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Analyzing Integrated Teng-Photovoltaic Cell-Based Hybrid Renewable Energy System for Increased Efficiency

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***Abstract:* -** Energy and environmental crises have multifaceted and profound interplay. While energy production fuels the economy and drives technological advancements it leads to a significant impact on the environment. Extraction of energy from fossil fuels accelerates climate crisis and emissions which in turn has a devastating effect on the planet through unprecedented damage due to rising sea levels, storms, and famines. Seeking alternative environmentally friendly ways of energy production has become the need of the hour. Wherein solar energy has been widely accepted as a potential remedy for the present energy and environmental challenges. However, there are challenges in realizing the complete potential of solar power due to their dependence on weather. Adverse weather exerts a negative impact on solar cell efficiency.

Hybridization is an innovative approach that merges various energy harvesting technologies, forming a more robust system by addressing the drawbacks of each source. This work proposes a hybrid system combining triboelectric nanogenerators, electromagnetic generators, and solar cells. Triboelectric nanogenerators (TENGs) harnesses electrical energy from mechanical energy. The kinetic energy from raindrops during rainy days could be harnessed by integrating TENGs with photovoltaic cells, thereby ensuring continuous electricity generation from solar panels. Application of this integrated harvester extends from extracting blue energy sources such as tidal energy and marine energy to roof-mounted solar panels.

***Keywords*:** TENG, solar panel, FS-EMG, blue energy

1. Introduction

Renewable energy is extracted from natural resources like solar and wind power that are not exhausted after consumption. Renewable energy sources are rapidly gaining traction as a replacement for conventional energy sources due to the scarcity of natural resources and their detrimental environmental impact [1]. Low carbon profile of solar energy has cemented it as a viable option for widespread usage. While poised to grow into a leading renewable energy contender, the constraints of handling enormous power capacity and long-distance transmission must be overcome [2]. The persistent energy and environmental problem could be solved by harvesting energy from sustainable sources using advanced energy conversion devices [3-5]. Photovoltaics cells have shown higher power conversion efficiency. These devices convert solar energy into electricity without emitting any pollutants [6-9].

However, the weather-driven variations and intrinsic intermittency of solar cells provide substantial hurdles for their deployment as standalone power sources, despite the evident benefits they have for the environment [10]. Despite significant advancements, the effectiveness of modern solar cells hinges on the presence of light. This dependency translates to minimal or no electricity generation during dark periods, limiting their applicability as a sole energy source. Addressing these challenges is critical to attaining the full potential of solar photovoltaic (PV) technology and transforming the global energy sector. Intriguing prospect of scavenging waste energy from the environment paves way for uninterrupted power generation. In pursuit of enhanced power generation, researchers have explored numerous hybrid system strategies. These designs integrate solar panels (PV) with other energy sources, such as thermal, kinetic and hydrodynamic to create a robust energy harvesting system [11-13].

Leveraging the triboelectric effect, as demonstrated in TENGs [14], offers an intriguing approach to addressing solar cell constraints. The triboelectric nanogenerator (TENG) is an innovative device that takes advantage of both triboelectrification and electrostatic induction. This novel technology captures mechanical energy and turns it into electricity, efficiently supplementing and improving the power production of solar panels, even in low-light conditions or darkness. This strategy tackles key limits in solar power systems, which could lead to considerable increases in dependability and efficiency. This lays the groundwork for a more robust and sustainable energy future [15-23]. For instance, one such approach involves coating solar cells with special materials, such as charge-enriched graphene oxide or transparent PDMS, to create a water-drop power system, aimed at capturing kinetic energy of falling raindrops to produce electricity, boosting the overall power output of the solar panel even during periods of low sunlight [24-27].

Even though incorporating raindrop energy harvesting into solar cells seems to be a promising solution, the current design lacks compactness. The addition of bulky pseudo capacitors or nanogenerators as independent components remains a hurdle to wider adoption. Separating the two energy collecting devices using an insulator, such as polyethylene terephthalate or glass, provides physical independence. However, for this design to work, an additional electrical connection, often a wire, is required. This adds complexity and possible failure points to the system. While combining a TENG's high voltage output with a solar cell's high current appears to be a perfect match for a hybrid energy system, current limits in TENG design create obstacles. Several limitations in existing TENG designs prevent the intended synergy with solar cells. These drawbacks include TENG materials' low transparency, high electrical resistance, which impedes current flow, and a bulky layered structure that affects overall efficiency.

Herein, a hybrid energy harvesting system (HEHS) combining CS-TENG and a FS-EMG, along with commercial waterproof silicon-based solar cells has been presented. The system consists of two distinct TENG units. The first unit utilizes a contact-separation mode design fabricated with copper and Kapton layers for mechanical energy conversion. The second unit adopts a hybrid TENG/Silicon (Si) tandem architecture for concurrent rain and solar energy harvesting. This is achieved by layering a transparent top sub-cell composed of silver (Ag) and PEDOT: PSS onto a conventional monocrystalline Si solar cell at the bottom.

