ISSN: 3116-3475
International Journal
of Education, Research, and Innovation Perspectives
Volume 2 Issue 10 (October 2026)

Exploring Materials and Modes for Improved Energy Output in Triboelectric Nanogenerator (TENG) and Solar Photovoltaic (PV) Hybrid Systems for Tropical Climate

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Date Submitted:
September 01, 2026

Date Accepted:
September 30, 2026

Date Published:
October 28, 2026

DOI:
10.5281/zenodo.23721013

ABSTRACT

This study aimed to optimize the energy output of a hybrid renewable energy system by evaluating material combinations and operational modes for a triboelectric nanogenerator (TENG) integrated with a solar photovoltaic (PV) panel. Designed for tropical climates such as the Philippines, the hybrid system sought to address the intermittency of solar energy by harvesting kinetic energy from rainfall using TENGs. Through a literature-informed material screening and prototype testing under simulated rainfall, key TENG configurations were assessed based on open-circuit voltage (Voc), material availability, simplicity, and cost-effectiveness. The results identified FEP-Stainless Steel in contact-separation mode as the optimal configuration, producing the highest Voc output. When integrated with a monocrystalline PV panel, the hybrid system achieved a 2.94% increase in energy output compared to a standalone PV panel. Despite constraints in real-time rainfall data and environmental simulation, the study demonstrates the feasibility of dual-mode energy harvesting for residential applications in tropical regions, offering a potential step forward in localized, sustainable energy generation.

Keywords: *Hybrid Energy Harvesting, Triboelectric Nanogenerator (TENG), Photovoltaic (PV), Rain Energy, Tropical Climate, Sustainable Power Generation*

INTRODUCTION

The increasing global demand for electricity, driven by population growth and urban development, continues to intensify pressure on energy infrastructure worldwide. As fossil fuel consumption accelerates climate change and environmental degradation, international agreements such as the Paris Agreement and the United Nations Sustainable Development Goals have urged nations to shift toward renewable and sustainable energy systems. The Philippines, positioned in the tropics and vulnerable to extreme weather events, faces a particular urgency in pursuing resilient and decentralized energy solutions. In this context, maximizing both solar and rainfall energy presents a unique opportunity for innovation in hybrid renewable technologies.

Photovoltaic (PV) systems, widely adopted in both grid-tied and off-grid contexts, are effective under sunny conditions but exhibit drastically reduced output during cloudy or rainy periods. Given that rainfall is a persistent environmental feature in the Philippines, especially in high-altitude regions such as Baguio and La Trinidad, this solar-only dependency compromises the reliability of power generation. Triboelectric

ISSN: 3116-3475
International Journal
of Education, Research, and Innovation Perspectives
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nanogenerators (TENGs), which harvest energy from mechanical motion such as raindrop impact via the triboelectric effect, offer a promising complement to PV systems. Several studies (Pang, 2021; Shao et al., 2017) suggest that hybridizing PV and TENG systems can bridge the gap in energy availability during transitional weather conditions. However, challenges such as energy transfer losses, impedance mismatches, and poor environmental adaptability of some TENG configurations remain poorly addressed in empirical literature.

This study responds to those gaps by developing a hybrid PV-TENG panel designed to harvest energy from both solar irradiance and rainfall, structured to operate under the unpredictable weather patterns typical of tropical climates. The research is framed within an exploratory sequential design. In the qualitative phase, material and configuration candidates were screened using a binary decision model that applied four criteria: energy output performance, rainfall compatibility, affordability, and material availability. Materials such as PTFE, FEP, aluminum, stainless steel, and PVC were selected for the TENG component, while monocrystalline silicon was selected for the PV portion due to its superior efficiency, environmental resilience, and local availability. For operational modes, contact-separation and single-electrode mechanisms were retained based on their moisture tolerance, structural simplicity, and documented performance in solid-liquid triboelectric nanogenerator applications.

These design decisions were grounded in extensive literature synthesis. Prior works have emphasized the effect of structural layout, droplet behavior, and surface compatibility on triboelectric output (Zhang et al., 2024), with some showing performance divergence from expectations based solely on triboelectric series rankings. Furthermore, studies by Wu et al. (2024) have demonstrated that inadequate rectification circuits and voltage stabilization significantly undermine energy harvesting efficiency even when using high-performance materials. These limitations underscore the need for rigorous design logic and real-environment simulation during testing.

This study contributes to the current body of knowledge by integrating design principles from literature with systematic material and mode selection, culminating in a prototype tested under simulated tropical conditions. The PV-TENG system was evaluated for open-circuit voltage output across various rainfall intensities and environmental settings, guided by performance benchmarks derived from prior studies. Ultimately, this research aims to inform the development of reliable hybrid energy harvesters suitable for climate-vulnerable, off-grid communities in the Philippines and other tropical regions.

METHODS

Research Design

This study adopted an exploratory sequential research design, integrating qualitative decision modeling with quantitative prototyping. The methodology is structured to directly address each of the four Statements of the Problem (SOPs), from material and mode selection through hybrid system construction and validation under simulated tropical environmental conditions. The four SOPs are: 1) Which combinations of TENG materials best satisfy all four design objectives (TENG output performance, material availability, rainfall 7 compatibility, and affordability) and which operational modes of TENG best satisfy all three design objectives (rainfall compatibility, TENG output performance, simplicity) simultaneously?; 2) Which of the TENG material combinations and operational modes yielded the highest open-circuit voltage under simulated rainfall conditions?; 3)What rainfall intensity yields the highest open-circuit voltage (Voc) output from the TENG portion of the hybrid PV-TENG panel?; 4) How much did the energy output of the hybrid PV-TENG panel increase compared to the control panel in terms of percentage?

Research Locale

Despite the wide range of possible installation sites for the hybrid PV-TENG panel, the researchers confined testing to residential rooftops, specifically in areas with adequate solar exposure and suitable

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International Journal
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conditions for installing a rainfall simulator. This decision ensured that the atmospheric conditions typically experienced by rooftops, such as direct sunlight and rainfall, were effectively replicated. The primary location selected was an uncovered residential parking space, chosen for its accessibility and compatibility with the simulator setup.

The researchers chose to focus on residential applications rather than commercial or industrial settings due to several key factors. First, residential households represent a substantial portion of energy consumers in the Philippines, and aligning with the government's ongoing push for renewable energy adoption at the household level supports national energy goals. Second, residential rooftops provide easier access and setup flexibility for prototype installation and data collection compared to more complex commercial or industrial environments. Lastly, the scale and affordability of the prototype system were designed with residential users in mind, making household deployment the most relevant and practical application for this study.

