effect, sound, water waves, human body motion, machines, and vehicles into electrical energy.

2.1.1. Piezoelectric Nanogenerators

The piezoelectric nanogenerators (PENGs) use the piezoelectric effect to capture green energy from ocean water waves, wind, biomechanical movements, and environmental mechanical vibrations. The output voltage of this type of nanogenerator is affected by mechanical deformations and the parameters of its piezoelectric layer. Mechanical vibrations in the environment can induce varied deformations in the piezoelectric nano-generators that generate the AC output voltage. A piezoelectric layer, a substrate, and two electrodes make up these nanogenerators. PENGs feature a basic structural design, easy performance, a simple construction method, high stability, and a low cost [36][37][38][39][40][41][42][43][44].

2.1.2. Electromagnetic Nanogenerators

Electromagnetic generators (EMGs) employ magnetic materials and coils to function according to the Faraday law. These generators may convert the kinetic energy of flowing water into electricity [45]. This wave flow is utilized to vary the location of the magnet material relative to the coil, resulting in a changing magnetic field that induces a voltage in the coil. However, as compared to triboelectric nanogenerators, these generators can have a larger volume and weight. Furthermore, EMGs require support structures that let them float on the water's surface [46]. The performance of electromagnetic nanogenerators is determined by the rate of change of the magnetic flux. EMGs can be made to function at frequencies comparable to those of ocean waves to scavenge energy from them. Ocean waves move randomly at low frequencies of roughly 1 Hz [47]. The EMGs' performance is limited by their low frequency. Due to wind sources and environmental mechanical vibrations, which may function at higher frequencies, EMGs are ideal for scavenging green energy.

2.1.3. Triboelectricity Nanogenerators

Triboelectric nanogenerators (TENGs) may gather green energy from irregular surroundings at low frequencies by connecting contact electrification with electrostatic induction. Blue energy, for example, may be extracted from ocean wave motion, which is fundamentally random and travels at low frequencies (near to 1 Hz) [48][49][50][51][52][53][54][55][56][57][58][59][60]. The benefits of triboelectric nanogenerators are their small weight, low cost, simple operation principle, and lack of sophisticated production [61][62][63][64]. To attain the highest performance, the triboelectric materials and electro-mechanical designs of the nanogenerators must be optimized [65][66][67][68][69][70][71]. As a result, optimizing the design of triboelectric nanogenerators is critical for improving the conversion of green energy into electric energy.

TENGs may be configured to function in four basic modes: vertical contact-separation (CS), lateral sliding (LS), single-electrode (SE), and freestanding triboelectric-layer (FSTL). TENGs usually require two triboelectric surfaces and two electrodes. Electron attraction between two triboelectric surfaces creates an electrostatic charge transfer from one surface to another in these operational modes. The displacement of the triboelectric layers changes their initial electrostatic state, resulting in an electric potential difference between the layers. The potential difference drives the current through the external load to balance the electrostatic state. The movement of the triboelectric layer in the opposite direction will generate a difference in the current flow. TENGs can therefore have alternating current (AC) voltages between their two output electrodes, depending on the triboelectric material type, operating mechanism, and green energy source.

2.1.4. Piezotronic Nanogenerators

The piezotronic nanogenerators harvest low-frequency vibration/friction energy into electricity by using the linked piezoelectric and semiconducting capabilities of nanowires/nanobelts, as well as the influence of a Schottky barrier at the metal-semiconductor [73][74]. These nanogenerators might be incorporated into textile strands to recycle energy generated by human movement. Thus, the piezoelectronic nanogenerator is a potentially useful technology for harvesting/recycling energy from the environment to power self-powered nanodevices that may be operated wirelessly and remotely. This technique will enable self-powered wireless nanosystems and nanodevices to have a sustained energy supply [75].

2.2. Thermal Energy

Thermoelectric and pyroelectric nanogenerators can transform thermal energy from the environment into electrical energy to power electronic devices.

Thermoelectric and Pyroelectric Nanogenerators

Another sort of green energy that may be obtained from the environment is thermal energy. This energy may be transformed into electric energy and used to power low-power electronic devices employing thermoelectric nanogenerators (TEGs) [76]. TEGs produce electricity by using the Seebeck effect to scavenge thermal energy caused by temperature differences between two thermoelectric (TE) materials (**Figure 1**). This temperature differential causes charge carriers to migrate from a high-temperature TE material to a low-temperature TE material [77][78]. A TEG's voltage output is proportional to the temperature gradient. TEGs, on the other hand, need significant temperature gradients across TE materials. TEGs are classified into two types: rigid thermoelectric nanogenerators and flexible thermoelectric nanogenerators, with the latter depending on their deformation properties. Stretchable, compressible, collapsible, lightweight, tiny in volume, affordable, and simple are advantages of TEGs [79][80][81]. Flexible TEGs have the potential to be employed in waste heat recovery [82][83][84], portable electronics [85][86][87], and human health monitoring due to their properties [88][89][90].

