A Thesis Submitted to the Sylhet Engineering College for the Degree of
Bachelor of Science in Electrical and Electronic Engineering

A Hybrid Model for Generating Electricity from Sunlight and Raindrop Energy by Using PV and Piezoelectric Material Respectively

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Abstract

This thesis presents an innovative hybrid energy harvesting system that combines photovoltaic (PV) cells and piezoelectric materials to generate electricity from sunlight and raindrop impacts, respectively. Under sunny conditions, PV cells efficiently convert solar energy into electricity. However, their performance drops sharply during cloudy or rainy weather, limiting their reliability in regions with variable climates. To overcome this limitation, the hybrid system incorporates piezoelectric transducers that convert the mechanical energy of falling raindrops into electrical energy during rainfall. Piezoelectric materials such as PZT or PVDF produce an electrical charge when subjected to mechanical stress, enabling energy generation even when solar irradiance is low. In this work, practical testing was limited due to constraints in laboratory access; however, data collected from small-scale setups and theoretical projections were used to estimate performance. When water droplets of approximately 300 mg is released from a height of 1 meter, an average output of around 110 mV is recorded from the PVDF layer. Based on terminal velocity conditions typical of natural rainfall, this output is projected to reach up to 1255 mV. Additionally, the solar panel, with dimensions of 110 mm by 20 mm, contributes approximately 50 mV from the area directly impacted by a single droplet. Together, the hybrid system can deliver an estimated total output of about 1305 millivolts under combined sun-and-rain conditions. The hybrid model intelligently integrates both energy sources on a single platform. In conclusion, this thesis demonstrates that a hybrid PV–piezoelectric energy harvesting system offers a robust, adaptable, and sustainable solution for continuous power generation across varying environmental conditions. It maintains energy generation during both sunny and rainy periods, making it highly suitable for off-grid applications in areas with frequent weather changes.

Keywords: Hybrid *Energy System, Photovoltaic (PV) Cells, Piezoelectric Energy Harvesting, Renewable Energy.*

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Chapter 1: Introduction

1.1 Background

The growing demand for clean and sustainable energy sources has intensified the exploration of alternative power generation methods. Solar energy, captured using photovoltaic (PV) cells, is abundant and widely utilized; however, its performance is significantly reduced during cloudy and rainy weather. To address this limitation, raindrop energy harvesting through piezoelectric materials offers a complementary solution. In this thesis, we propose a hybrid model that integrates PV and piezoelectric technologies, enabling power generation during both sunny and rainy seasons. This dual-source system ensures a more consistent energy supply and supports the goal of energy sustainability. It is especially beneficial in regions that experience frequent weather fluctuations.

1.2 How Energy From Raindrop is Collected?

Rainfall energy can be effectively harnessed using piezoelectric materials, which have the unique ability to convert mechanical stress into electrical energy through the piezoelectric effect. When raindrops strike the surface of a piezoelectric material, their kinetic energy generates minute mechanical vibrations within the crystal structure. These vibrations cause a displacement of internal charges, leading to the accumulation of electrical potential across the material. The amount of electricity produced is influenced by factors such as the size, speed, and frequency of raindrops, as well as the material's sensitivity. Each raindrop impact contributes a small amount of energy, but when accumulated over time or across large surfaces, the output becomes significant. The harvested electricity can either be stored in capacitors or batteries, or used to power low-energy electronic devices. This method of energy harvesting is particularly useful in regions with frequent rainfall, where solar energy may be intermittent. Integrating piezoelectric harvesting into hybrid systems ensures a more reliable and continuous power supply.

1.3 Solar Energy Harvesting

Solar energy harvesting is the process of capturing sunlight and converting it into usable forms of energy, primarily electricity or heat. It is a sustainable and renewable energy solution that leverages the abundant and clean energy provided by the sun.

The sun emits vast amounts of energy in the form of electromagnetic radiation. This energy can be harvested using various technologies, with the most common being Photovoltaic (PV) systems. Photovoltaic (PV) systems are technologies that convert sunlight directly into electricity using the photovoltaic effect. They are one of the most widely used and practical methods for harvesting solar energy, and they form the core of modern solar power generation. The photovoltaic effect occurs when photons (light particles) strike a semiconductor material, such as silicon, causing electrons in the material to become excited and move, creating an electric current. This process generates direct current (DC) electricity.

1.4 Existing Models For Energy Harvesting

Numerous existing models have been developed to harvest energy from environmental sources, especially from raindrop impacts using piezoelectric materials. These studies primarily focus on single-source systems, where mechanical energy from rainfall is converted to electrical output through different structural configurations. Although these approaches demonstrate the feasibility of raindrop energy harvesting, they lack integration with solar energy systems. Since sunlight and rainfall often occur at different times or in alternating patterns, a hybrid system that captures both forms of energy can significantly improve energy reliability. This section explores some of the key models developed for raindrop energy harvesting, laying the groundwork for understanding how our proposed dual-source hybrid system builds upon and advances this foundational work.

1.4.1 Cantilever-Based Energy Harvesting System

Figure 1.1 shows a cantilever-based energy harvesting system. This structure compares two types of piezoelectric transducers PVDF and PZT. When a raindrop hits the free end of the cantilever, it causes vibrations. These vibrations are converted into electricity by the piezoelectric material, demonstrating one method of energy harvesting from raindrop impacts. [11].

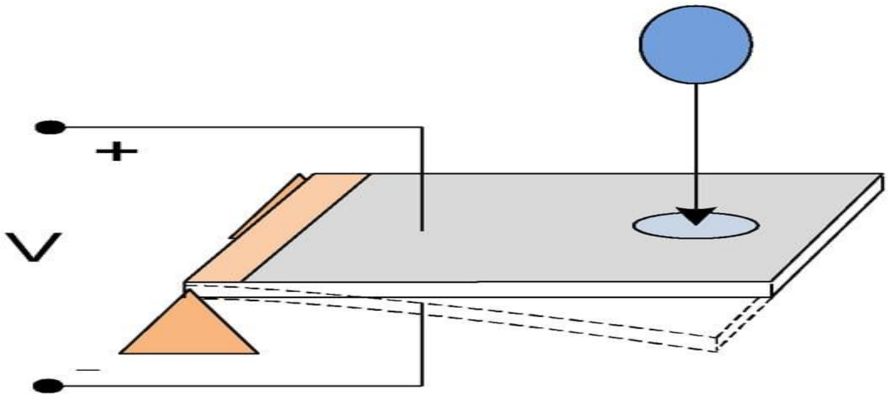

Figure 1.1: Cantilever Structure

1.4.2 Vibration Energy Harvesting System using Sandwiched Structure

Figure 1.2 shows a sandwiched piezoelectric structure for vibration energy harvesting. In this setup, a PVDF film were used as piezo-electric materials. The film had dimensions of 35 mm × 80 mm × 52 mm, being sandwiched by two silver electrode plates. The film was attached to a machined aluminium alloy block. A water droplet was produced using a syringe with a flat-tipped needle.