2. Proposed system

The HEHS incorporates three components: a standalone contact-separation mode triboelectric nanogenerator (CS-TENG), electromagnetism-based freestanding-sliding mode electromagnetic generators (FS-EMGs), and a rain droplet-based hybrid TENG/ solar cell unit. The CS-TENG has a four-centimetre square Kapton film as its basis. One side of this film is coated with silver to form an electrode, while the opposite surface confronts a copper sheet of the same size, which serves as the second triboelectric layer. The FS-EMG unit has been structured with a disc-type copper coil sandwiched in between two magnets. One magnet is mounted to the top of the CS-TENG device, while the other possessing opposite magnetic polarity is attached to the external sheet. Hybrid TENG/ solar cell unit is positioned on the top of the box. This hybrid solar cell combines the photovoltaic and triboelectric effects. When lighted, it can generate energy between the bottom silver (Ag) electrode and the middle Ag1 electrode via the photovoltaic effect. Raindrops touching the cell can also cause a triboelectric effect, which allows electricity to be generated between the bottom Ag electrode and the top Ag2 electrode.

2.1 Materials

Triboelectrification arises from the transfer of electrons at the interface between two contacting materials. The flow and intensity of electrons traveling between materials is determined by their electron affinity [28]. The substance with a stronger electron affinity will attract electrons away from the other material. This results in a negative charge on the electron acceptor substance. In contrast, the substance with a lower electron affinity will transfer electrons to the other material, resulting in a positive charge on its own. The propensity of a material to donate and accept electrons can be generally predicted by its position in the triboelectric series.

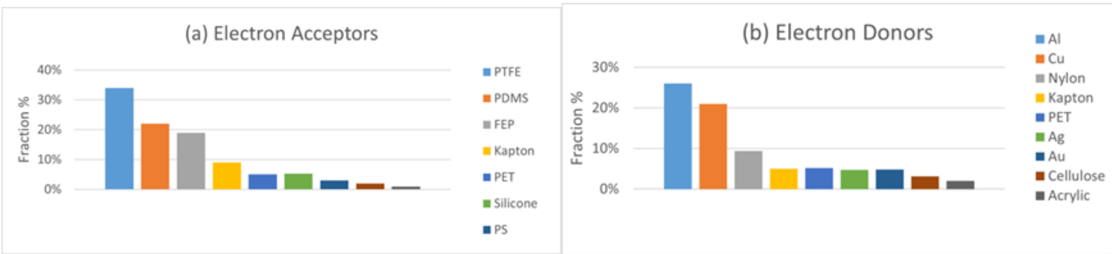

Figure 1(a) Triboelectric series of electron acceptors and Figure 1(b) Triboelectric series of electron donors

From figure 1(a) and 1(b), copper is the second-best electron donor as well as, Kapton and PTFE are among the best electron acceptors. Consequently, the hybrid power unit is made up of these materials. PEDOT: PSS has been used in hybrid TENG/Si solar cell because of its conductivity properties [29]. Apart form that silver electrodes have been used instead of aluminium electrodes used most of the works in order to enhance conductivity.

2.2 Fabrication of the hybrid energy system

PTFE sheets of 1 millimetre thickness were first cut into desired shapes using a laser cutter to create a substrate. A CS-TENG unit is fabricated using a 4 cm x 4 cm Kapton film. One side of this film is coated with a silver film to function as an electrode. The other triboelectric layer is a copper sheet of identical dimensions. A piece of PEDOT film was used as an electrical interconnector between the two triboelectric layers. Three magnets, 2.5 cm in diameter were stacked together and affixed onto the TENG. Three magnets, with opposite polarization to those mentioned earlier, were attached to a separate, movable 5 cm x 10 cm PTFE sheet. This movable sheet could slide relative to the sealed box. A thin layer of PEDOT:PSS was deposited onto the monocrystalline silicon solar cell surface using a spin-coating technique at varying speeds. Subsequently, the film was annealed at 60°C for 15 minutes to improve its properties. Finally, a top silver electrode (Ag2) was applied using conductive silver paste.

2.3 Working mechanism

The figure 2 depicts the operational principle of the hybrid TENG/ solar cell unit. This strategy takes advantage of the interaction of two phenomena: contact electrification and electrostatic induction. These happen at the point where a solid material meets a liquid [30, 31, 32]. When a raindrop falls on the PEDOT: PSS film, it promptly generates both negative and positive charges. When the Ag2 electrode comes into contact with the charged raindrop, there is a swift transfer of electrons from Ag electrode to the raindrop. In the electricity generation process, the rain droplet serves a dual purpose. Firstly, raindrops serve as a positive triboelectrification component. The "spreading-shrinking" process at the interface between PEDOT: PSS and raindrop is the fundamental driving force behind electron transport. Additionally, the raindrop serves as a conductive bridge, establishing connections between the PEDOT: PSS, Ag2, and Ag electrodes.

