Transient Thermal Analysis of a Hybrid Energy Harvester

Varun Gopalakrishnan¹, Swetha S Manian ¹, Karen A ¹, Niranjan H¹, Venugopal T¹, Feroskhan M¹

¹School of Mechanical Engineering, VIT Chennai Campus, Chennai Vandalur - Kelambakkam road, Chennai-600127

*Corresponding e-mail: feroskhan.m@vitc.ac.in

Abstract
The seasonal nature of solar panels and windmills has been a major challenge towards realizing sustainable energy. Over the years, several attempts have been made to perfect a device capable of harnessing the energy of wind and rain, titled as triboelectric and piezoelectric nano generators. Although such technologies yield promising results, a superior energy device can be achieved by addition of solar cells to wind and rain energy harvesting devices. Hybrid Nano generators are expected to be the future of commercially sustainable energy generation which are used to simultaneously harvest wind, rain, and solar energy. Though a substantial amount of work has been done with regard to such energy harvesting modules, studies that test their environmental capabilities are limited. In this study, a hybridized power panel comprising of dual-mode triboelectric nano generator and a solar cell have been tested under majorly solar, majorly windy, majorly rainy, and normal tropical conditions. Average temperature attained by the panel in such conditions have been studied through a transient thermal analysis done using Ansys Fluent. The results obtained are used to calculate thermal strain in the panel for different cases. The proposed model is an innovative way to make use of energy.

1. Introduction
Climate change and carbon neutrality have evolved to become topics of daily conversations over the last decade. People from all walks of life have begun to understand the need for sustainable and renewable energy sources. Solar power and wind energy have been gaining tremendous popularity as two of the cleanest sources of energy production, thereby addressing pressing issues like the sustainability of fossil fuel dependency, global warming and other health related problems. In addition to providing environmental benefits, solar power and wind energy creates new job opportunities, impacts economic growth and are seen as safe investment options, especially in the wake of the pandemic. Experts have suggested that wind farms are seen as havens in the storm that is COVID-19. However, it should be noted that such clean sources of energy comes at a high cost that involves their production, distribution and installation as well. Despite their popularity, it should be noted that such sources of energy are highly seasonal. Countries like Denmark receive only about 6 hours of sunlight during their winters whereas countries like Saudi Arabia have abundant sunlight all through the year. As a corollary, it can be understood that the performance of solar panels and windmills depend on geography [1].

Apart from solar and wind power, energy generated through rain drops have also been gaining a considerable amount of attention from the research community. However, even such energy harvesters are susceptible to geographical conditions. In an attempt to circumvent this issue, several devices capable of harnessing the energy of both sun, wind and rain simultaneously have been designed and tested over the last few years. These devices are called as hybrid energy harvesters. The following section aims to put together the inferences made through the years with regards to the development of hybrid energy harvesters.
1.1. Literature Review

Triboelectric Nanogenerators (TENG) are devices that are capable of generating energy from rain and wind. As quoted by Choi et al. [2], a TENG is a device that works on the basis of the principle of contact electrification. The use of super hydrophobic materials with self cleaning abilities makes TENG a highly versatile device that harnesses the energy of the environment with a decent electrical output. Lai et al. [3] synthesized a waterproof and fabric based multifunctional TENG that is capable of harvesting the energy generated from tiny natural impacts of wind and rain. Positive variations in the output voltage and the short-circuit current on changing the speed of wind and rain rate was observed by Lai et al. In a further study, Choi et al. [4] shed light on to the need for TENGs to be commercialized and thereby synthesized a TENG using Fluorinated Ethylene Polypropylene (FEP). This TENG exploits the thermostatic properties of FEP because of which the chances of industrially perfecting this device is relatively easier. Surface modification using nanotechnology was employed by Choi et al. in order to fabricate the nanotopographical TENG with FEP contact layers. This device exhibited an electrical performance of about 280% in the solid-water contact mode. Liu et al. [5] developed a highly-integrated TENG to completely harvest all forms of energy available in raindrops. Saccular contact separation mode based TENG (SCS-TENG) and a TENG with interdigitated electrodes (I-TENG) were fabricated to harness the kinetic energy of the raindrops. In addition to that, strip shaped interdigitated TENGs (SI-TENG) was used to harness the electrostatic energy of the rain. The combination of SCS-TENG, I-TENG and SI-TENG in parallel leads to the generation of a current of 95.4 μA and this is what is referred to as a highly integrated TENG.