One limitation in site selection was the difficulty of installing the rainfall simulator in areas without access to a water pump or motor. Other key considerations included sufficient irradiance and exposure to varying weather conditions. The selected location, which is a residential uncovered parking space on Youngland Street, Camp 7, Baguio City, was deemed ideal. This open, outdoor setting allowed for sufficient solar exposure and accommodated the installation of a rainfall simulator.

Baguio City, located in a Type 1 climate zone characterized by a distinct dry season during the study period, provided relatively stable conditions for solar data collection. However, it is acknowledged that Baguio's unique climatic profile—including cooler temperatures, higher elevation, and different solar angles compared to lowland areas—may limit the generalizability of results to all residential settings across the Philippines. While the rainfall simulator allowed the team to compensate for the lack of natural rain during dry months, regional differences in climate could influence actual hybrid panel performance in other locations. This limitation is recognized and should be considered when applying the results to broader contexts.

The prototype and simulator were installed in this environment to evaluate the system's performance under controlled yet realistic conditions that closely mimic those encountered in typical rooftop applications.

By focusing on residential homes as the intended application setting, the study identifies residential homeowners as the primary population of interest. The hybrid PV-TENG panel is designed to generate and store electrical energy in a battery system, which can then be used to power household electrical devices, such as outdoor lighting fixtures.

Sampling Technique

Selection of TENG Materials and Modes and PV Cell Type

The first phase of the study focused on identifying triboelectric materials, operational modes, and photovoltaic (PV) cell types in accordance with the system's performance goals and environmental context. This phase began with a review of published scientific literature, datasheets, and locally available material catalogs to generate an initial pool of nineteen candidate materials commonly used in triboelectric nanogenerator applications.

To screen these candidates, four design objectives were established to evaluate their suitability as triboelectric layers: output performance, rainfall compatibility, affordability, and availability. These objectives were applied using a binary decision model with short-circuit logic, wherein materials that failed to meet even one of the four criteria were excluded from further consideration. This process ensured that only materials meeting all design objectives progressed to the prototyping phase.

A similar procedure was employed for determining the operational modes of the TENG component. Candidate modes were reviewed based on three design objectives: solid-liquid compatibility, mechanical

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simplicity, and structure adaptability. These considerations reflected the need to ensure not only energy harvesting potential but also resilience under fluctuating environmental conditions typical of tropical climates.

For the photovoltaic component, the selection of a suitable PV cell was guided by three design objectives: efficiency, availability, and water-resistance. These were based on performance metrics documented in prior studies as well as practical considerations related to field deployment in the Philippine context.

The outcomes of this screening process established the material pairings, operational configurations, and PV cell type to be used in subsequent fabrication and testing procedures.

Construction of the Hybrid PV-TENG Panel and Evaluation of PV and TENG Portions

The construction of the hybrid photovoltaic-triboelectric nanogenerator (PV-TENG) panel was guided by the qualitative selections made in the initial material and mode screening phase. The hybrid panel integrated the selected PV cell type and TENG configurations, which had been identified through binary short-circuit logic as suitable based on defined design objectives.

Prior to full hybrid integration, the individual subsystems were assessed separately to establish their baseline behavior and contribution potential. The photovoltaic (PV) portion was evaluated by recording its open-circuit voltage (Voc), short-circuit current (Isc), and output power on an hourly basis over a 24-hour period under simulated rainfall conditions. These trials were conducted three times and averaged to ensure consistency. The purpose of this assessment was to determine the diurnal window during which the PV subsystem's performance was weakest and where the TENG could meaningfully supplement energy output. The resulting data provided a temporal map of PV efficiency, revealing periods of negligible solar contribution.

The TENG portion was evaluated by its material pairing and operational mode. Each configuration constructed based on the screened materials and their assigned mode was subjected to rainfall simulation. The generated output was measured in terms of open-circuit voltage (Voc) using a digital multimeter, with each trial lasting 30 seconds. A bridge rectifier was included in the circuit to stabilize the output. This procedure established the electrical behavior of each TENG configuration under controlled, repeatable conditions, setting the foundation for later hybrid performance comparison.

Together, these assessments informed the selection of components used in the hybrid system and clarified the distinct roles of each subsystem across various environmental scenarios. All tests at this stage focused solely on subsystem characterization, and no integration data or performance comparisons were analyzed during this phase.

Evaluation of TENG Portion Performance Under Variable Rainfall Intensities

This phase focused on determining how varying levels of rainfall intensity influenced the output performance of the triboelectric nanogenerator (TENG) portion of the hybrid system. The evaluation was designed to address the third statement of the problem by introducing rainfall intensity as a controlled environmental variable.

Three rainfall intensity ranges (7-12 mm/min, 13-18 mm/min, and 19-24 mm/min) were established through calibration of the rainfall simulator using a rain gauge. These intensities were selected to reflect levels commonly observed in tropical climates. The simulator's valve positions were manually adjusted and marked to correspond to these defined flow rates, allowing for controlled and repeatable test conditions despite equipment limitations.

Each of the previously constructed TENG configurations—based on the material pairs and operational modes selected during earlier phases—was subjected to each of the three intensity conditions. The testing setup involved a 30-second exposure to simulated rainfall for every configuration. For each trial, the open-circuit voltage (Voc) was measured using a digital multimeter. Tests were conducted both

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International Journal
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with and without the inclusion of a capacitor in the circuit to capture the influence of energy storage on output characteristics.

All measurements were conducted in triplicate under each rainfall intensity condition to ensure data reliability and reduce experimental variability. The purpose of this phase was to isolate the influence of rainfall intensity on the electrical output of the TENG portion, which in turn would inform the selection of parameters for final hybrid system integration. No data interpretation or comparison was performed at this stage.

Evaluation of the Hybrid PV-TENG System

This phase involved the integration and evaluation of the hybrid photovoltaic-triboelectric nanogenerator (PV-TENG) panel using the triboelectric material pair, operational mode, and rainfall intensity condition previously identified during component-level testing. The system was assembled to incorporate both the photovoltaic and triboelectric subsystems into a shared circuit, with each input routed through a Double-Pole Double-Throw (DPDT) switch and connected to a common capacitor bank. Rectifier circuits were included to ensure unidirectional current flow from both subsystems into the capacitor.

The hybrid panel was tested under three irradiance conditions (low, medium, and high) based on prior hourly performance characterization of the PV panel. These irradiance conditions corresponded to specific times of day and were paired with a consistent rainfall intensity, matching the condition previously used to evaluate TENG performance.

During each 30-second trial, the system's electrical behavior was monitored in real time. Voltage and current readings were recorded every second using two digital multimeters. Power was computed from the corresponding values of voltage and current at each time point, and energy output was calculated as the sum of power values across the 30-second interval.