During the process harnessing mechanical kinetic energy from ocean waves by lower power unit, the lower magnet oscillates back and forth with the wave motion, causing the upper magnet to move vertically. Simultaneously, the dual layers of the TENG undergo repeated cycles of contact and separation. Triboelectric effect and electrostatic induction act as the fundamental operating principles of CS-TENG [33,34]. During stage 1, the bottom magnet is misaligned with the coil. This misalignment decreases the magnetic attraction between the magnets, preventing the two triboelectric layers from coming together. In stage 2, as the bottom magnet moves further forward, the top layer is drawn downwards. In stage 3, the lower magnet overlaps the copper coil, causing the Kapton film and copper sheet to come into contact due to a strong attractive force between the two magnets. Surface tribo-charges are produced when electrons flow from Cu to Kapton.

In the FS-EMG unit, the motion of permanent magnets caused by ocean waves induces a change in the magnetic flux through the copper coil. This change in flux, following Lenz's Law, results in the generation of a current within the coil.

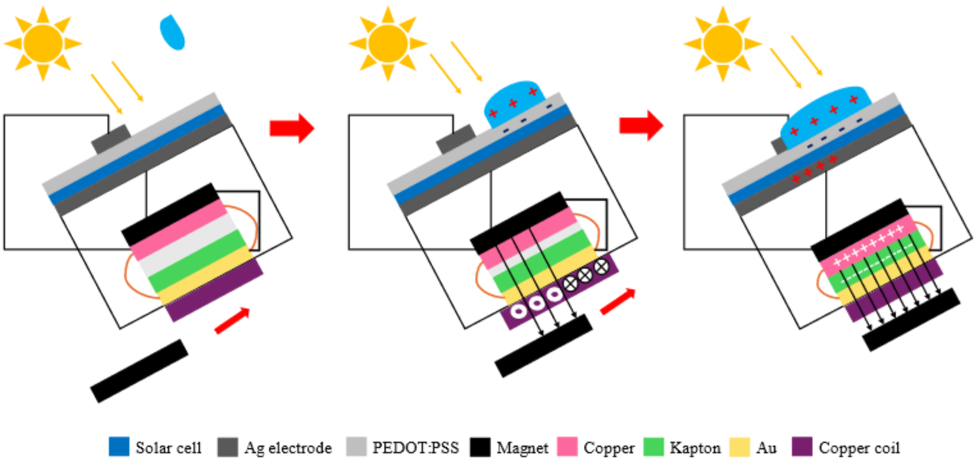

Figure 2. Working mechanism of hybrid energy unit

Figure 3. Fabricated HRES unit

3. Result and Discussion

The output voltage and current signals generated by the system were captured using a programmable Keithley electrometer. The components of the HEHS unit were examined for their electrical performance. Four ocean weather simulations were used to power up a 33 μF capacitor and monitor its voltage. The resulting voltage curves are presented in Figure 3,4,5 and 6. To enable capacitor charging with both AC outputs from the TENG and EMG, two bridge rectifiers were used to convert them into DC signals. Under cloudy or rainy conditions with low-frequency (0.5 Hz) ocean movements, only the TENGs can operate. In this scenario (Figure 3), a peak voltage of 7.2 V was obtained. Under sunny conditions, even with persistent low-frequency (0.5 Hz) ocean motion, the solar cell unit (SC unit) rapidly charges the capacitor to 2.8V. The coupling effect between TENG and Solar cell harnessed a peak voltage of 8.2 V (Figure 4). At high-frequency (2 Hz) ocean movements and without sunlight, the capacitor's voltage initially rises sharply to 2.8 V due to EMG contributions (Figure 5). Subsequently, the TENGs take over and continuously charge the capacitor to a higher voltage of 9.2 V. During high-frequency (2 Hz) ocean movements with sufficient sunlight (Figure 6), the combined contributions of EMGs and the solar cell unit (SC) lead to a rapid rise of voltage up to 11 V.