Piezoelectric nanogenerators (PENG) are devices that are capable of converting vibrational energy into electrical energy through the piezoelectric effect. With the surge in research related to sustainable energy systems, piezoelectric materials have been gaining a lot of importance over the last few years. With regards to the materials to be used in the fabrication of PENG, a substantial amount of data is available from which the optimum material combination can be chosen based on the application and the expected output levels of that particular application. Zinc oxide (ZnO) nanowires are popular choices for the fabrication of PENG, where ZnO nanowires used as such produces a $V_{OC}$ of 1.26 mV and $I_{SC}$ of 28.8 nA. Halogen doped ZnO nanowires are also used to fabricate PENG alongside Sulphur, Silver, Lithium, Vanadium and Gallium doped ZnO nanowires. In addition to that, Lead Zirconate Titanate (PZT) is also gaining attention as materials to be used in PENG in the form of crystals and ribbons. Barium titanate (BaTiO$_3$) based compounds have also been used in the fabrication of PENG, where BaTiO$_3$ used as such produces a $V_{OC}$ of 21 mV and $I_{SC}$ of 1.3 nA. In places where a higher degree of optical transparency and mechanical flexibility is required, organic materials like Polyvinylidene Fluoride (PVDF) are used to make rain energy harvesters [6].

Guigon et al. [7, 8] conducted experimental and theoretical studies on the applications of PVDF membrane in rain energy harvesters. This study shows that a single droplet of 3 mm diameter impinging a PVDF membrane at 4.5 ms$^{-1}$ produces a power of 17 μW. In another study by Perara et al. [9], it was shown that heavy thunderstorms can actually generate a maximum power of 2.231 x 10$^{-9}$ W with the help of PENGs. Vatansever et al. [10] have documented that the power generated from piezoelectric beams under rainfall can be utilized in low-power electronic applications. In the study led by Viola et al. [11], rain energy harvesters fabricated using PZT and PVDF were compared based on a specific set of parameters. This study recommended PVDF as the better material for fabricating rain energy harvesters owing to their better energy generating capabilities, economic availability and lack of toxicity when compared to PZT-made energy harvesters. A PVDF-made cantilever was fabricated by Wong et al. [12] and its performance with regards to harvesting energy from raindrops was compared with that of the conventional PVDF bridge transducer. In case of the cantilever structure, it was observed that the water droplets pass through the structure and splash on the ground. In case of the bridge structure, the splashing of the droplets happened on the bridge itself, thereby improving the chances of energy absorption in this case. Hence it was concluded that the PVDF bridge
transducer produced higher voltage and therefore has a better performance than the cantilever transducer.

Wijewardhana et al. [13] fabricated a triboelectric water motion active transducer (TWMAT) based on solid-liquid contact electrification and this device generates the energy from both wind and rain. Parandeh et al. [14] built an eco-friendly TENG using poly(caprolactone), graphite oxide and cellulose paper that was capable of a maximum power density of 72.5 mW m\(^{-2}\). Zhang et al. [15] proposed a novel windmill inspired nanogenerator to harness the energy of mild breeze. At a wind speed of 1.8 m s\(^{-1}\), the device is successfully driven with the output power of TENG being 0.95 mW.

Although the combination of wind and rain water harvesting technologies are yielding promising results, a superior energy harvesting device can be achieved by the addition of solar cells to wind and rain energy harvesting devices. Such devices are called as hybrid nanogenerators or hybrid energy harvesters, which can be used to simultaneously harvest wind, rain and solar energy. Wang et al. [16] fabricated a Hybrid Nanogenerator that consisted of a solar cell and a TENG with a combined device area of 120 x 22 mm. This device harvested a maximum power of 24 mW through the TENG and 8 mW through the solar cell. The incorporation of a moth’s eye mimicking TENG (MM-TENG) and a solar cell together as a hybrid Nanogenerator was put forth by Yoo et al. [17] to circumvent the inability of solar cells to work during the non-summer months of the year. The MM-TENG consists of moth’s eye mimicking quartz glass, interdigitated AgNW electrode combined together by an optically clear adhesive. The maximum short circuit current (I\(_{SC}\)) and open circuit voltage (V\(_{OC}\)) generated by this Hybrid Nanogenerator was recorded to be 24.4 μA and 18.4 V respectively.

The possibility of having an ultrathin unified harvesting module (UHM) was put forth by Roh et al. [18] which is made up of a solar cell, a wind-TENG and a rain-TENG. Without incorporating any energy storage device, the synthesized UHM was able to light up 62 LEDs. Roh et al. also tested the applicability of the UHM as a self-powered weather sensor in places with significant space constraints. A practically synthesizable hybrid power panel was proposed by Zheng et al. [19] that consists of a dual-mode TENG and a silicon solar cell. One of the unique aspects of this hybrid energy harvester is that the dual-mode TENG of this device is capable of harnessing both rain and wind energies. The contact-TENG is responsible for sapping the energy of the wind through the PTFE films and nylon surface. Considering the wind speed to be 2.7 m/s, the short circuit current density (J\(_{SC}\)) and the V\(_{OC}\) of the contact-TENG is observed to be 3.1 mA m\(^{-2}\) and 10.7 V respectively. With a resistance of less than 0.01 MΩ, the average power density achieved by the dual-mode TENG remains to be small whereas it achieves its maximum values of 6 mW m\(^{-2}\), 86 mW m\(^{-2}\) and 8 mW m\(^{-2}\) at a resistance of 5, 0.2, and 1 MΩ, respectively. Tang et al. [20] synthesized an all-weather solar cell using p-electron enriched reduced graphite oxide film and a dye sensitized solar cell. This device is found to deliver an optimal solar-electric conversion efficiency of 6.53%.