For each environmental condition, the hybrid PV-TENG system was tested alongside a standalone PV panel operating under the same conditions. The standalone PV panel served as a control to benchmark the hybrid panel's energy output and enable the assessment of the TENG subsystem's contribution under matched environmental scenarios.

RESULTS AND DISCUSSION

TENG Materials and Modes and PV Cell Type

The material screening process yielded five triboelectric materials (fluorinated ethylene propylene (FEP), polytetrafluoroethylene (PTFE), polyvinyl chloride (PVC), stainless steel, and aluminum) that satisfied all four design objectives, namely, output performance, rainfall compatibility, availability, and affordability. The application of short-circuit binary logic excluded any material that failed to meet even one of these criteria. The justification for each of the five selected materials is presented in Table 1, which outlines the evidence supporting their compliance with the stated objectives.

Two operational modes, contact-separation and single-electrode, were selected based on their fulfillment of the following design objectives, specifically rainfall compatibility, output performance, and simplicity. These modes were reviewed in the context of their suitability for moisture-exposed energy harvesting applications and are justified in Table 2.

For the photovoltaic portion of the hybrid system, monocrystalline silicon was selected as the cell type based on the design objectives of performance output, rainfall compatibility, modular availability, and cost-efficiency as shown in Table 3. This selection was informed by literature review and supplier documentation.

These selections defined the fixed material and configuration parameters for all subsequent fabrication, testing, and system integration procedures.

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Table 1. *Justification Summary for Selected TENG Materials Based on Design Objectives*

Material	Output Performance	Rainfall Compatibility	Availability	Affordability
Aluminum	Proven high output when paired with PTFE/FEP	Reliable in wet environments as collector electrode	Locally available in retail stores or online platforms	100 sq. cm ~ Php 150
FEP	High Voc >200V in multilayer configurations	Proven performance in raindrop and SL-TENGs	Locally available in retail stores or online platforms	280 sq. cm ~ Php 280
PTFE	Voc ~300V in standard TENG setups	Highly stable in liquid-contact TENGs	Locally available in retail stores or online platforms	10 mm x 1 m roll ~ Php 100
PVC	Moderate output up to 150V in film-electrode designs	Modified membranes function in SL applications	Locally available in retail stores or online platforms	~ Php 280 for 100 A4 sheets
Stainless Steel	Good stability and moderate output	Corrosion-resistant and SL-compatible	Locally available in retail stores or online platforms	100 sq. cm ~ Php 200

Table 2. *Justification Summary for Selected TENG Operational Modes Based on Design Objectives*

Operational Mode	Rainfall Compatibility	Output Performance	Simplicity
Contact-Separation	Used extensively in raindrop and SL-TENG setups with consistent results	High output in various designs, with peak voltages >100V reported	Straightforward layer-by-layer structure; easy to fabricate and integrate
Single-Electrode	Demonstrated effectiveness in rainfall-based and moisture-exposed applications	Moderate to high performance suitable for low-complexity systems	Minimal wiring and structural components required; ideal for basic SL-TENGs

Table 3. *Justification Summary for Selected TENG Operational Modes Based on Design Objectives*

PV Cell Type	Performance Output	Rainfall Compatibility	Modular Availability	Cost-Efficiency
Monocrystalline Silicon (Mono-Si)	Highest commercial efficiency (~18-22%) with stable long-term output	Encapsulated designs resist moisture and environmental degradation	Widely available in multiple sizes and formats	Higher initial cost but excellent long-term output and durability

Evaluation of PV and TENG Portions

The photovoltaic portion was assessed across a 24-hour cycle under actual environmental conditions to identify its energy production profile. Open-circuit voltage (Voc), short-circuit current (Isc), and output power (in milliwatts) were recorded at hourly intervals across three trials. The averaged data (refer to Table 4) and corresponding trends (refer to Figure 1) showed minimal output during nighttime and early morning hours, with average power values remaining below 0.002 mW between 00:00 and 05:00 and again from 18:00 to 23:00. In contrast, peak performance occurred between 11:00 and 15:00, reaching up to 796.19 mW at 15:00. This temporal variation established the critical need for a supplemental energy source to cover low-output periods. Following this, triboelectric nanogenerator (TENG) configurations were tested to determine their supplemental potential. A total of 72 configurations were constructed by combining six material pairs, two operational modes, three rainfall intensities, and two capacitor conditions, with each configuration undergoing three voltage trials. The raw and computed data were compiled into a recording table (refer to Table 5), while pivot tables summarized key performance trends.

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Table 4. *Average Hourly PV Portion Output Based on Three Trials*

Hour	Temperature (°C)	Open-Circuit Voltage (V)	Short-Circuit Current (mA)	Output Power (mW)
0:00	18.00	0.0197	0.001	0.0000197
1:00	17.67	0.0193	0.002	0.0000313
2:00	17.67	0.0200	0.002	0.0000487
3:00	17.67	0.0247	0.004	0.0000987
4:00	17.67	0.1283	0.015	0.0027050
5:00	17.67	0.2547	0.033	0.0083840
6:00	18.67	3.3333	12.000	40.0920000
7:00	19.67	5.0800	60.167	305.7520000
8:00	20.33	6.3233	10.000	63.2333333
9:00	21.00	5.4367	50.100	264.1896667
10:00	22.00	5.6433	54.167	301.7050000
11:00	23.33	5.6433	179.067	1010.4706667
12:00	23.67	5.3467	62.967	325.4996667
13:00	24.33	5.1067	112.033	572.1160000
14:00	24.33	5.8067	10.000	58.0666667
15:00	23.67	5.1533	154.500	796.1900000
16:00	23.00	5.2567	105.037	553.1901667
17:00	22.33	5.0533	87.907	445.4987333
18:00	22.00	3.6133	12.377	44.9581667
19:00	21.00	0.0167	0.001	0.0000167
20:00	20.00	0.0117	0.001	0.0000117
21:00	19.33	0.0413	0.002	0.0000700
22:00	18.67	0.0367	0.003	0.0001367
23:00	18.67	0.0153	0.001	0.0000153

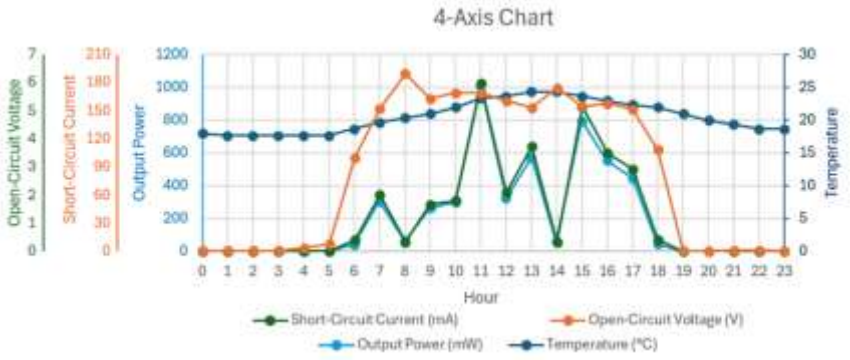


Figure 1. *Average Hourly PV Cell Portion Based on Three Trials*

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Table 5. *Open-Circuit Voltage of Tested TENG Configurations Based on Three Trials and Their Average*