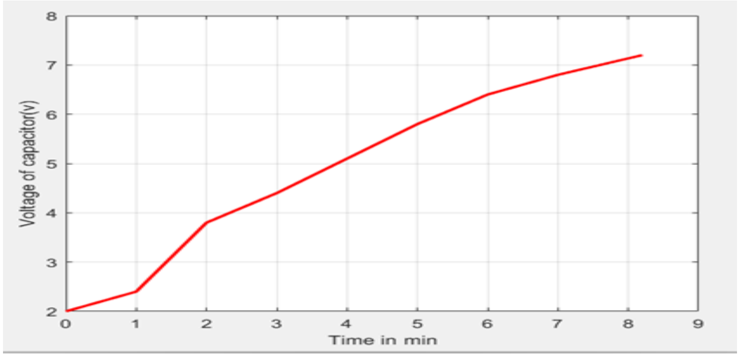

Figure 3 Output voltage of TENG

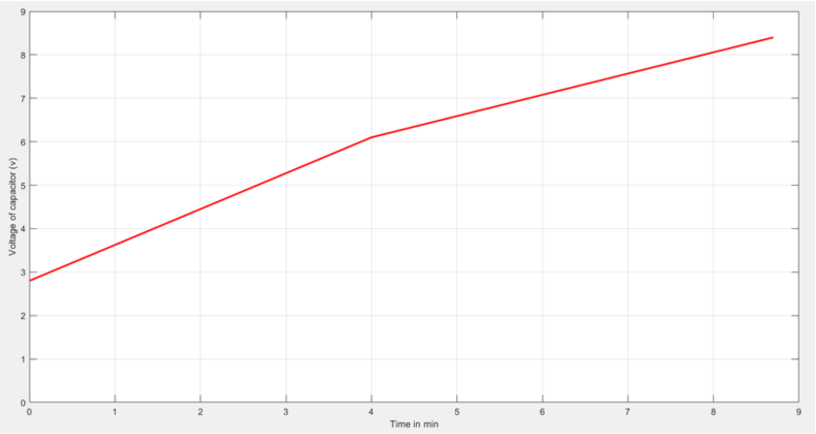

Figure 4 Output voltage of TENG + EMG

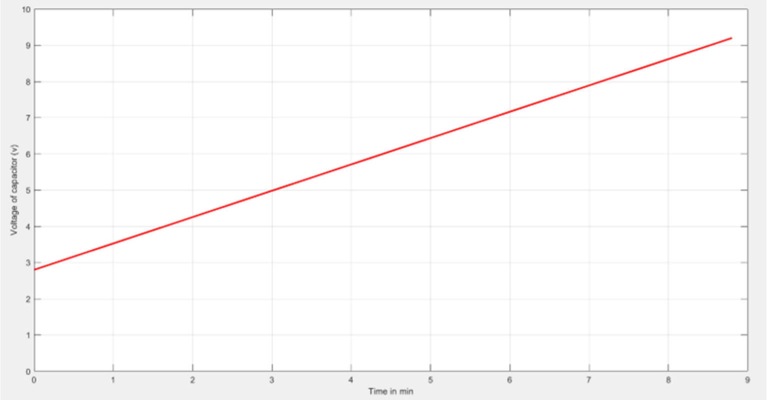

Figure 5 Output voltage of TENG + Solar Cell

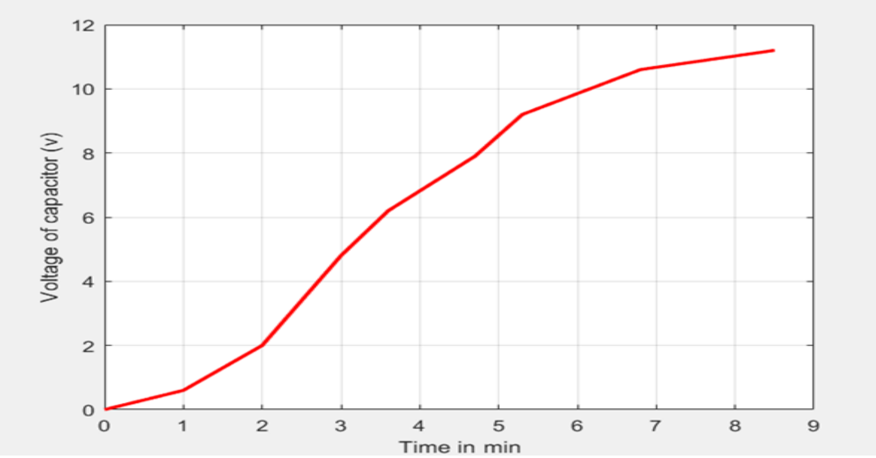

Figure 6 Output voltage of TENG + EMG + Solar Cell

4. Conclusion

This work proposes a novel HEHS designed to harvest energy from ocean waves. The unit integrates three key components: CS-TENGs, FS-EMGs, and a hybrid TENG/ solar cell unit. The TENG performs a vital function by producing an increased output voltage to compensate for the poor performance of EMG at low-frequency wave motion. This study successfully demonstrated the ability of the HEHS to harvest both blue energy and solar energy under simulated ocean conditions. The ingenious design, with its efficient energy harvesting and user-friendly operation, presents a promising and sustainable model for harnessing blue energy in real-world applications.

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