The hybrid nanogenerator synthesized by Liu et al. [21] combined the advantages of bare solar cells and water drop triboelectric nanogenerators (WD-TENG) using nano wrinkled polydimethylsiloxane (nw-PDMS). The V\(_{OC}\), J\(_{SC}\) and the power conversion efficiency of the device was noted to be 0.54 V, 40.70 mA cm\(^{-2}\) and 13.57% respectively. Zheng et al. [22] recorded a hybrid energy harvesting device synthesized from traditional silicon solar cells by coating its surface with polytetrafluoroethylene film (PTFE), indium tin oxide (ITO) and polyethylene terephthalate (PET). 0.6 V of V\(_{OC}\) and 350 Am\(^{-2}\) were the V\(_{OC}\) and the I\(_{SC}\) that was recorded by Zheng et al. on investigating the electrical properties of silicon solar cell. On the other hand, on coating the solar cell with the above mentioned materials, the V\(_{OC}\) and J\(_{SC}\) increased to 30 V and 4.2 mA m\(^{-2}\) respectively. Wang et al. [23] constructed a hybrid nanogenerator using TENG and PENG with materials like (Ba\(_{0.83}\)Ca\(_{0.16}\))(Ti\(_{0.907}\)Zr\(_{0.093}\))O\(_3\) (BCZTO)/polydimethylsiloxane (PDMS) as a piezoelectric layer and Ba(Ti\(_{0.6}\)Zr\(_{0.4}\))O\(_3\) (BZTO)/PDMS as a triboelectric layer. This device was capable of producing a maximum output voltage of 390 V and a current density of 47 mA m\(^{-2}\).
Inversely polarized ferroelectric PVDF/BaTiO$_3$ nanocomposite films were used by Lapcinskis et al. [24] to make a hybrid-tribo-piezoelectric nanogenerator. When compared to the most advanced TENG device made, this device has a 3-fold higher $V_{OC}$ and thus expands the scope for the research on other flexible nanogenerators. On the other hand, He et al. [25] fabricated a hybrid-tribo-piezoelectric nanogenerator based on ZnO nanoflakes and PDMS composite films using a cost-effective fabrication process. This device was capable of producing a power output of 28.2 mW cm$^{-2}$ and was also able to light up 180 green LEDs without the need for an additional energy storage device.

1.2. Literature Gap

Thus, with about 25 papers extensively reviewed on the uses of TENG, PENG and hybrid-nanogenerators in creating a sustainable tomorrow, it was identified that all of these papers were published based on actual practical experimentation and validation. Although the respective properties of the combination of material systems used for the different energy harvesters were identified, a distinct path towards the commercialization of these technologies were not laid. In addition to that, it was also understood that many of the devices reported above were subjected to only laboratory testing conditions. In order to further the understanding of such energy harvesting modules, it is imperative to subject them to all possible atmospheric conditions. This is necessary so as to identify the optimal atmospheric condition for a given energy harvester and provides an opportunity to enhance those energy harvesting modules that do not perform so well in a given geographical region.

On further extending the literature review in search of studies that have computationally modelled and analyzed energy harvesting devices, we found that Zhe et al. [26] investigated the performance of a solar panel under different wind velocities in addition to studying the temperature distribution patterns of the solar panel. Rekha et al. [27] also studied the performance of a photovoltaic thermal air collector using Ansys simulation and CFD analysis. Abdullah et al. [28] used Ansys fluent - CFD module to assess the overall performance of a hybrid photovoltaic thermal air collector in order to improve the efficiency of the photovoltaic cells. In another study by Syafiqah et al. [29], thermal analyses of air and water cooled photovoltaic panels were conducted to understand the dependence of the performance of the panel on its temperature. Yang et al. [30] took a further step and performed modal analysis of the fabricated 3D-TENG in order to arrive at an optimum design that is capable of exhibiting excellent performances even in high vibration environments. Table 1 presents a summary of the literature review conducted.