TENG Material Pair	TENG Operational Mode	Rainfall Intensity mm/min	Voc (V, dc)				Voc (V, dc)			
			With Capacitor				Without Capacitor			
			Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
PTFE/Al	CS	7-12	0.36	0.345	0.378	0.361	0.252	0.247	0.261	0.253
PTFE/Al	CS	13-18	0.344	0.339	0.357	0.347	0.308	0.298	0.313	0.306
PTFE/Al	CS	19-24	0.355	0.352	0.354	0.354	0.43	0.416	0.422	0.423
PTFE/Al	SE	7-12	NC	NC	NC	NC	0.12	0.11	0.09	0.107
PTFE/Al	SE	13-18	NC	NC	NC	NC	0.216	0.221	0.209	0.215
PTFE/Al	SE	19-24	NC	NC	NC	NC	0.221	0.217	0.203	0.214
PVC/Al	CS	7-12	0.014	0.009	0.011	0.011	0.265	0.271	0.259	0.265
PVC/Al	CS	13-18	0.187	0.018	0.195	0.133	0.2	0.218	0.02	0.146
PVC/Al	CS	19-24	0.17	0.164	0.179	0.171	0.157	0.145	0.154	0.152
PVC/Al	SE	7-12	NC	NC	NC	NC	0.062	0.058	0.066	0.062
PVC/Al	SE	13-18	NC	NC	NC	NC	0.085	0.094	0.079	0.086
PVC/Al	SE	19-24	NC	NC	NC	NC	0.086	0.093	0.083	0.087
FEP/Al	CS	7-12	0.596	0.611	0.603	0.603	0.326	0.319	0.332	0.326
FEP/Al	CS	13-18	0.736	0.729	0.742	0.736	0.42	0.49	0.52	0.477
FEP/Al	CS	19-24	0.54	0.498	0.545	0.528	1.05	1.04	0.992	1.027
FEP/Al	SE	7-12	NC	NC	NC	NC	0.206	0.278	0.289	0.258
FEP/Al	SE	13-18	NC	NC	NC	NC	0.192	0.211	0.194	0.199
FEP/Al	SE	19-24	NC	NC	NC	NC	0.355	0.324	0.364	0.348
PTFE/SS	CS	7-12	0.014	0.303	0.044	0.120	0.014	0.012	0.009	0.012
PTFE/SS	CS	13-18	0.303	0.297	0.041	0.214	0.044	0.051	0.044	0.046
PTFE/SS	CS	19-24	0.044	0.041	0.046	0.044	0.046	0.044	0.049	0.046
PTFE/S	SE	7-12	NC	NC	NC	NC	0.077	0.086	0.075	0.079

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PTFE/SS	SE	13-18	NC	NC	NC	NC	0.075	0.071	0.079	0.075
PTFE/SS	SE	19-24	NC	NC	NC	NC	0.086	0.082	0.087	0.085
PVC/SS	CS	7-12	0.065	0.049	0.069	0.061	0.014	0.012	0.011	0.012
PVC/SS	CS	13-18	0.655	0.7	0.723	0.693	0.611	0.627	0.643	0.627
PVC/SS	CS	19-24	0.914	0.9	1	0.938	0.585	0.612	0.591	0.596
PVC/SS	SE	7-12	NC	NC	NC	NC	0.224	0.212	0.198	0.211
PVC/SS	SE	13-18	NC	NC	NC	NC	0.204	0.232	0.203	0.213
PVC/SS	SE	19-24	NC	NC	NC	NC	0.22	0.19	0.209	0.206
FEP/SS	CS	7-12	0.923	0.963	0.952	0.946	1.315	1.215	1.3	1.277
FEP/SS	CS	13-18	1.183	1.179	1.187	1.183	1.232	1.221	1.278	1.244
FEP/SS	CS	19-24	1.12	1.24	1.137	1.166	1.016	1.02	1.067	1.034
FEP/SS	SE	7-12	NC	NC	NC	NC	0.65	0.75	0.71	0.703
FEP/SS	SE	13-18	NC	NC	NC	NC	0.47	0.5	0.67	0.547
FEP/SS	SE	19-24	NC	NC	NC	NC	0.75	0.79	0.8	0.780

Material pair performance is summarized in Table 6 and visualized in Figure 2, which presents the average Voc for each pairing. Among the tested combinations, FEP/Stainless Steel yielded the highest output, with 1.098 V under capacitor condition and 0.931 V without capacitor. Operational mode comparisons, shown in Table 7 and Figure 3, indicate that the Contact-Separation mode consistently outperformed the Single-Electrode mode across material pairs. With capacitor integration, Contact-Separation achieved an average Voc of 0.478 V, compared to 0.249 V for Single-Electrode.

Table 6. *Average Open-Circuit Voltage (Voc) per Material Pair, with and without Capacitor*

TENG Material Pair vs. Voc		
TENG Material Pair	Voc	
	With Capacitor	Without Capacitor
1. PTFE/Aluminum	0.354	0.253
2. PVC/Aluminum	0.105	0.133
3. FEP/Aluminum	0.622	0.439
4. PTFE/Stainless Steel	0.126	0.057
5. PVC/Stainless Steel	0.564	0.311
6. FEP/Stainless Steel	1.098	0.931

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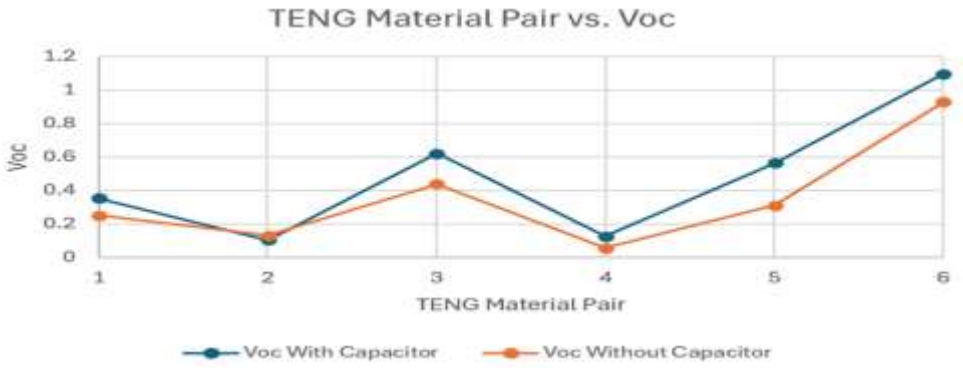