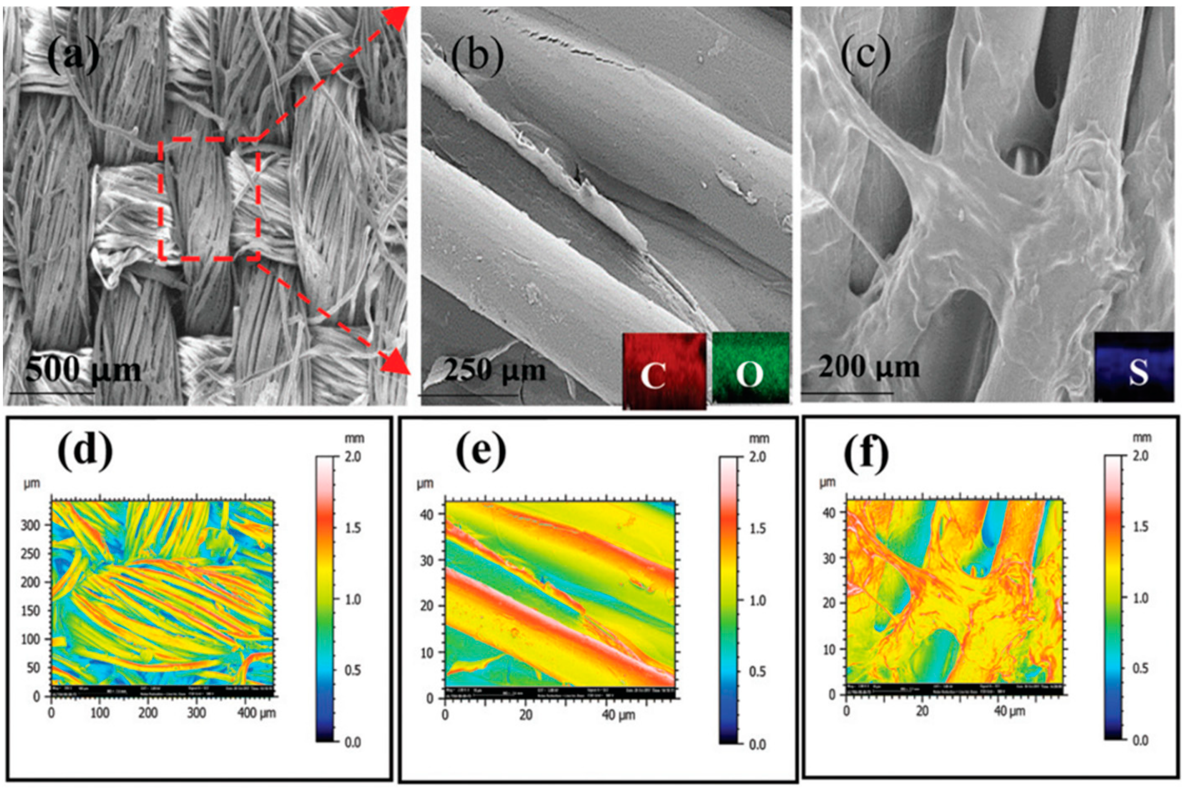

Figure 1. Reduced graphene oxide poly(3,4-ethylenedioxythiophene): poly (styrenesulfonate) (rGO-PEDOT:PSS) film-coated fabric of the flexible and washable thermoelectric nanogenerator fabricated by Khoso et al. [78]. This nanogenerator has potential application for harvesting green energy from human body heat. FESEM images with magnifications of (**a**) 500 µm and (**b**) 250 µm rGO-coated fabric and (**c**) 200 µm of rGO-PEDPT:PSS coated fabric.

(**d**–**f**) Color mapping of SEM images' infrared rendering. Reprinted with permission from [78]. Copyright ©2021, Royal Society of Chemistry.

Pyroelectric nanogenerators (PyENGs) use the variation in spontaneous polarization inside pyroelectric materials to transform heat energy into electric energy. This is generated by oscillations of electric dipoles caused by a change in time-dependent temperature [91][92]. The creation of electric current through materials having a non-center symmetrical crystalline structure when subjected to a time-dependent temperature gradient is referred to as the pyroelectric effect [93][94].

Pyroelectric nanogenerators have been identified as the energy collectors of the future, with the potential to be a viable energy technology for scavenging thermal energy in everyday life [94]. Thus, PyENGs and TEGs may have significant uses in powering future intelligent electronic sensors and IoT-connected wearable devices. More investigations on inorganic and organic materials, structure, performance, and reliability are required for the development of these nanogenerators.