1.3. Objective

Based on the literature reviewed, it was clear that computational analysis of hybrid energy harvesters has not been done yet. Inspired by the work done by different groups, a suitable hybrid energy generator has been designed using Solidworks [31] and the performance of the designed model has been tested under 4 weather conditions: Majorly solar, Majorly windy, Majorly rainy and Normal Tropical conditions. This is achieved by performing a transient thermal study using Ansys 19.2 [32]. Based on the results obtained, the thermal strain induced in the panel is calculated for different geographical locations after which the suitable atmospheric conditions for the installation of such panels are proposed from thermal strain point of view. With due consideration of economical factors, the designed model exhibits an innovative way to make use of the various forms of energy around us, while also widening the possibilities for the commercialization of household sustainable energy generation.
Table 1. Summary of the Literature Review conducted

| Author               | Work Done                                                                 |
|----------------------|---------------------------------------------------------------------------|
| Choi et al. [2]      | Contact electrification of TENG                                           |
| Lai et al. [3]       | Waterproof fabric-based TENG                                              |
| Choi et al. [4]      | FEP based TENG                                                           |
| Liu et al. [5]       | Highly integrated TENG                                                   |
| Mahapatra et al. [6] | Materials used in the fabrication of TENG and PENG                       |
| Guigon et al. [7, 8] | Applications of PVDF membrane in rain energy harvesters                  |
| Perara et al. [9]    | Harvesting the kinetic energy of rain droplets                           |
| Vatansever et al. [10]| Piezoelectric beams to harvest energy from rain                          |
| Viola et al. [11]    | PZT and PVDF made rain energy harvesters                                  |
| Wong et al. [12]     | PVDF cantilever and bridge transducer                                    |
| Wijewardhana et al. [13]| Triboelectric water motion active transducer                           |
| Parandeh et al. [14] | Eco-friendly TENG                                                        |
| Zhang et al. [15]    | Windmill inspired nanogenerator                                           |
| Wang et al. [16]     | Hybrid Nanogenerator                                                     |
| Yoo et al. [17]      | Moth's eye mimicking TENG + Solar cell                                   |
| Roh et al. [18]      | Ultrathin Unified harvesting module                                      |
| Zheng et al. [19]    | Dual-mode TENG + Solar cell                                              |
| Tang et al. [20]     | All-weather solar cell                                                   |
| Liu et al. [21]      | Water drop-TENG + Solar cell                                             |
| Zheng et al. [22]    | Hybrid energy harvester using traditional silicon solar cells            |
| Wang et al. [23]     | Hybrid energy harvester using TENG and PENG materials                    |
| Lapcinskas et al. [24]| Polarized ferroelectric Hybrid-Tribo-Piezo electric nanogenerator      |
| He et al. [25]       | ZnO nanoflakes based Hybrid-Tribo-Piezo electric nanogenerator          |
| Zhe et al. [26]      | Investigation of solar panel under different wind velocities            |
| Rekha et al. [27]    | CFD analysis of photovoltaic thermal air collector                       |
| Abdullah et al. [28] | CFD analysis of a hybrid thermal photovoltaic air collector             |
| Syafiqah et al. [29] | CFD analyses of water and air-cooled photovoltaic panels                |
| Yang et al. [30]     | Modal analysis of vibrational energy harvesting 3D-TENG                  |
2. Methodology

Figure 1. Flowchart describing the method of study

Drawing upon the work done by different groups of authors, firstly, a Solidworks model of the hybrid energy panel is designed. Importing the model into Ansys fluent, the respective material layers are defined by inputting properties like density, thermal conductivity, and specific heat capacity. Boundary conditions based on the considered location of study are defined and meshing is done following which temperature plots are obtained for the particular geographical condition. The same exercise is carried out for all chosen geographical locations after which the maximum and the minimum temperature reached by the panel is compared and suitable inferences are drawn from the data obtained during the study. A flowchart of the method of study has been shown in Figure 1 and the Solidworks model of the designed hybrid energy harvester has been shown in Figure 2. The properties of the materials used in the hybrid energy harvester has been presented in Table 2.

Figure 2. The designed hybrid energy harvester
### Table 2. Properties of the materials used in the hybrid energy generator

| Material Layer       | Dimension                  | Thermal conductivity (W/mK) | Specific Heat Capacity (J/KgK) | Density (Kg/m³) |
|----------------------|----------------------------|----------------------------|--------------------------------|-----------------|
| FEP                  | 4cm x 6cm x 125um          | 0.20                       | 1100                           | 2150            |
| ITO                  | 1cm x 3cm x 125um          | 4                          | 380                            | 6800            |
| Amorphous Silicon    | 4cm x 6cm x 1000um         | 1.8                        | 992                            | 2330            |
| Aluminium oxide      | 4cm x 6cm x 400um          | 25                         | 750                            | 3950            |
| PTFE                 | 4cm x 6cm x 100um          | 0.25                       | 1050                           | 2160            |
| Neodymium magnets    | 5mm x 5mm x 500um          | 8.955                      | 502.416                        | 7500            |

### 3. Results and Discussions

The results obtained from our study are presented in the following section.

#### 3.1. Assumptions

The following assumptions have been made with regards to the transient thermal analysis of the energy harvester in Ansys Fluent 19.2.