Figure 2. *Average Open-Circuit Voltage (Voc) per Material Pair, with and without Capacitor*

Table 7. *Average Voc by TENG Operational Mode, with and without Capacitor*

TENG Operational Mode vs. Voc		
TENG Operational Mode	Voc	
	With Capacitor	Without Capacitor
1. Contact-Separation	0.478	0.459
2. Single-Electrode	NC	0.249

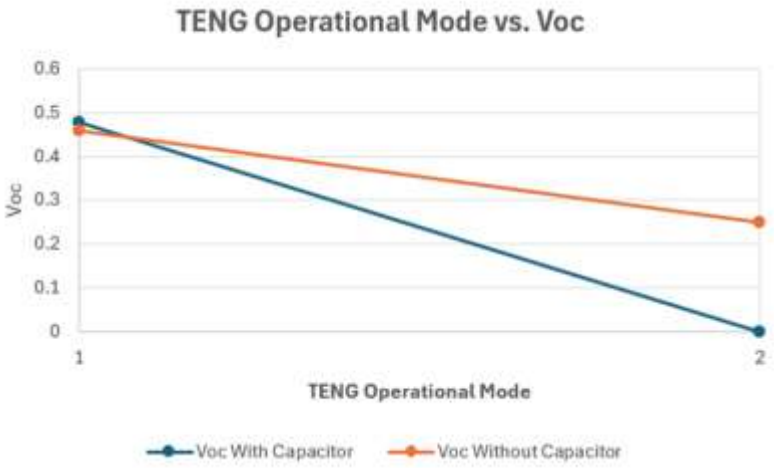


Figure 3. *Average Voc by TENG Operational Mode, with and without Capacitor*

Capacitor influence was also examined. Table 8 highlight the increase in Voc observed when capacitors were integrated, particularly for material pairs with high triboelectric polarity such as FEP/Aluminum and FEP/Stainless Steel. These findings provide the basis for determining the optimal configuration to be used in subsequent hybrid testing.

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Table 8. *Effect of Capacitor Integration: Voc Improvement per Material Pair*

Material Pair	Voc Difference (With - Without)
FEP/Stainless Steel	+0.167 V
FEP/Aluminum	+0.193 V
PVC/Stainless Steel	+0.253 V
PTFE/Aluminum	+0.101 V
PVC/Aluminum	-0.028 V
PTFE/Stainless Steel	+0.069 V

Evaluation of TENG Portion Performance Under Variable Rainfall Intensities

To investigate the influence of rainfall intensity on triboelectric nanogenerator (TENG) performance, three intensity levels, 7-12 mm/min, 13-18 mm/min, and 19-24 mm/min, were tested using a manually controlled rainfall simulator. For each level, the open-circuit voltage (Voc) was measured across multiple trials using the TENG configurations previously selected through SOP 1 and SOP 2. These configurations included various material-mode combinations with and without capacitor integration.

The results are averaged in Table 9 and visualized in Figure 4. Among the three tested conditions, the medium rainfall intensity range of 13-18 mm/min produced the highest average open-circuit voltage values: 0.5508 V with a capacitor and 0.3484 V without. In contrast, the lowest intensity range (7-12 mm/min) generated an average of 0.3505 V with a capacitor, while the highest range (19-24 mm/min) slightly underperformed the medium level, with average outputs of 0.5333 V and 0.4166 V, respectively, under capacitor and non-capacitor conditions.

These results quantify the relationship between rainfall intensity and triboelectric energy output, providing a data-driven basis for selecting optimal environmental conditions in the system-level integration phase.

Table 9. *Average Voc per Rainfall Intensity Range, with and without Capacitor*

Rainfall Intensity vs. Voc		
Rainfall Intensity	Voc	
	With Capacitor	Without Capacitor
1) 7-12 mm/min	0.3505	0.297083333
2) 13-18 mm/min	0.550816667	0.348405556
3) 19-24 mm/min	0.533277778	0.416555556

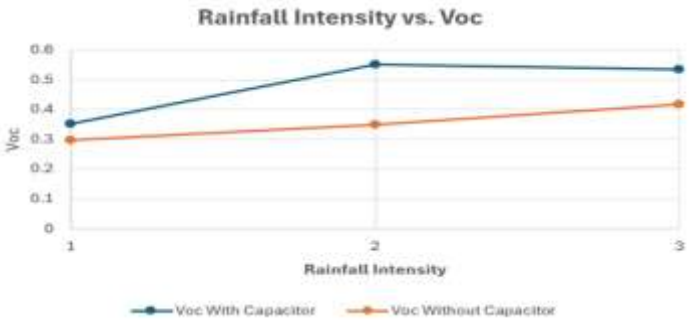


Figure 4. *Average Voc per Rainfall Intensity Range, with and without Capacitor*

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Evaluation of TENG Portion Performance Under Variable Rainfall Intensities

The final phase involved testing the hybrid PV-TENG panel under three simulated environmental conditions: Sunny While Rainy, Cloudy While Rainy, and Dark While Rainy. The configuration used in this test combined the selected triboelectric material pair (FEP-Stainless Steel) operating in Contact-Separation mode under a fixed rainfall intensity of 13-18 mm/min, integrated with a monocrystalline PV panel. Each environmental scenario was tested using both the hybrid panel and a standalone PV panel, with the latter serving as a control benchmark. Voltage, current, and power were recorded every second for a 30-second interval. The total energy output (in milliwatt-seconds, mWs) and percentage increase were computed from these time-series values.

In the Sunny While Rainy condition, the standalone PV panel recorded a total energy output of 6507.67 mWs, while the hybrid PV-TENG panel yielded 6662.09 mWs. This corresponds to an energy increase of 154.42 mWs or 2.37%. Detailed second-by-second values and cumulative energy computations are presented in Table 10, with corresponding performance trends visualized in Figure 5.

Under the Cloudy While Rainy condition, the control panel produced 3406.70 mWs, while the hybrid panel reached 3529.00 mWs. This resulted in a higher increase of 122.30 mWs, equivalent to 3.59%. The tabulated voltage, current, and power values over time are shown in Table 11, with the corresponding scatter plot presented in Figure 6.

For the Dark While Rainy condition, where solar irradiance was minimal, the standalone PV panel generated 33.02 mWs, while the hybrid panel yielded 33.99 mWs. This represents an energy increase of 0.97 mWs or 2.93%. Detailed recordings and calculations are provided in Table 12, and the corresponding figure is shown in Figure 7.

A summary of all three environmental scenarios is presented in Table 13, which compiles the total energy outputs of both systems and the calculated percentage increases. These data confirm consistent gains in energy output across varying solar conditions when the TENG subsystem is integrated.