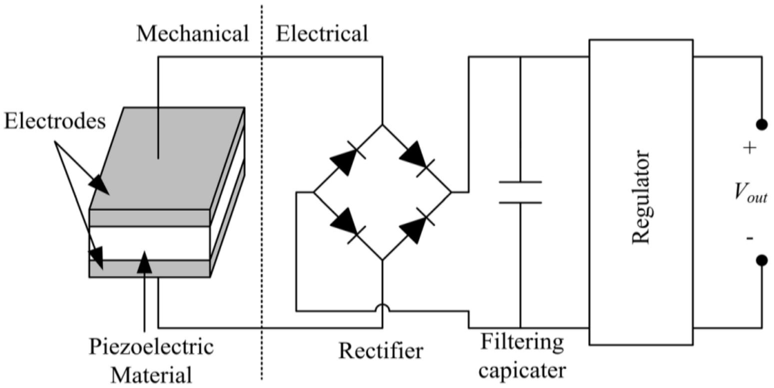

Figure 1.2: Sandwiched Structure

In this research, we developed a hybrid model designed to harvest energy from both raindrops and solar radiation by integrating piezoelectric materials and photovoltaic (PV) cells. While our conceptual framework addresses the need for dual-source energy harvesting in variable weather conditions, our experimental work primarily focused on the raindrop energy harvesting aspect. This focus was influenced by limitations in budget, laboratory infrastructure, and available measurement tools.

Since no prior studies fully integrate raindrops and solar harvesting in this specific configuration, direct performance comparisons are limited. Therefore, we benchmarked the piezoelectric component of our system against existing research that evaluates energy output from raindrops impacts on piezoelectric films. These comparisons served to validate the feasibility of mechanical-to-electrical energy conversion under simulated rainfall conditions. Given the extensive body of research and well-established performance data available on PV systems, we considered the solar energy contribution as an additive component in our hybrid model. Although we did not experimentally validate the PV subsystem due to practical constraints, its expected performance is supported by findings from existing literature. In future stages of this work, we aim to fully integrate and test the PV subsystem alongside the piezoelectric unit under real environmental conditions to comprehensively evaluate the overall performance of the hybrid model.

1.5 Objectives

1. Develop a hybrid energy harvesting system utilizing both raindrop and solar energy in the same vertical space.
2. To develop a functional hardware prototype demonstrating the proposed hybrid energy harvesting model.
3. To investigate and select optimal materials (PV and piezoelectric) suitable for hybrid integration with high energy conversion efficiency.

1.6 Why PVDF Material as Piezoelectric

PVDF is preferred for raindrop energy harvesting because it is flexible, lightweight, and sensitive to low-impact forces. Unlike rigid materials like **PZT** and **quartz**, PVDF effectively converts the small energy from raindrops into electricity. It is also lead-free, easy to fabricate, and environmentally safe, making it ideal for practical and versatile applications.

1.7 Significance of Hybrid Model

The significance of this thesis lies in its novel approach to addressing the limitations of single-source renewable energy systems by introducing a hybrid model that integrates solar and rainfall energy harvesting. Traditionally, photovoltaic (PV) systems have been the most widely adopted form of renewable energy, but their performance is highly dependent on sunlight availability, which can be unpredictable in many regions. This hybrid model introduces piezoelectric materials that can convert the kinetic energy of raindrops into electricity, effectively complementing the PV system during periods of low solar irradiance.

This dual-functionality significantly improves energy reliability, making the system particularly beneficial for off-grid applications, remote monitoring systems, and smart infrastructure in urban environments. The research encourages the practical use of piezoelectric technology, which has often remained underutilized despite its potential. By integrating it into a functional and tested energy solution, the study provides a blueprint for diversified energy harvesting systems that are more resilient to environmental changes. Moreover, the model aligns with the goals of sustainable development by promoting cleaner energy sources and reducing reliance on fossil fuels. It also opens new opportunities for deploying hybrid systems in developing regions where consistent power supply remains a challenge. The compact and scalable nature of the proposed system makes it adaptable to various use-cases—from powering individual electronic devices to serving as part of a larger distributed energy network. By emphasizing smart energy conversion, storage, and management, the study contributes to the advancement of intelligent energy systems designed for the evolving demands of smart cities and IoT-based infrastructure. It lays a strong foundation for future research into integrated renewable energy platforms that leverage multiple natural resources, and it sets a precedent for innovation in green energy solutions.

1.8 Thesis Structure

In the chapters that follow, the significance of the presented research is expanded upon through the provision of both contextual background and novel contributions, systematically organized to guide the reader through the progression of the work.

Chapter 1: An introduction to the fundamental principles of hybrid renewable energy systems is provided, focusing on the integration of photovoltaic (PV) and piezoelectric technologies. The background, problem statement, objectives, significance, and scope of the study are discussed to establish the research context.

Chapter 2: A comprehensive review of existing literature is undertaken, covering solar energy harvesting through PV cells, raindrop energy harvesting using piezoelectric materials, and previously developed hybrid energy models. Comparative studies and relevant experimental findings are summarized to highlight research gaps and justify the proposed system.

Chapter 3: The design and methodological framework of the proposed hybrid energy harvesting system are described. The individual PV and piezoelectric subsystems are detailed, including their working principles, circuit design, and integration approach. The experimental setup, measurement procedures, and system configuration are presented.

Chapter 4: Results obtained from the experimental implementation are presented and analyzed. The performance of the PV system, piezoelectric system, and the combined hybrid system is evaluated, with an emphasis on efficiency, power output, and operational feasibility. Observations are compared with existing literature to assess the advantages and limitations of the proposed design.

Chapter 5: The overall contributions of the research are summarized. Broader implications for sustainable and hybrid renewable energy generation are discussed, and recommendations are provided for future work, including potential material improvements, circuit optimizations, and scaling strategies for real-world applications.