1. All materials used in this device are assumed to have isotropic properties and independent of temperature.
2. A heat flux of 1000 W/m² acts on the energy generator, which accounts for the solar irradiation on the panel.
3. The temperature to which the panel is exposed is equal everywhere.
4. Ohmic heating in the panel is considered to be negligible.
5. Because of the absence of the mechanical frame in the design of the hybrid energy harvester, the mechanical strain generated in the design is ignored.

#### 3.2. Thermal analysis of energy harvester under the majorly sunny condition

- Location: Ahmedabad
- Ambient Temperature: 35 °C
- Average wind speed = 3.8 m/s

As described in Duffie et al. [33] the convective heat transfer coefficient (h) as a function of wind velocity (v) for photovoltaic modules can be given as

\[ h = 2.8 + 3.0v \]  

(1)

Substituting the average wind speed value of 3.8 m/s in the above equation, we obtain the value of the convective heat transfer coefficient for the given situation to be 14.2 W/m²°C.
From the below-showed temperature distributions of the hybrid energy harvesting module at 35°C and a wind speed of 3.8m/s, it can be said that the panel reached a maximum temperature of 109.53°C and a minimum temperature of 34.803°C. These temperature distribution visuals were obtained after exposing the panel to a heat flux of 1000 W/m² with a convection coefficient of 14.2 W/m² °C. Figures 3-5 shows the temperature distribution on the energy harvesting module. The temperature gradient across each material layer in the energy harvester is shown in Figures 6-13.

Figure 3. Temperature distribution (°C) on the energy harvesting module

Figure 4. Temperature distribution (°C) on the energy harvesting module
Figure 5. Temperature distribution (°C) on the energy harvesting module

Figure 6. Temperature distribution (°C) across the ITO electrodes

Figure 7. Temperature distribution (°C) across the FEP film

Figure 8. Temperature distribution (°C) across the solar cell (Amorphous Silicon)

Figure 9. Temperature distribution (°C) across the Aluminum oxide electrode-1
Figure 10. Temperature distribution (°C) across the Neodymium magnet-1

Figure 11. Temperature distribution (°C) across the PTFE film

Figure 12. Temperature distribution (°C) across the Neodymium magnet-2

Figure 13. Temperature distribution (°C) across the Aluminum oxide electrode-1
From the above visuals (Figure 6-13), a temperature difference of about 74.727°C is observed across the layers of the hybrid energy harvester. While the ambient temperature is 35°C, the energy harvesting module attains a maximum temperature of 109.53°C in one hour and this is observed on the FEP film, ITO electrodes, Amorphous silicon cell, and Aluminium oxide electrode-1. The minimum temperature points measuring 34.803°C occur on the Neodymium magnets and the Aluminium electrode-2. Intermediary temperatures are also observed as shown in the above figures. The average temperature of the panel after an hour of exposure to a heat flux of 1000 W/m² is noted to be 79.508°C.

### 3.3. Thermal analysis of energy harvester under the majorly windy condition:

- **Location:** Ramakkalmedu
- **Ambient Temperature:** 30 °C
- **Average wind speed = 9.72 m/s**

Substituting the average wind speed value of 9.72 m/s in equation 1, we obtain the value of the convective heat transfer coefficient for the given situation to be 31.96W/m²°C.

Figure 14 shows the temperature distribution of the hybrid energy harvesting module at 30°C and a wind speed of 9.72 m/s, it can be said that the panel reached a maximum temperature of 63.113°C and a minimum temperature of 29.912°C. These temperature distribution visuals were obtained after exposing the panel to a heat flux of 1000 W/m² with a convection coefficient of 31.96 W/m² °C. A temperature difference of about 33.20°C is observed across the layers of the hybrid energy harvester in this case. While the ambient temperature is 30°C, the energy harvesting module attains a maximum temperature of 63.113°C in one hour and this is observed on the FEP film, ITO electrodes, Amorphous silicon cell, and Aluminium oxide electrode-1. The minimum temperature points measuring 34.803°C occur on the Neodymium magnets and the Aluminium electrode-2. Intermediary temperatures are also observed as shown in the above figures. The average temperature of the panel after an hour of exposure to a heat flux of 1000 W/m² is noted to be 49.775°C.

![Temperature distribution on the energy harvesting module](image)

**Figure 14.** Temperature distribution (°C) on the energy harvesting module

### 3.4. Thermal analysis of energy harvester under the majorly rainy condition:
- Location: Cherrapunji
- Ambient Temperature: 20°C
- Average wind speed = 1.55 m/s

Substituting the average wind speed value of 3.8 m/s in equation 1, we obtain the value of the convective heat transfer coefficient for the given situation to be 7.45 W/m²°C.

Figure 15 shows the temperature distribution of the hybrid energy harvesting module at 20°C and a wind speed of 1.55 m/s, it can be said that the panel reached a maximum temperature of 162.05°C and a minimum temperature of 19.624°C. These temperature distribution visuals were obtained after exposing the panel to a heat flux of 1000 W/m² with a convection coefficient of 7.45 W/m²°C.