Table 10. *Comparison of Energy Output Between Control PV Panel and Hybrid PV-TENG Panel during Sunny while Rainy Condition*

Time (s)	**AVERAGE**					
	Control Panel			Hybrid PV-TENG Panel		
	Output Voltage (V)	Output Current (mA)	Output Power (mW)	Output Voltage (V)	Output Current (mA)	Output Power (mW)
1	5.2	88.33333333	459.3333333	5.2	88.33333333	459.3333333
2	5	88.33333333	441.6666667	5	88.33333333	441.6666667
3	5	88.33333333	441.6666667	5	88.33333333	441.6666667
4	5	88.33333333	441.6666667	5	88.33333333	441.6666667
5	5	87.66666667	438.3333333	5	87.66666667	438.3333333
6	5	87.66666667	438.3333333	5	87.66666667	438.3333333
7	5	87	435	5	87	435
8	5	87	435	5	87	435
9	5	85.66666667	428.3333333	5	85.66666667	428.3333333
10	5	85.66666667	428.3333333	5	85.66666667	428.3333333
11	5	85.66666667	428.3333333	5	85.66666667	428.3333333
12	5	85.33333333	426.6666667	5	85.33333333	426.6666667
13	5	84.33333333	421.6666667	5	84.33333333	421.6666667
14	5	84.33333333	421.6666667	5	84.33333333	421.6666667

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15	5	84.33333333	421.6666667	5	84.33333333	421.6666667
16	4.066666667	0	0	4.6	18	82.53333333
17	4.066666667	0	0	4.566666667	12.66666667	57.5
18	4.033333333	0	0	4.366666667	3.366666667	14.15
19	4.033333333	0	0	4.2	0.023333333	0.100333333
20	4.033333333	0	0	4.016666667	0.013333333	0.0535
21	4.033333333	0	0	3.983333333	0.003666667	0.0146
22	4.003333333	0	0	3.933333333	0.003333333	0.013066667
23	3.766666667	0	0	3.78	0.003	0.01134
24	3.766666667	0	0	3.766666667	0.003	0.0113
25	3.766666667	0	0	3.62	0.002333333	0.00846
26	3.766666667	0	0	3.62	0.002	0.00724
27	3.613333333	0	0	3.52	0.002	0.00704
28	3.613333333	0	0	3.52	0.001666667	0.00584
29	3.613333333	0	0	3.5	0.001	0.0035
30	3.613333333	0	0	3.5	0.001	0.0035
Total Output in mW·s	6507.6667			6662.0897		
Energy Increase in Percentage (%)				2.3729%		

Table 11. *Comparison of Energy Output Between Control PV Panel and Hybrid PV-TENG Panel during Cloudy while Rainy Condition*

Time (s)	**AVERAGE**					
	Control Panel			Hybrid PV-TENG Panel		
	Output Voltage (V)	Output Current (mA)	Output Power (mW)	Output Voltage (V)	Output Current (mA)	Output Power (mW)
1	4.566666667	52.33333333	239.4666667	4.566666667	52.33333333	239.4666667
2	4.366666667	52	227.4666667	4.366666667	52	227.4666667
3	4.366666667	52	227.4666667	4.366666667	52	227.4666667
4	4.366666667	52	227.4666667	4.366666667	52	227.4666667
5	4.366666667	52.33333333	228.9666667	4.366666667	52.33333333	228.9666667
6	4.366666667	52.33333333	228.9666667	4.366666667	52.33333333	228.9666667
7	4.366666667	52	227.6333333	4.366666667	52	227.6333333
8	4.366666667	52.33333333	229.1333333	4.366666667	52.33333333	229.1333333
9	4.333333333	52.33333333	227.3333333	4.333333333	52.33333333	227.3333333
10	4.333333333	51.66666667	224.4	4.333333333	51.66666667	224.4
11	4.333333333	51.66666667	224.4	4.333333333	51.66666667	224.4
12	4.333333333	51.66666667	224.4	4.333333333	51.66666667	224.4
13	4.333333333	51.66666667	224.4	4.333333333	51.66666667	224.4
14	4.3	51.66666667	222.6	4.3	51.66666667	222.6
15	4.3	51.66666667	222.6	4.3	51.66666667	222.6

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16	4.133333333	0	0	4.233333333	13.2	55.75333333
17	4	0	0	4.2	10.93333333	46.02
18	4	0	0	4.1	4.933333333	20.26
19	3.9	0	0	4.033333333	0.023333333	0.096666667
20	3.833333333	0	0	4.033333333	0.02	0.084333333
21	3.633333333	0	0	3.966666667	0.004	0.015866667
22	3.633333333	0	0	3.866666667	0.003333333	0.012766667
23	3.633333333	0	0	3.833333333	0.003333333	0.012666667
24	3.566666667	0	0	3.8	0.002666667	0.010066667
25	3.533333333	0	0	3.8	0.002333333	0.008766667
26	3.4	0	0	3.666666667	0.002333333	0.008466667
27	3.266666667	0	0	3.6	0.002	0.0072
28	3.266666667	0	0	3.6	0.001333333	0.004733333
29	3.133333333	0	0	3.6	0.001	0.0036
30	3.133333333	0	0	3.6	0.001	0.0036
Total Output in mW·s	3406.7000			3529.0021		
Energy Increase in Percentage (%)				3.5900%		

Table 12. *Comparison of Energy Output Between Control PV Panel and Hybrid PV-TENG Panel during Dark while Rainy Condition*

Time (s)	**AVERAGE**					
	Control Panel			Hybrid PV-TENG Panel		
	Output Voltage (V)	Output Current (mA)	Output Power (mW)	Output Voltage (V)	Output Current (mA)	Output Power (mW)
1	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
2	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
3	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
4	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
5	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
6	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
7	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
8	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
9	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
10	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
11	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
12	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
13	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
14	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
15	2.693333333	0.816666667	2.201166667	2.693333333	0.816666667	2.201166667
16	2.276666667	0	0	2.596666667	0.253333333	0.660733333

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17	2.276666667	0	0	2.556666667	0.036666667	0.093666667
18	2.276666667	0	0	2.616666667	0.032666667	0.084573333
19	2.276666667	0	0	2.58	0.018333333	0.0471
20	2.276666667	0	0	2.543333333	0.008333333	0.02105
21	2.276666667	0	0	2.54	0.004	0.01016
22	2.276666667	0	0	2.53	0.003666667	0.009286667
23	2.27	0	0	2.513333333	0.003	0.00754
24	2.27	0	0	2.503333333	0.003	0.00751
25	2.266666667	0	0	2.486666667	0.002666667	0.00663
26	2.266666667	0	0	2.486666667	0.002	0.004973333
27	2.266666667	0	0	2.483333333	0.002	0.004966667
28	2.266666667	0	0	2.48	0.001666667	0.004133333
29	2.266666667	0	0	2.48	0.001333333	0.003306667
30	2.266666667	0	0	2.48	0.001333333	0.003306667
Total Output in mW·s	33.0175			33.9864		
Energy Increase in Percentage (%)				2.9346%		