1.9 Summary

This chapter lays the groundwork for understanding the motivation behind developing a dual-source energy harvesting system. It introduces the hybrid integration of photovoltaic (PV) and piezoelectric technologies as a solution to overcome the limitations of standalone renewable systems under inconsistent weather conditions. The chapter clearly defines the research problem, outlines the objectives, and explains the methodology and scope. Special emphasis is placed on addressing the issue of energy generation during rainy weather, which conventional PV systems fail to resolve. By presenting a new concept suited for varying climates, this chapter sets the stage for the rest of the thesis.

Chapter 2: Literature Review

The global transition toward clean energy has intensified research into renewable technologies capable of offering decentralized and weather-adaptive power generation. Among the various approaches explored, harvesting energy from sunlight and raindrop impacts has garnered attention due to their complementary availability in nature. This chapter critically examines the technological advancements and research developments in photovoltaic (PV) and piezoelectric energy harvesting, with a focus on their integration in hybrid systems aimed at uninterrupted power generation across diverse environmental conditions.

Photovoltaic technology is well established for converting solar radiation into electrical energy through the photovoltaic effect. However, its efficiency is heavily reliant on clear sunlight, which poses a limitation in regions experiencing frequent cloud cover or rainfall. On the other hand, piezoelectric materials can convert mechanical stress into electricity, offering a viable alternative energy source when sunlight is unavailable. The synergy between these two technologies forms the basis of hybrid energy harvesters, which aim to ensure consistent power generation by switching or combining outputs based on prevailing environmental conditions.

Raindrop-based piezoelectric energy harvesting has seen significant progress over the last decade. **Ilyas and Swingler** [1] conducted an in-depth study on the performance of PVDF (polyvinylidene fluoride) under raindrop impacts. Their research demonstrated that even low-mass raindrops can induce voltages in flexible piezoelectric films. **Guigon** et al. [2] extended this work by experimentally analyzing voltage generation from droplet impacts, confirming the repeatability and effectiveness of energy capture under controlled conditions. These early contributions laid the foundation for using raindrop energy in practical micro-power applications.

With the need to increase energy yield and device scalability, **Li** et al. [3] developed a droplet-based electricity generator capable of harvesting energy from large-scale rainfall. Their system utilized hierarchical nanostructures to enhance charge generation from droplet motion and friction. **Jeon** et al. [4] proposed a multifunctional device combining self-cleaning surfaces with hybrid energy harvesting using both PV and piezoelectric layers. This integration allowed simultaneous power generation from sunlight and raindrops while preventing surface fouling, thereby increasing long-term efficiency.

Addressing structural challenges in hybrid systems, **Liu** et al. [5] introduced an all-inorganic hybrid energy harvester optimized for both sunlight and raindrop collection. The material robustness and hydrophobic surface design provided stable performance in changing weather. In a complementary study, **Chavan** et al. [6] presented a system using a hybrid solar panel embedded with piezoelectric materials to increase energy availability during low-light conditions. These contributions underline the growing need for multi-modal energy harvesting devices.

Pang et al. [7] reviewed hybrid systems incorporating triboelectric nanogenerators (TENGs) alongside PV and piezoelectric harvesters. Their review noted that integrating multiple energy types could provide superior power output for self-powered systems. Meanwhile, Han et al. [8] focused on piezoelectric–electromagnetic hybrids, offering insight into how combining mechanical energy harvesting methods can improve energy density and operational bandwidth. Sustainability and intelligent energy management are also crucial in hybrid energy system design. **Gowthami** [9] advocated for smart management of solar-piezoelectric hybrids to power low-cost, off-grid applications. Her work emphasized integrating energy-efficient materials and low-power control circuitry. **Chua** et al. [10] provided a comprehensive review of interface circuits for raindrop-piezoelectric harvesters. Their work outlined circuit topologies such as full-wave rectifiers, voltage multipliers, and power conditioning units essential for optimizing energy transfer and storage.

Understanding the design parameters of raindrop harvesting, **Wong** et al. [11] offered a systematic review of energy extraction using piezoelectric materials. They discussed factors such as droplet velocity, surface area, and material thickness, which influence the voltage output. Further studies by **Hajra** et al. [12] introduced advanced nanostructured hybrids integrating solar and mechanical energy harvesters. These systems enable stretchable, transparent, and wearable devices with improved responsiveness to environmental input.
The output characteristics of raindrop-based energy harvesters are further elaborated by **Teoh** et al. [13], who analyzed asynchronous droplet impacts on piezoelectric arrays. Their work concluded that droplet spacing, size, and randomness significantly affect peak voltage and charging capacity. Enhancing the design to accommodate these dynamics could yield more efficient systems for outdoor deployment.

Bao et al. [14] presented a novel photovoltaic-triboelectric hybridized nanogenerator capable of simultaneously capturing energy from light and liquid droplets. Their design featured transparent electrodes and a layered structure that preserved optical access for PV while utilizing triboelectric and piezoelectric surfaces to collect mechanical energy. In the realm of smart systems, **Xie** et al. [15] developed a hybrid nanogenerator for powering distributed sensor nodes. Their intelligent sensing system harvested ambient energy from multiple sources, supporting autonomous operation in smart cities and agricultural monitoring.

Furthermore, for undergraduate-level research and practical implementation, hybrid models provide a valuable opportunity to explore low-cost, compact prototypes capable of operating in real-world, variable weather conditions. The use of PVDF films layered above or alongside PV cells allows effective energy collection during both rain and shine. The functional hardware prototype developed in this study is based on such a structure, enabling direct experimental validation of theories discussed across the literature. This not only supports educational outcomes but also offers insights into scalable designs for small-scale rural electrification or IoT deployment in weather-sensitive regions.

In conclusion, the reviewed literature provides strong evidence supporting the integration of PV and piezoelectric technologies in hybrid energy harvesting systems. Each reference contributes uniquely to understanding the materials, design configurations, interface circuits, and real-world applications necessary to realize an efficient hybrid model. PVDF remains a preferred choice for raindrop harvesting due to its mechanical flexibility and piezoelectric efficiency. The continued evolution of nanostructured materials and adaptive electronics further enhances the feasibility of hybrid platforms. This thesis builds upon these foundational works to design and implement a layered system that combines PV and piezoelectric materials, aiming to deliver reliable micro-scale power generation under varying environmental conditions.

2.1 Summary

This chapter reviews photovoltaic systems, piezoelectric energy harvesting, and existing hybrid models, emphasizing the potential of PVDF for raindrop energy capture. It identifies a research gap in combining solar and raindrop energy into a single system, establishing the novelty and technical basis of the proposed model.