Figure 15. Temperature distribution (°C) on the energy harvesting module

A temperature difference of about 142.426°C is observed across the layers of the hybrid energy harvester in this case. While the ambient temperature is 20°C, the energy harvesting module attains a maximum temperature of 162.05°C in one hour and this is observed on the FEP film, ITO electrodes, Amorphous silicon cell, and Aluminium oxide electrode-1. The minimum temperature points measuring 19.624°C occur on the Neodymium magnets and the Aluminium electrode-2. Intermediary temperatures are also observed as shown in the above figures. The average temperature of the panel after an hour of exposure to a heat flux of 1000 W/m² is noted to be 104.84°C.

3.5. Thermal analysis of energy harvester under normal tropical conditions:

- Location: Pune
- Ambient Temperature: 32°C
- Average wind speed = 0.7 m/s

Substituting the average wind speed value of 3.8 m/s in equation 1, we obtain the value of the convective heat transfer coefficient for the given situation to be 4.9 W/m²°C.

Figure 16 shows the temperature distributions of the hybrid energy harvesting module at 32°C and a wind speed of 0.7 m/s, it can be said that the panel reached a maximum temperature of 32.09°C and a
The minimum temperature of 32°C. These temperature distribution visuals were obtained after exposing the panel to a heat flux of 1000 W/m² with a convection coefficient of 4.9 W/m²°C.

A temperature difference of about 0.09°C is observed across the layers of the hybrid energy harvester in this case. While the ambient temperature is 32°C, the energy harvesting module attains a maximum temperature of 32.09°C in one hour and this is observed on the FEP film, ITO electrodes, Amorphous silicon cell, and Aluminium oxide electrode-1. The minimum temperature points measuring 32.9°C occur on the Neodymium magnets and the Aluminium electrode-2. Intermediary temperatures are also observed as shown in the above figures. The average temperature of the panel after an hour of exposure to a heat flux of 1000 W/m² is noted to be 32.054°C.

Figure 16. Temperature distribution (°C) on the energy harvesting module

4. Calculations

The thermal strain caused due to the expansion of the material layers in the panel because of exposure to a heat flux of 1000 W/m² under different atmospheric conditions is calculated based on the following formula:

\[ \varepsilon^T = \alpha(\Delta T) \]  \hspace{1cm} (2)

Where \( \varepsilon^T \) is the thermal strain, \( \alpha \) is the coefficient of thermal expansion, and \( \Delta T \) is the temperature change.

\[ (\Delta T) = \text{Average Temperature of the panel} - \text{Ambient temperature} \]

Since the dimensions of the FEP film, Amorphous silicon cell, PTFE film, and the Aluminium electrodes are the same and equal to that of the whole energy harvesting module, thermal strain for these components are calculated and the highest value of thermal strain among these components is realized as the maximum thermal strain occurring in the energy harvester. From equation 2, it is clear that the thermal strain induced is directly proportional to the coefficient of thermal expansion of the
material involved. From Table 4, it is clear that PTFE has the highest thermal expansion coefficient value of about $16 \times 10^{-5} \text{K}^{-1}$, and thus, calculating the thermal strain induced in the PTFE film would yield the maximum thermal strain induced in the hybrid energy harvester for a given boundary condition.

Table 3: Thermal expansion coefficients of the materials used in the hybrid energy harvester

| S. No | Material Layer | Dimension           | Thermal Expansion coefficient (K$^{-1}$) |
|-------|----------------|---------------------|------------------------------------------|
| 1     | FEP            | 4cm x 6cm x 125 um  | $12 \times 10^{-5}$                      |
| 2     | Amorphous Silicon | 4cm x 6cm x 1cm    | $3 \times 10^{-6}$                      |
| 3     | Aluminium oxide | 3cm x 6cm x 0.4mm   | $8 \times 10^{-6}$                      |
| 4     | PTFE           | 3cm x 6cm x 100um   | $16 \times 10^{-5}$                     |

**Case I: Majorly Sunny conditions (Ahmedabad)**
Thermal strain in PTFE film $\epsilon_{PTFE} = 16 \times 10^{-5} \times (79.508 - 35) = 7.12 \times 10^{-3}$

**Case II: Majorly Windy conditions (Ramakkalmedu)**
Thermal strain in PTFE film $\epsilon_{PTFE} = 16 \times 10^{-5} \times (49.775 - 30) = 3.16 \times 10^{-3}$

**Case III: Majorly Rainy conditions (Cherrapunji)**
Thermal strain in PTFE film $\epsilon_{PTFE} = 16 \times 10^{-5} \times (104.84 - 20) = 13.57 \times 10^{-3}$

**Case IV: Normal Tropical conditions (Pune)**
Thermal strain in PTFE film $\epsilon_{PTFE} = 16 \times 10^{-5} \times (32.054 - 32) = 8.64 \times 10^{-6}$