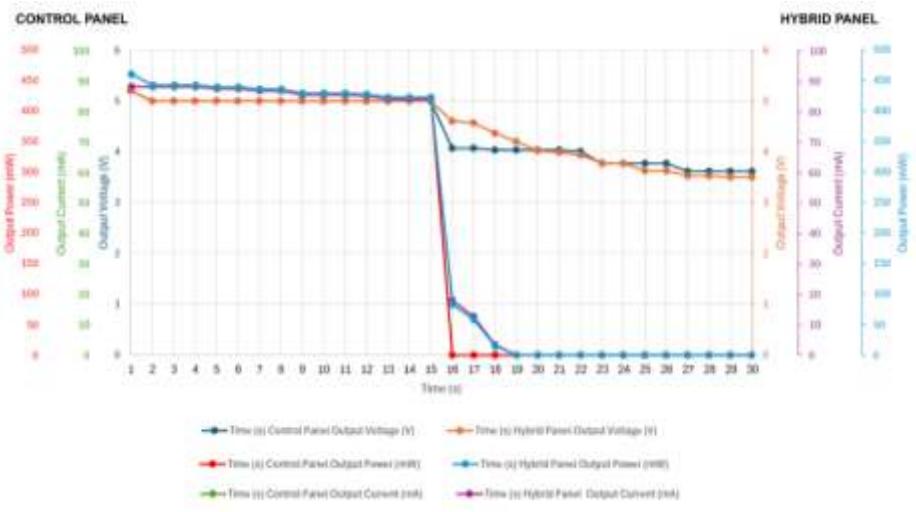


Figure 5. *Comparison of Energy Output Between Control PV Panel and Hybrid PV-TENG Panel during Sunny while Rainy Condition*

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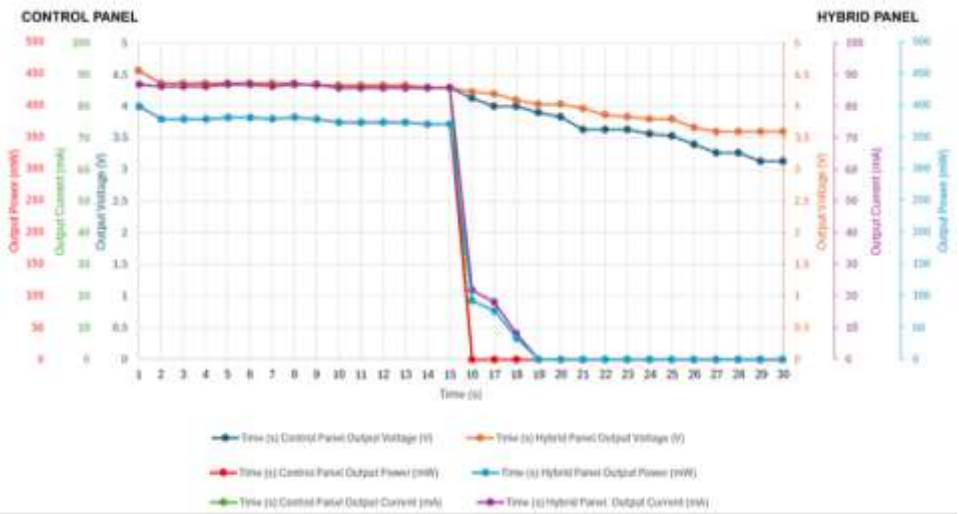


Figure 6. *Comparison of Energy Output Between Control PV Panel and Hybrid PV-TENG Panel during Cloudy while Rainy Condition*

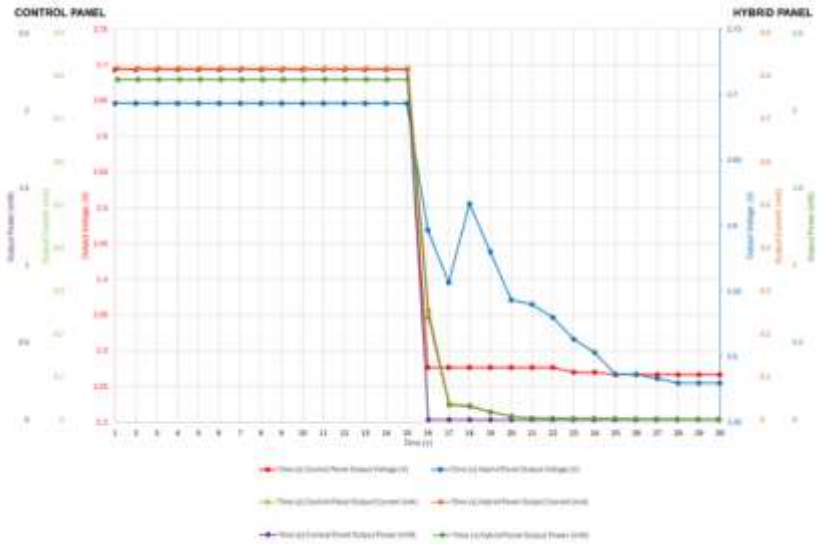


Figure 7. *Comparison of Energy Output Between Control PV Panel and Hybrid PV-TENG Panel during Dark while Rainy Condition*

Table 13. *Comparison Summary of Energy Output Between Control PV Panel and Hybrid PV-TENG Panel*

Condition	Control Panel Energy (mWs)	Hybrid PV-TENG Panel Energy (mWs)	Energy Increase (%)
Sunny While Rainy	6507.67	6662.09	2.37%
Cloudy While Rainy	3406.7	3529	**3.59%**
Dark While Rainy	33.02	33.99	2.93%

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Interpretation of Results

The hybrid PV-TENG system's ability to capture energy both from solar radiation and rainfall is a key strength of this study. As shown in the results, the highest energy output occurred under Cloudy While Rainy conditions, where the TENG subsystem significantly boosted energy harvesting. This finding aligns with previous studies by Zhang et al. (2024), who suggested that hybrid systems combining renewable energy sources, such as PV and TENGs, are particularly beneficial in regions with fluctuating environmental conditions. In this case, the TENG compensated for the decrease in solar energy during periods of low irradiance.

Even when solar energy was available, the TENG still contributed additional energy, though the increase was modest compared to the more drastic improvements seen during periods of cloudy and rainy conditions. This suggests that the hybrid system is more effective during adverse weather, providing additional energy during times when solar energy alone might be insufficient.