Chapter 3: Methodology

3.1 Overview

The proposed hybrid energy harvesting system integrates both solar photovoltaic (PV) technology and piezoelectric energy harvesting to generate electricity from two naturally occurring sources: sunlight and rainfall. The system is designed to maximize energy output within a compact vertical structure, making efficient use of space while providing energy resilience across varying weather conditions.

3.2 System Design

The proposed hybrid energy harvesting system is designed using a compact, four-layer structure that enables the simultaneous collection of solar and raindrop energy. Each layer plays a critical role in the overall performance and functionality of the system. The layers are arranged in a vertically stacked configuration, allowing the system to optimize energy conversion from both environmental sources within the same physical footprint.

3.2.1 Base Layer (Glass Sheet)

Figure 3.1 shows the base layer of the hybrid energy harvesting system. The base layer consists of a flat glass sheet, which serves as the primary structural foundation of the system. It provides mechanical support and ensures the stability of all the upper layers. The glass is chosen for its rigidity, flatness, and environmental resistance, allowing it to withstand changes in temperature, humidity, and exposure to moisture. This layer also helps maintain the alignment and integrity of the piezoelectric and solar components during operation and testing.

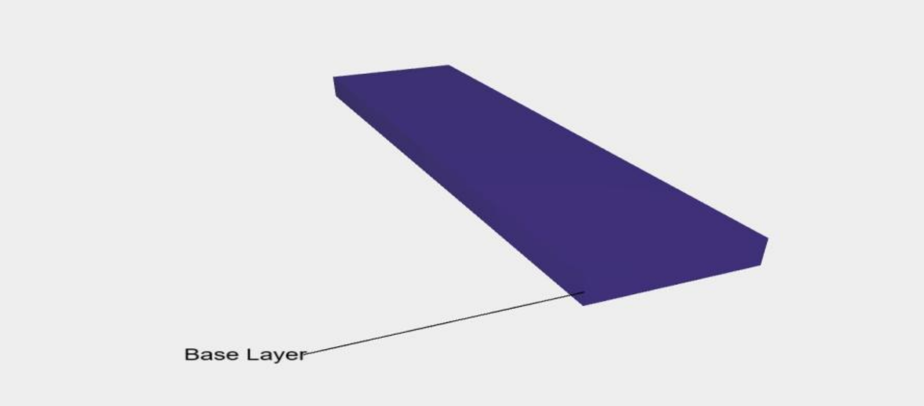

Figure 3.1: Base Layer

3.2.2 Rail Layer (Spacer Layer)

Figure 3.2 demonstrates the rail or spacer layer in the system design. Situated directly above the glass base, the rail layer functions as a spacer that creates a narrow air gap between the base and the piezoelectric layer. This gap is essential for enabling mechanical deformation of the piezoelectric film when impacted by raindrops. Without this spacing, the PVDF film would be in direct contact with the rigid glass, restricting its movement and, consequently, its ability to generate electricity through the piezoelectric effect. The rail layer thus plays a vital role in facilitating the dynamic response needed for effective energy harvesting from rainfall.

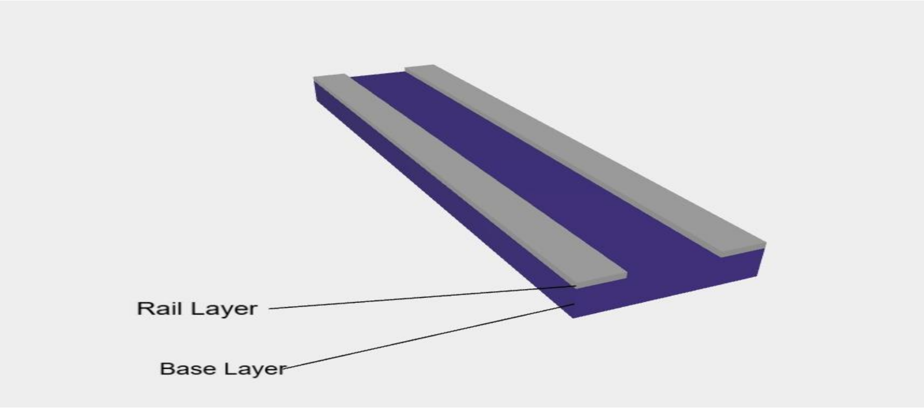

Figure 3.2: Rail Layer

3.2.3 Piezoelectric Layer (PVDF Film)

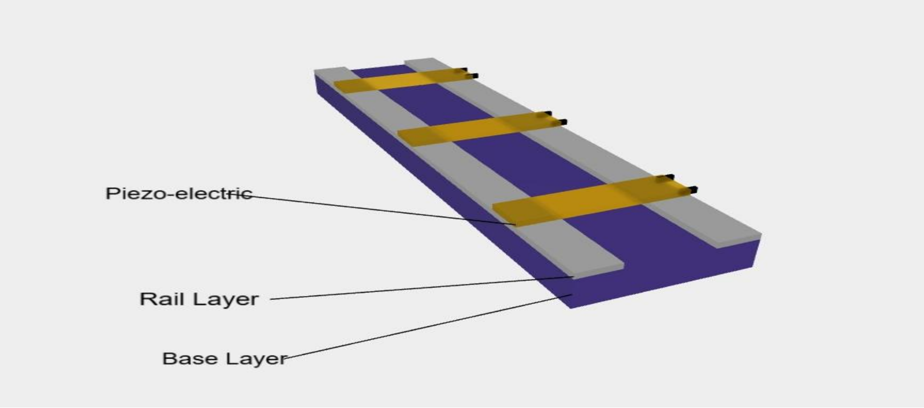

Figure 3.3: Piezoelectric Layer

The PVDF film-based piezoelectric layer is depicted in **Figure 3.3**. The piezoelectric layer is composed of multiple PVDF (Polyvinylidene Fluoride) films connected in parallel. PVDF is a highly responsive and flexible piezoelectric material known for its effectiveness in converting mechanical stress into electrical energy. When raindrops strike the surface of the structure, the force is transmitted to the PVDF layer, causing it to flex and generate an electric charge. The use of multiple films increases the surface area available for energy collection, thereby enhancing the output of the piezoelectric component during rainfall events.