5. Inference
From Figure 17, the difference between the average temperature achieved by the different layers of the hybrid energy generator is lowest (0.054°C) under the normal tropical conditions viz., Pune. The lowest heat transfer coefficient value (4.9 W/m$^2$°C) was also recorded in the case of Pune. The thermal strain induced in the PTFE film was also found to be low ($8.64 \times 10^{-6}$) under normal tropical conditions. These inferences collectively suggest that the designed hybrid energy harvester is most suitable for places with a normal tropical atmospheric condition, like Pune. Following Pune, Ramakkalmedu seems to offer the next ideal condition for setting up this energy harvester followed by Ahmedabad and Cherrapunji.
Table 4. Summary of the observations made

| Place          | Ambient Temperature (°C) | Wind speed (m/s) | Heat transfer Coefficient (W/m²°C) | The average temperature of the panel (°C) |
|----------------|--------------------------|------------------|-----------------------------------|------------------------------------------|
| Ahmedabad      | 35                       | 3.8              | 14.2                              | 79.508                                   |
| Ramakkalmedu   | 30                       | 9.72             | 31.96                             | 49.775                                   |
| Cherrapunji    | 20                       | 1.55             | 7.45                              | 104.84                                   |
| Pune           | 32                       | 0.7              | 4.9                               | 32.054                                   |

Figure 17. Plot of the average temperature attained by the panel for the respective time period
6. Conclusion
The design and the thermal analysis of the hybrid energy generator capable of harnessing the energy of sun, wind, and rain have hence been completed using the help of Solidworks and Ansys fluent 19.2. Out of the four different weather conditions chosen, the panel reached a maximum temperature of 104.84 °C under majorly rainy conditions with a convection coefficient of 7.45 W/m²°C as observed in Cherrapunji. The minimum panel temperature was recorded to be 32.054 °C as observed under normal tropical conditions in Pune with a convection coefficient of 4.9 W/m²°C. The thermal strain induced in the panel was calculated based on which Pune i.e., normal tropical conditions was concluded to be the most suitable environment for maintaining the designed energy panel followed by Ramakkalmedu, Ahmedabad, and Cherrapunji.

References
[1] The Future of Renewable Energy. 2020https://www.inspirecleanenergy.com/blog/clean-energy-101/future-of-renewable-energy
[2] D Choi, D W Kim, D Yoo, K J Cha, M La and D S Kim, 2017 Spontaneous occurrence of liquid-solid contact electrification in nature: Toward a robust triboelectric nanogenerator inspired by the natural lotus leaf, Nano Energy, 36: 250-259
[3] Y C Lai, Y C Hsiao, H M Wu and Z L Wang, 2019 Waterproof Fabric-Based Multifunctional Triboelectric Nanogenerator for Universally Harvesting Energy from Raindrops, Wind, and Human Motions and as Self-Powered Sensors, Adv. Sci. 6.
[4] D Choi, D Yoo and D S Kim, 2015 One-Step Fabrication of Transparent and Flexible Nanotopographical-Triboelectric Nanogenerators via Thermal Nanoimprinting of Thermoplastic Fluoropolymers, Adv. Mater. 27.
[5] X Liu, A Yu, A Qin and J Zhai, 2019 Highly Integrated Triboelectric Nanogenerator for Efficiently Harvesting Raindrop Energy, Adv. Mater. Technol. 4.
[6] BMahapatra, K Kumar Patel, Vidya and PK Patel, A review of recent advancements materials for piezoelectric/triboelectric nanogenerators, Materials Today: Proceedings
[7] R Guigon, J Chaillout, T Jager and G Despesse, 2008 Harvesting raindrop energy: theory. Smart Materials and Structures, 17(1):015038
[8] RGuigon, JChaillout, TJager andGDespesse, 2008Harvesting raindrop energy: experimental study. Smart Materials and Structures, 17(1):015039
[9] K C RPerara, BG Sampath, VDassanayake and BHapuwatte, 2004 Harvesting of kinetic energyof raindrops. World Academy of Science, Engineering and Technology, 8(2).
[10] DVatanser, R L Hadimani, TShah and EStores, 2011 An investigation of energy harvesting from renewable sources with PVDF and PZT. Smart Materials and Structures; 20(5): 1-6
[11] F Viola, PRomano, RMiceli and GAcciari, 2013 Harvesting rainfall energy by means of piezoelectric transducer. International conference on Clean Electrical Power, Alghero.
[12] V K Wong, J H Ho and A B Chai, 2016 Piezoelectric energy harvesting in varying simulated rain conditions. ARPN Journal of Engineering and Applied Sciences 11(1).
[13] K R Wijewardhana, T Z Shen, E N Jayaweera, AShahzad and J K Song, 2018 Hybrid nanogenerator and enhancement of water-solid contact electrification using triboelectric charge supplier, *Nano Energy*, 52:402-407

[14] S Parande, MKharazaiha and FKarimzadeh, 2019 An eco-friendly triboelectric hybrid nanogenerators based on graphene oxide incorporated polycaprolactone fibers and cellulose paper, *Nano Energy*, 20, 59: 412-421

[15] Y Zhang, Q Zeng, Y Wu, J Wu, S Yuan, D Tan, C Hu and X Wang, 2020 An Ultra-Durable Windmill-like Hybrid Nanogenerator for Steady and Efficient Harvesting of Low-Speed Wind Energy, *Nano-Micro Lett.*, 12.