2.3. Hybrid Nanogenerators

In the meantime, hybrid nanogenerators may harvest/recycle green energy from the environment by using several energy acquisition mechanisms or numerous connected nanogenerators with the same energy acquisition method (**Figure 2**). In hybrid nanogenerators, for example, piezoelectric, pyroelectric, triboelectric, and electromagnetic phenomena can be used. In comparison to individual nanogenerators, this nanogenerator type can provide high and efficient power density [95]. Recent research has led to the development of hybrid nanogenerators based on piezoelectric–pyroelectric [96][97][98], triboelectric–piezoelectric [31][99][100][101][102][103][104][105][106][107][108][109][110][111][112][113][114][115][116][117], electromagnetic–triboelectric [118][119][120][121][122][123][124][125][126][127][128][129][130][131][132], triboelectric–piezoelectric–pyroelectric [133][134][135][136], triboelectric–piezoelectric–electromagnetic [137][138][139][140][141][142][143][144][145][146][147][148], and photovoltaic–triboelectric effect [149][150][151][152][153][154].

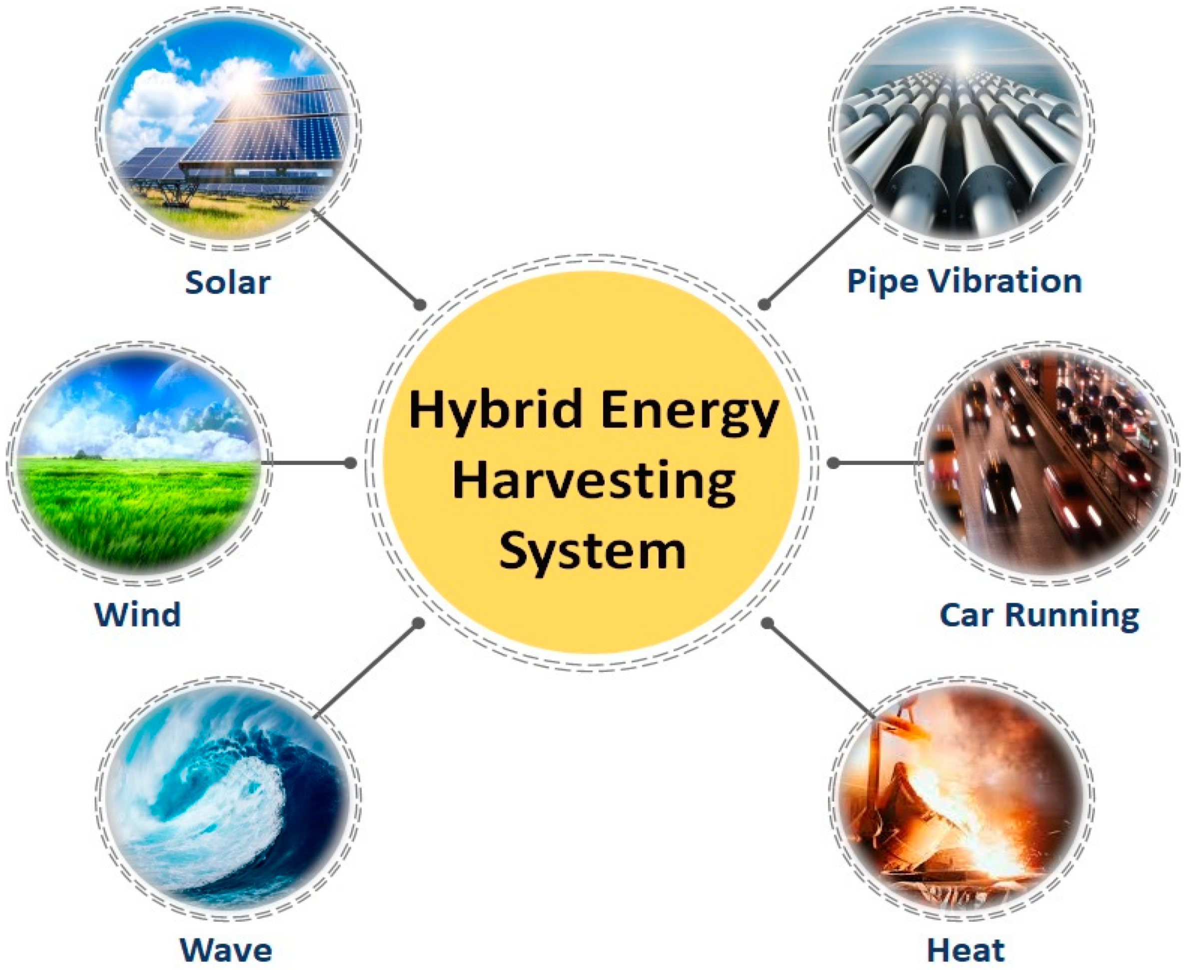

Figure 2. Potential applications of hybrid nanogenerators.

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