3.2.4 Solar Panel Layer (Semi-Flexible PV Panel)

Figure 3.4 illustrates the solar panel layer placed at the top of the hybrid model. The uppermost layer of the structure is a semi-flexible solar panel, which serves a dual purpose. Its primary function is to harvest solar energy during daylight by converting sunlight into electrical energy using the photovoltaic effect. Additionally, the solar panel acts as a mechanical interface that transfers the impact force of falling raindrops to the underlying piezoelectric layer. The semi-flexibility of the panel allows it to deform slightly upon impact, ensuring that the energy from raindrops is efficiently delivered to the PVDF films beneath. This integration of functions within a single layer contributes to the overall compactness and effectiveness of the hybrid model. Together, these four layers form a unified system capable of harvesting energy under varying weather conditions. The layered configuration allows for optimized use of vertical space and enhances the practicality of the model for all-weather renewable energy applications.

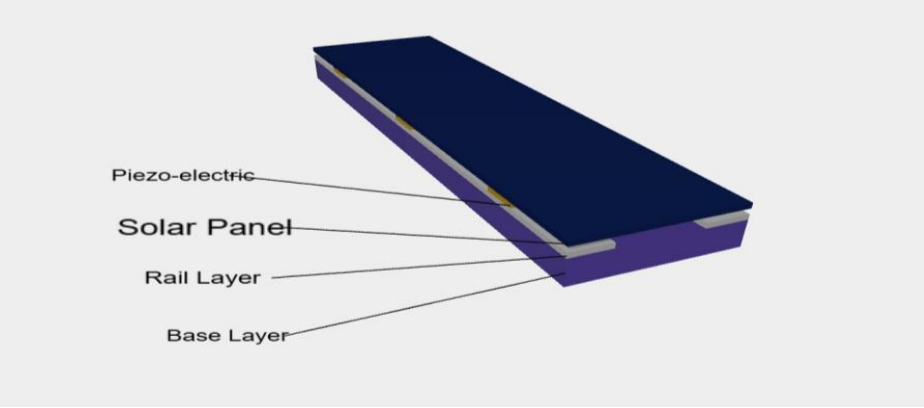

Figure 3.4: Solar Panel Layer

3.3 Construction process

The system was constructed following these steps:

- The glass base was prepared and cut to the required dimensions.
- The rail layer was installed to create the necessary air gap for PVDF film flexure.
- Three PVDF films were mounted in parallel configuration on top of the rail layer, with proper electrical contacts established to measure the piezoelectric output.

- The semi-flexible solar panel was carefully aligned and mounted on top of the PVDF films, forming the final layered structure.

3.4 Working Principle

The proposed hybrid energy harvesting system is designed to simultaneously capture energy from two distinct sources: sunlight and rainfall. The core concept revolves around a layered structure where each layer serves a complementary purpose, allowing efficient use of the same physical space. Under sunny conditions, the uppermost layer a semi-flexible photovoltaic (PV) solar panel absorbs sunlight and converts it directly into electrical energy via the photovoltaic effect. This ensures continuous energy generation during daylight hours.

When rainfall occurs, the system transitions into a dual-mode operation. As raindrops strike the surface of the solar panel, their kinetic energy is transferred to the panel in the form of localized mechanical vibrations. These vibrations are subsequently transmitted to the underlying layer of polyvinylidene fluoride (PVDF) films, which possess intrinsic piezoelectric properties. The piezoelectric effect causes these films to generate an electric charge in response to mechanical deformation induced by the raindrop impacts.

The rail layer positioned between the glass base and the PVDF films introduces a deliberate air gap, allowing the PVDF films to flex more effectively upon impact, thereby enhancing the energy conversion efficiency. The glass base provides structural support, maintaining the mechanical integrity of the system during both solar and rainfall harvesting. This dual-mode operation allows the system to continuously harvest energy across varying weather conditions, whether during sunny periods, rainy days, or even mixed weather scenarios. The hybrid nature of the design offers a distinct advantage by improving the overall energy density and reliability of renewable energy generation, particularly in geographic regions characterized by alternating sunny and rainy weather patterns.

3.5 Model Evaluation

To effectively evaluate the proposed hybrid energy harvesting model, it is essential to understand key concepts particularly terminal velocity and the projected electrical output at terminal velocity. Terminal velocity refers to the highest constant speed a falling object, such as a raindrop, can achieve when the downward pull of gravity is perfectly balanced by the upward force of air resistance. At this point, the raindrop ceases to accelerate and continues to fall at a uniform speed.

In the context of energy harvesting, this velocity is crucial because the kinetic energy transferred to the piezoelectric material depends on the speed of the falling raindrop. The projected output at terminal velocity is an estimate of the electrical energy that a droplet can generate when falling at this steady speed. This value is extrapolated from the output obtained during controlled experiments typically when droplets are released from a height of one meter. By applying the relationship between velocity and energy output, the system's performance under real-world rainfall conditions can be predicted more accurately.

3.6 Hardware implementation

3.6.1 Hardware Selection

To implement the model in real life we need to measure two parameters from atmosphere one is sunlight and other one is raindrop energy. To measure these parameters following components are required-

- Thin film solar panel (110 mm × 20 mm)
- PVDF film (LDTO-028K)
- A flat glass sheet
- A guided pipe
- Multimeter

3.6.2 Building The Hardware

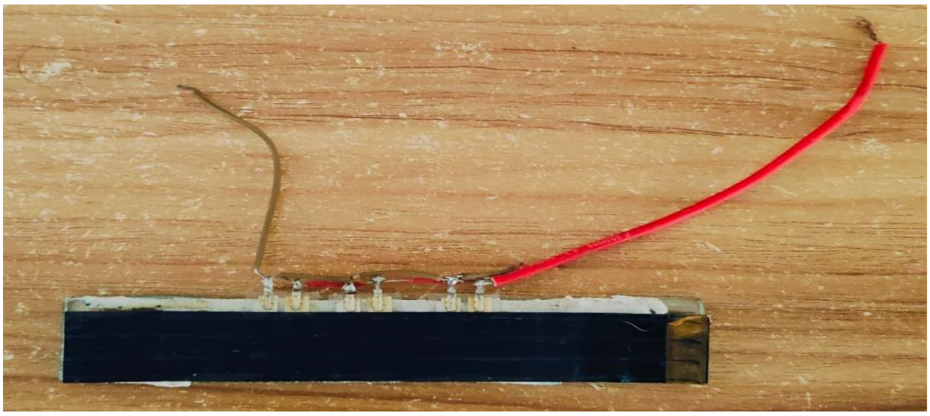

Figure 3.5: Hardware Implementation of Hybrid Model

Figure 3.5 shows the actual hardware implementation of the hybrid energy harvesting system. To measure the data, we require one thin film solar panel, three PVDF film and one flat glass sheet

3.6.3 Experimental Setup

Figure 3.6 demonstrates the experimental setup used to test the energy harvesting system. To validate the functionality and effectiveness of the proposed hybrid energy harvesting system, a practical experimental setup was constructed and tested under controlled conditions. The aim was to assess the energy output generated from both sunlight and raindrop impacts using the integrated PV and piezoelectric layers.