In particular, the system's performance during Dark While Rainy conditions, where there was minimal solar irradiance, underscores the TENG's potential as a reliable supplementary energy source. The relatively small but noticeable increase in energy output (2.93%) suggests that TENGs can function independently of PV systems, offering backup energy harvesting capabilities, especially during nighttime or in overcast conditions.

Triangulation of Results

The results of this study are supported by triangulation, a method that enhances the validity and reliability of the findings by using multiple data sources and methodologies. In this case, triangulation was achieved by integrating multiple factors: performance data from both the PV and TENG systems, environmental variables such as solar irradiance and rainfall patterns, and the energy output measurements under these varied conditions. This approach strengthens the conclusions drawn, as it minimizes the potential biases that could arise from relying on a single source of data or methodology.

The hybrid system's efficiency was tested across different weather scenarios, which allowed for a more comprehensive understanding of its performance. Triangulation also helped validate the energy output measurements, as the data collected from both the solar and triboelectric systems were consistent with theoretical predictions and previous research on hybrid energy systems. This multi-source validation of the data helps ensure that the results presented are reliable and robust.

Comparison with Existing Literature

The findings in this study are consistent with earlier research on hybrid energy systems, especially regarding the challenges associated with the impedance mismatch between TENGs and PV systems. As observed by Zhao et al. (2021), and supported by the results of this study, TENGs operate at high impedance, which can make energy transfer to PV systems less efficient. This issue needs to be addressed through better energy management circuits and impedance matching to improve energy transfer efficiency.

Moreover, the impact of rainfall on TENG performance aligns with the work of Wang et al. (2012), who suggested that moderate rainfall intensities can enhance TENG efficiency by improving the triboelectric charge generation process. However, this study also highlighted that very high rainfall intensities lead to oversaturation, which reduces the energy-harvesting capabilities of the TENG. This observation is in agreement with previous studies by Zhang et al. (2017), who noted that water droplets' kinetic energy plays a crucial role in TENG output, but beyond a certain threshold, performance begins to decline.

Practical Implications and Applications

The findings suggest that a hybrid PV-TENG system has significant potential in off-grid applications or locations where energy demands fluctuate due to variable weather. The triangulation of

results, combining both the solar and TENG data, offers a clearer picture of how the hybrid system can provide continuous energy in varying environmental conditions. For instance, the hybrid system could be useful for powering low-energy devices such as environmental sensors, lighting systems, and communication equipment in remote areas, where maintaining a continuous energy supply is critical.

Additionally, the ability of the system to continue functioning during cloudy or rainy conditions adds resilience to renewable energy networks, which are often disrupted by inconsistent weather patterns. For areas with frequent rainfall or cloudy days, such as tropical or coastal regions, integrating TENGs with PV systems could lead to more reliable and efficient energy harvesting.

Limitations of the Study

Despite the promising results, the study has several limitations. One of the primary challenges is the impedance mismatch between the TENG and PV system. While the hybrid system produced encouraging results, the efficiency of energy transfer could have been higher with the implementation of impedance-matching circuits, which would allow for better synchronization between the TENG's high-voltage output and the PV system's low-current input.

Another limitation was the use of a manually controlled rainfall simulator, which introduced some variability in the intensity and behavior of rainfall. Future studies could benefit from automated simulators that more accurately replicate natural rainfall dynamics. Additionally, long-term performance testing in real-world environments is necessary to evaluate the system's durability and reliability under sustained operational conditions.

Future Research Directions

Future research should focus on optimizing the hybrid system by addressing the following areas:

1. Energy Transfer Efficiency: Developing circuits that improve the energy transfer between the TENG and PV system will be critical to maximizing the hybrid system's performance. Research into impedance-matching solutions would likely improve the overall energy output of the system.
2. Material Optimization: Exploring new materials for the TENG, particularly those with better triboelectric properties, could significantly enhance the energy harvesting capability. Testing different material combinations and surface treatments may yield improvements in performance under various environmental conditions.
3. Field Testing: Conducting long-term field tests in different climatic regions will provide valuable insights into the hybrid system's real-world performance. These tests should focus on the system's ability to handle variable weather patterns over extended periods.
4. Integration with Energy Storage Systems: Integrating energy storage technologies, such as supercapacitors or batteries, would help store the harvested energy more efficiently, ensuring that it is available for use during periods of low energy generation.
5. Scalability and Cost-Effectiveness: Assessing the scalability of the hybrid system for larger applications and evaluating the cost-effectiveness of such systems will be crucial for commercial deployment, particularly in off-grid areas.

CONCLUSION

Anchored in a structured exploratory sequential design, this study successfully integrated qualitative material selection with quantitative performance validation and system-level testing. Each SOP yielded conclusions that reinforced the practical feasibility and contextual relevance of a hybrid PV-TENG energy harvesting system.

1. The FEP-Stainless Steel material pair combined with Contact-Separation operational mode demonstrated the highest open-circuit voltage among all configurations tested, under the simulated rainfall intensities and capacitor conditions applied. While budgetary constraints guided material

availability, conclusions about performance are framed within these testing parameters rather than an absolute claim of superiority.

2. The use of capacitors significantly enhanced TENG output voltages by stabilizing charge accumulation, particularly for high-polarity material pairs and moderate rainfall intensities. This highlights the critical role of energy storage components in hybrid system optimization.
3. The 13-18 mm/min rainfall intensity range yielded the highest open-circuit voltage among the tested intensities, suggesting an optimal balance between droplet impact and sliding behavior. This validated its use in the final system-level testing and underscored the influence of environmental parameters on TENG output.
4. The integration of the optimized TENG configuration with monocrystalline PV cells was tested under three environmental conditions, namely, sunny while rainy, cloudy while rainy, and dark while rainy. Across all conditions, the hybrid PV-TENG panel consistently outperformed the control PV-only panel. The highest relative energy increase (3.59%) occurred during cloudy while rainy conditions, where solar output was suppressed and the TENG's compensatory contribution was most prominent. Gains of 2.37% and 2.93% under sunny while rainy and dark while rainy conditions, respectively, further demonstrated the hybrid system's functionality across varying solar inputs. While modest in magnitude, these improvements affirm the potential of hybridization as a practical solution to reduce PV system vulnerability to environmental variability, particularly in rainfall-prone and off-grid settings.

These findings affirm the potential of PV-TENG hybrid systems as practical solutions to improve energy resilience in off-grid or rainfall-prone areas. While the improvements in energy output were modest, the results highlight the value of multi-source energy systems in mitigating the vulnerability of solar-only configurations to environmental variability. The methodological approach presented here offers a replicable model for future work, emphasizing the integration of design logic, environmental simulation, and contextual constraints to advance renewable energy innovations suited to tropical climates.

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