[16] S Wang, X Wang, Z L Wang and Y Yang, 2016 Efficient Scavenging of Solar and Wind Energies in a Smart City, *ACS Nano*, 10:5696-5700

[17] D Yoo, S C Park, S Lee, JY Sim, I Song, D Choi, H Lim and D S Kim, 2019 Biomimetic anti-reflective triboelectric nanogenerator for concurrent harvesting of solar and raindrop energies, *Nano Energy*, 57: 424-431

[18] H Roh, I Kim and D Kim, 2020 Ultrathin unified harvesting module capable of generating electrical energy during rainy, windy and sunny conditions, *Nano Energy*, 70:104515

[19] L Zheng, G Cheng, J Chen, L Lin, J Wang, Y Liu, H Li and Z L Wang, 2015 A Hybridized Power Panel to Simultaneously Generate Electricity from Sunlight, Raindrops, and Wind around the Clock, *Adv. Energy Mater.*, 5, 1501152.

[20] Q Tang, X Wang, P Yang and B HeA Solar Cell That Is Triggered by Sun and Rain, 2016*Angew. Chemie*, 28:5329-5332

[21] X Liu, KCheng, P Cui, H Qi, H Qin, GGu, W Wang, S Wang, G Cheng and Z Du, 2019 Hybrid energy harvester with bi-functional nano-wrinkled anti-reflective PDMS film for enhancing energies conversion from sunlight to raindrops, *Nano Energy*, 66:104188

[22] L Zheng, Z H Lin, GCheng, W Wu, X Wen, S Lee and Z L Wang2014 Silicon-based hybrid cell for harvesting solar energy and raindrop electrostatic energy, *Nano Energy*, 9:291-300

[23] W Wang, J Zhang, Y Zhang, F Chen, H Wang, M Wu, H Li, Q Zhu, H Zheng and R Zhang 2020 Remarkably enhanced hybrid piezo/triboelectric nanogenerator via rational modulation of piezoelectric and dielectric properties for self-powered electronics, *Appl. Phys. Lett.*, 116, 1-6.

[24] L Lapčinskis, K MāLnieks, ALinarts, J BlūMs, K N Šmits, MJārvekūlg, M R Knite and AŠutka, 2019 Hybrid Tribo-Piezo-Electric Nanogenerator with Unprecedented Performance Based on Ferroelectric Composite Contacting Layers, *ACS Appl. Energy Mater.*, 24027-4032.

[25] W He, Y Qian, BS Lee, F Zhang, A Rasheed, J E Jung and D J Kang, 2018 Ultrahigh Output Piezoelectric and Triboelectric Hybrid Nanogenerators Based on ZnO Nanoflakes/Polydimethylsiloxane Composite Films, *ACS Appl. Mater. Interfaces*, 10, 44415-44420.

[26] L WZhe, M I Yusoff, Mlrwanto and ARazak, 2016 Investigation of Solar Panel Performance Based on Different Wind Velocity Using ANSYS, *Indones. J. Electr. Comput. Sci.*, 456-463.

[27] L Rekha, C VVazhappilly and C RMelvinraj, 2016 Numerical Simulation for Solar Hybrid Photovoltaic Thermal Air Collector, *Procedia Technol.*, 24, 513-522.

[28] A L Abdullah, SMisha, N Tamaldin, M A MRosli and F ASachit, 2019 Numerical analysis of solar hybrid photovoltaic thermal air collector simulation by ANSYS, *CFD Letters*, 11, 1-11.
[29] Z Syafiqah, N A M Amin, Y M Irwan, M S A Majid and N A Aziz, 2017 Simulation study of air and water cooled photovoltaic panel using ANSYS, J. Phys. Conf. Ser. 908 0-7.

[30] J Yang, J Chen, Y Yang, H Zhang, W Yang, P Bai, Y Su and Z L Wang, 2014 Broadband vibrational energy harvesting based on a triboelectric nanogenerator, Adv. Energy, Mater. 4.

[31] M Lombard, 2018 Introducing Solidworks, Mastering Solidworks

[32] I. ANSYS, Ansys 19.2 Capabilities

[33] Duffie J A, Beckman W A1991Solar engineering of thermal processes, 3rd ed. New York: Wiley – Interscience)