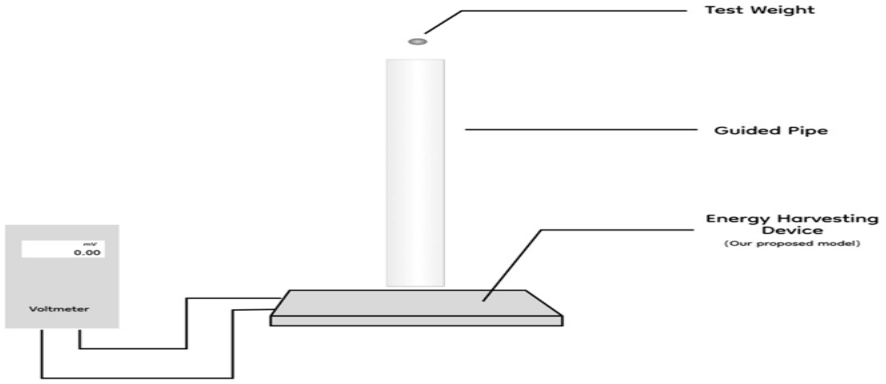

Figure 3.6: Experimental Setup for energy harvesting

3.6.4 Fabrication Challenges

During fabrication, several challenges were encountered:

- Ensuring consistent and even mounting of the PVDF films without damaging them.
- Preventing mechanical damping that could reduce piezoelectric output.
- Achieving reliable electrical contacts without introducing noise into the measurement system.
- Balancing structural rigidity with flexibility to optimize energy transfer from raindrop impacts.

3.7 Comparative Analysis of Hybrid Renewable Energy Systems

Hybrid renewable energy systems combining multiple energy harvesting mechanisms have been extensively studied to address the limitations of individual sources and enhance system reliability. Among the most researched are solar-wind hybrid systems, where solar photovoltaic (PV) generation is complemented by wind turbines to provide more consistent energy output across varying weather conditions. Solar-wind systems are particularly effective in regions where wind speeds tend to increase during cloudy or stormy weather, partially compensating for the reduction in solar irradiance.

Solar-thermal hybrid systems are another well-established approach, where solar panels are combined with thermal collectors to simultaneously generate electrical and thermal energy. These systems are widely used in industrial and residential heating applications but typically require larger physical footprints and more complex integration than purely electrical hybrid systems.

By contrast, the solar-raindrop hybrid model proposed in this thesis offers a unique advantage in terms of compactness and complementary functionality. It leverages two environmental phenomena—sunlight and rainfall—that often alternate in tropical and temperate regions. Unlike wind-based hybrids, the solar-raindrop system requires no moving mechanical parts, resulting in potentially lower maintenance requirements and quieter operation. Moreover, its layered architecture enables efficient use of limited surface area, making it suitable for urban environments or small-scale off-grid applications.

However, it is important to note that the total energy output from raindrop harvesting remains significantly lower than that of wind or thermal counterparts. The main strength of the solar-raindrop hybrid lies not in maximizing total power generation, but in improving system resilience and maintaining energy output during periods of low solar availability. In this sense, it offers a complementary and sustainable solution for locations where frequent rainfall coincides with variable solar conditions. As research progresses, integrating this concept with broader multi-source hybrid platforms (e.g., combining solar, wind, and piezoelectric harvesting) could further enhance its practicality and appeal.

3.8 Summary

This chapter describes a four-layer hybrid system combining PV cells and PVDF piezoelectric films to harvest solar and raindrop energy. It covers material selection, structure, wiring, and a conceptual energy storage framework. The low-cost prototype is designed for efficient operation in varying weather conditions.

Chapter 4: Results and Discussion

4.1 Measurement

In this experiment, water droplets were released from a height of 1 meter to strike the piezoelectric PVDF layer. The output voltage generated by each droplet impact were recorded using a digital multimeter. Multiple droplets were tested, and the average output was calculated to assess the piezoelectric response.

Table 4.1: Measured Average Output From Raindrops Impact at 1m Height

Droplet mass (mg)	Voltage (mV)	Average (mV)
300	117	110
	116	
	97	
268	60	73
	89	
	68	
202	62	45
	40	
	32	
80	22	15
	12	
	11	

The table 4.1 presents the voltage output generated by PVDF films when impacted by water droplets of varying masses from a 1-meter height. Results show a clear trend: as droplet mass increases, the average voltage output also rises. Heavier droplets (300 mg) produced the highest average output (110 mV), while lighter ones (80 mg) generated only 15 mV. This confirms the positive relationship between impact energy and piezoelectric response. The consistency across multiple trials highlights the system's reliability and sensitivity to droplet impacts.

4.2 Calculating Terminal Velocity

The data shown in table 4.1 corresponds to droplets released from a height of 1 meter. Using the equations $s = ut + \frac{1}{2}gt^2$ & $v = u + gt$, the calculated velocity is approximately 4.41 m/s. To compare these values with their respective terminal velocities, we must first determine the terminal velocity for each droplet size. During terminal velocity, the drag force is equal to the force due to gravity which is,

$$mg = \frac{1}{2} C_D \rho_{air} V_t^2 \frac{\pi D^2}{4} \tag{i}$$

Re-arranging the terms we get ,

$$V_t = \sqrt{\frac{8mg}{C_D \rho_{air} \pi D^2}} \tag{ii}$$

After plugging the values of the constants and simplification,

$$V_t = \frac{7.14\sqrt{m}}{D} \tag{iii}$$

The induced voltage (V_{out}) is proportional to the applied stress which is proportional to the energy during impact.

$$V_{out} \propto mv^2 \tag{iv}$$

$$V_{\mathrm{out}1} = \left(\frac{V_{t1}}{Vhte_{t2}}\right)^2 \times V_{\mathrm{out}2} \tag{v}$$

4.3 Projecting Output to Terminal Velocity

The output measured from 1-meter droplet impacts was then projected to estimate the output at terminal velocity. Table 4.3 presents the measured voltage output of the hybrid energy harvesting system under controlled droplet impact conditions for droplets of varying masses. The table lists four different droplet masses ranging from 80 mg to 300 mg, along with their corresponding terminal velocities. Two sets of voltage measurements are provided: (1) the voltage output when droplets were released from a height of 1 meter in the laboratory setup, and (2) the projected voltage output when droplets are assumed to fall at their calculated terminal velocities, representing natural rainfall conditions.

Table 4.2: Raindrop Falling at Terminal Velocity

Mass (mg)	Terminal Velocity (m/s)	Voltage (mV) When dropped from 1m	Voltage (mV) When falling with Terminal Velocity
300	14.89	110	1255
268	14.79	73	821
202	13.93	45	449
80	11.93	15	110

4.4 Discussion

The performance of the proposed hybrid energy harvesting system is compared to an existing model based on key parameters, as summarized in Table 4.4.

The comparison highlights improvements in several important aspects of the design. The diameter of the raindrop used in our proposed model was significantly larger (8.3 mm) compared to that in the existing model (3.57 mm), resulting in a greater impact area and thus a larger kinetic energy transfer to the piezoelectric layer. Correspondingly, the impact speed was also higher in our model (4.41 m/s) versus 2.96 m/s in the reference model.
In terms of voltage output at the tested impact speed, the existing model achieved 100 mV, while our prototype generated 110 mV. However, when projected to terminal velocity conditions, which better represent real-world rainfall scenarios, both systems performed at a similar level. The existing model produced a projected voltage of **1079** mV, while our proposed model yielded **1255** mV.

Since the area impacted by a single raindrop is considerably smaller than the total area of the PV cell, it is necessary to calculate the output corresponding only to the affected portion. This impacted area can be approximated by the area of a circle with the same diameter as the droplet. Using the formula $A = \frac{\pi D^2}{4}$, the area for an 8.3 mm diameter droplet is calculated to be approximately 54.1 mm². In comparison, the total surface area of the PV cell is 2200 mm². The full open-circuit voltage output of the PV cell, based on its dimensions (110 mm × 20 mm), is 2 V. Accordingly, the output voltage corresponding to the impacted area of 54.1 mm² is approximately **50 mV**. Based on this calculation, the hybrid model yields an effective output of **1305 mV** for the impacted area of 54.1 mm² under terminal velocity conditions.

Table 4.4: Comparative Analysis Between Existing and Proposed Hybrid Model

parameter	Existing Model (Sandwiched Structure)	Proposed Hybrid Model (PV + Piezoelectric)
Energy Source	Raindrop only	Sunlight + Raindrop
Piezoelectric Material	PVDF (Single layer)	PVDF (Triple-layer)
Raindrop Diameter	3.57 mm	8.3 mm
Impact Speed	2.96 m/s	4.41 m/s
Output For Impact Speed	100 mV	110mV
Terminal Velocity	9.76 m/s	14.89 m/s
Projected output for terminal velocity	1079 mV	1255 mV
Solar Panel Area	Not available	110 mm × 20 mm (semi-flexible PV)
PV Output	Not available	50 mV
Total Output	1079 mV	1305 mV
System Type	Single-source	Dual-source hybrid
Weather Adaptability	Rain only	Rain + Sun (All-weather adaptable)
Expected use case Suitability	Wet climate only	Mixed climates (tropical, temperate regions)

This result demonstrates that our hybrid system, despite using a flexible layered configuration with PVDF films and semi-flexible PV panels, delivers improved energy harvesting performance relative to existing piezoelectric-only approaches. From a design perspective, the mechanical complexity of the hybrid system is lower, as it uses a flat layered structure without moving parts such as cantilevers or vibrating membranes. This not only simplifies the manufacturing process but also reduces the likelihood of mechanical failure and the need for maintenance. The absence of moving components contributes to the long-term durability and stability of the system. The hybrid system works efficiently in both sunny and rainy conditions, ensuring year-round usability, especially in tropical and subtropical areas. Its compact, low-maintenance design is well-suited for rural or remote applications. It is ideal for powering small electronics, off-grid sensors, and IoT devices.

4.5 Hybrid System Integration

In this thesis, a functional hardware prototype of the hybrid energy harvesting system was successfully developed, integrating photovoltaic (PV) and piezoelectric components within a compact layered structure. While the hardware focused on demonstrating the feasibility of harvesting energy from both sunlight and raindrop impacts, a fully integrated Energy Management and Storage System (EMSS) was not implemented in the current prototype due to project scope and time limitations.

However, the inclusion of an EMSS is an essential next step toward making the hybrid system practical for real-world applications. The proposed architecture for the EMSS involves separately conditioning the electrical outputs of the PV and piezoelectric subsystems before combining them for efficient storage and utilization. The PV subsystem generates a relatively stable DC output when exposed to sunlight. In the future, this output should be connected to a DC-DC converter equipped with a Maximum Power Point Tracking (MPPT) algorithm to ensure optimal energy harvesting under varying irradiance conditions. This would allow the PV system to deliver consistent power even during partial shading or intermittent sunlight.
The piezoelectric subsystem, in contrast, produces irregular high-voltage, low-current pulses corresponding to raindrop impacts. These pulses would first be routed through a full-wave bridge rectifier to convert them to DC. A filtering stage using capacitors would be required to smooth out the resulting voltage before directing it to the storage unit.

For energy storage, a combination of supercapacitors and rechargeable batteries is recommended. Supercapacitors are well-suited for storing the quick bursts of energy from piezoelectric transducers, while batteries provide long-term storage for continuous load operation. The EMSS would manage the charging of both storage components and control the power delivery to connected loads.

The ability to operate both energy sources in parallel would enhance system resilience. During periods of bright sunlight, the PV system would serve as the primary energy source, while during rainy or overcast conditions, the piezoelectric system would supplement stored energy. A well-designed EMSS would ensure that energy harvested from both sources is efficiently utilized and that the system can maintain a stable power output even under varying environmental conditions.

Although not implemented in the current hardware prototype, the proposed EMSS represents a clear path for future development and will be a key focus for further improving the hybrid energy harvesting system's performance, reliability, and practical usability.

4.6 Issues and Challenges

The development and implementation of the proposed hybrid energy harvesting system presented several issues and challenges. First, the energy output from the piezoelectric component remains relatively low compared to the photovoltaic (PV) subsystem. While PV cells can generate significant power under optimal sunlight, the electrical energy harvested from raindrop impacts is small and depends heavily on droplet size, velocity, and material properties. Optimizing the piezoelectric layer and improving mechanical energy transfer efficiency remains an area for further development.

System integration also proved challenging, as combining PV and piezoelectric outputs requires careful design of the power management circuit. The two energy sources exhibit different electrical characteristics, and their simultaneous operation demands intelligent switching and energy storage control to avoid inefficiencies or losses.

Material compatibility and structural design introduced additional complexity. The PVDF films need to flex upon raindrop impacts without compromising the light absorption of the PV layer. Balancing transparency, mechanical durability, and electrical performance of the layered structure required iterative testing and careful material selection.

Durability and weatherproofing of the system also pose concerns. The prototype needs to withstand environmental stresses such as UV exposure, temperature changes, and prolonged wet conditions. Ensuring long-term stability of both PV and piezoelectric components under real-world operating conditions will require further testing and design improvements.

Finally, the system's scalability and cost-effectiveness remain key challenges. Integrating additional components, such as protective coatings and advanced power electronics, increases both complexity and cost. It is essential to ensure that the energy gains from the hybrid approach justify these added investments, particularly for larger-scale deployments. Addressing these challenges is crucial for advancing the practical viability of hybrid PV-piezoelectric energy harvesting systems. Continued research and optimization efforts are needed to enhance system efficiency, durability, and economic feasibility.

4.7 Summary

This chapter translates the prototype's performance into measurable outcomes through experimentation. Voltage outputs from PV-only, piezoelectric-only, and combined hybrid modes are recorded and compared. The findings show that hybrid operation offers greater reliability and energy continuity, particularly under changing weather conditions. Factors such as droplet size and impact height are analyzed in relation to piezoelectric output. The chapter also includes performance benchmarking against similar studies, acknowledging the absence of real-time PV testing due to project constraints. These results affirm the concept's practical promise and point toward avenues for optimization.

Chapter 5: Conclusion and Future Works

5.1 Conclusion

The growing global demand for renewable and sustainable energy solutions has driven innovation in harvesting energy from various ambient sources. This thesis presented the conceptualization, design, and implementation of a novel hybrid energy harvesting system that integrates photovoltaic (PV) technology and piezoelectric materials specifically PVDF to simultaneously collect energy from both sunlight and rainfall. This work demonstrates a meaningful step toward maximizing energy output from multiple environmental sources using a compact, cost-effective, and environmentally friendly structure.

The motivation behind this project was rooted in the realization that conventional energy systems often neglect intermittent but frequent natural energy forms, such as kinetic energy from raindrops. While solar energy harvesting is well-established, it is rendered less effective during rainy or overcast weather. Conversely, raindrops, which are a direct manifestation of mechanical energy, offer a valuable, often overlooked opportunity for power generation. By coupling solar panels with piezoelectric layers in a vertically integrated manner, this research addressed the challenge of energy inconsistency due to changing weather conditions and introduced a more resilient and versatile system for micro-scale energy harvesting.

Moreover, the project offered a comparative perspective by analyzing existing models, such as cantilever-based systems and sandwiched structures, highlighting the advantages of PVDF in terms of flexibility, responsiveness to small forces, and environmental safety. While the solar layer's function was conventional, its integration with the piezoelectric layer under a shared framework demonstrated a new architectural approach to energy harvesting—one that makes efficient use of limited space and multiple ambient sources.

The results indicated that even in its initial prototype form, the piezoelectric component of the system performed comparably to earlier systems in terms of responsiveness and output voltage. This suggests that with further optimization—through material improvements, design refinements, and energy management circuitry, the system could serve as a viable energy harvesting solution in environments characterized by alternating sun and rain.

Importantly, the proposed hybrid system has a wide range of practical implications. It holds potential for powering standalone sensors, remote monitoring stations, small IoT devices, and low-power electronics in urban and rural settings where stable power supply is not always guaranteed. In developing regions or emergency situations, where infrastructure may be limited, such hybrid energy devices could offer a decentralized and low-maintenance source of energy.

In conclusion, this research successfully demonstrates that hybrid energy harvesting—combining solar and raindrop-based piezoelectric generation—is both practical and promising. It opens a new frontier in renewable energy systems that are adaptive, efficient, and environmentally sustainable. As the world moves toward greener technologies, this approach contributes meaningfully to the growing body of knowledge and provides a strong foundation for future innovation in multi-source energy harvesting systems.

5.2 Environmental Impact and Sustainability Analysis

The proposed hybrid energy harvesting system offers a sustainable alternative to conventional power sources by utilizing two naturally abundant and renewable energy forms—sunlight and rainfall. Unlike fossil-fuel-based micro-power systems, this model generates electricity without emitting greenhouse gases or other pollutants, contributing to a significant reduction in carbon footprint over time. The use of monocrystalline photovoltaic cells, known for their long lifespan and energy efficiency, enhances the system's environmental value. Moreover, the integration of PVDF (Polyvinylidene Fluoride) as the piezoelectric material presents a safer and more eco-friendly option compared to traditional lead-based piezoelectric ceramics, such as PZT. PVDF is non-toxic, recyclable, and stable under varying environmental conditions, making it suitable for long-term outdoor deployment. Additionally, the compact design and shared surface area of the PV and piezoelectric layers reduce material usage and land footprint, making the system scalable for urban or remote applications. Overall, this hybrid model not only aligns with global sustainable development goals but also paves the way for clean, decentralized energy solutions in diverse climatic regions.

5.3 Future Work

While the initial prototype and testing offer promising outcomes, there are several avenues for further improvement and exploration:

1. **Material Optimization:** Future designs could experiment with different types or composite layers of photovoltaic and piezoelectric materials to improve energy conversion efficiency, including multilayer PVDF or more advanced materials such as ZnO nanowires or flexible PZT composites.

2. **Structural Enhancements:** Improving the mechanical coupling between the solar panel and the piezoelectric film may increase the efficiency of energy transfer from raindrops to the piezoelectric layer. Designs using micro-patterned or textured surfaces can also enhance raindrop impact response.

3. **Environmental Testing:** Field tests under varying real-world weather conditions (e.g., heavy rain, oblique raindrop angles, fluctuating sunlight) would provide more comprehensive insights into the system’s durability and performance.

4. **Collaboration with local authorities, utility companies, and stakeholders Power Management Circuitry:** Designing an efficient power conditioning circuit (rectification, voltage regulation, and storage control) would be critical to maximize the usable output of the harvested energy.

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