

Raindrop Kinetic Energy Piezoelectric Harvesters and Relevant Interface Circuits: Review, Issues and Outlooks

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Abstract: As an ecological source of renewable energy, the available kinetic energy of rainfall is not trifling, especially in tropical countries at the equators. The research on the use of piezoelectric transducer to harvest raindrop kinetic energy is gaining more and more attention recently. This article reviews the state-of-the-art energy harvesting technology from the conversion of raindrop kinetic energy using piezoelectric transducers as well as its interface circuits for vibration-based energy harvesters. Performance of different types of piezoelectric harvesters in terms of power output, area power density and energy conversion efficiency are compared. Summaries of key problems and suggestions on the optimization of the performance of the piezoelectric harvesters are also provided for future works. *Copyright © 2016 IFSA Publishing, S. L.*

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1. Introduction

This Global climate changes is already an alarming issue, the main contribution to this changes is due to the emission of CO₂ as a result of burning of fossil fuel and other conventional resources. The search for a reliable renewable energy sources and harvesting of these renewable energies is thus becoming the most urgent challenges for the sustainable development of human civilization today.

In tropical countries such as Malaysia, Indonesia, Philippines, Myanmar, India, Panama, Brazil, Nicaragua, the yearly rain rate were measured to be more than 2000 mm per year [1-2], which were rather significant. Hence, raindrop energy is one of an important renewable energy source in these countries. The main form of energy carries by a raindrop is kinetic energy and when the water drop impacted on

the surface of a hard material, the impact caused mechanical vibration.

Piezoelectric materials are able to convert mechanical energy to electrical energy because of the unique property known as the direct piezoelectric effect. When a piezoelectric material is subjected to a tensile stress or compressive, due to the asymmetric nature of their unit cell, an electric field is generated across the mater, resulting in current flow. Since the piezoelectric material can directly convert mechanical vibration into electrical energy in a simple structure [3-4, 50], it is able to be used to harvest the rain kinetic energy.

Moreover, the mechanism is simple and straightforward, which is important for mass production. Therefore, it has becoming a key material for harvesting the kinetic energy of the falling raindrop. Harvesting raindrop kinetic energy by means

of impacting the piezoelectric material has gained a greater interest in recent years.

Different from macro energy harvesting technology which generates kW or MW level power, piezoelectric energy harvester is a micro energy harvesting technology that generates only mW or μ W level power. Therefore, piezoelectric harvester can be a good small scale energy device which is used for powering small scale remote and wireless electronics and self-powered sensors [5-8] that requires to function at low plant load factors.

The most common form of piezoelectric is crystals such as Rochelle salt, quartz, berlinite but they are also found as polymers (plastics) such as polyvinylfluoride (PVF), polyvinylidene fluoride (PVDF), porous Polypropylene (PP), fluoroethylenepropylene (FEP) and ceramics such as barium titanate (BaTiO₃), lead titanate (PbTiO₃), lead-zirconate (PbZrO₃), lead zirconate titanate (PZT) and etc.

The two mainly used materials were PVDF and PZT and the two main structures used were cantilever beam structure and bridge structure. Wong, *et al.* [9] have done a survey on piezoelectric water drop energy harvesting in 2014, however, comparison of performances of such types of harvesters in terms of energy conversion efficiency and area power density are still lacking.

In this paper, the main focus is on the water drop kinetic energy harvesting using piezoelectric transducers and the performance of the piezoelectric transducers. More types of harvesters and latest publications were reviewed and discussed in this paper. Since the available energy of water drop is very small, the conversion efficiency of the interface circuit also becomes an important issue. In the literature, several solutions were suggested to enhance the circuit conversion efficiency of the interface circuits for vibration based piezoelectric harvesters [34-49]. Template provides authors with most of the formatting specifications needed for preparing their articles.

1.1. Rate, Raindrop Diameter, Terminal Velocity and Kinetic Energy

According to the NASA website [10], there are four types of rains i.e. light stratiform rain (LSR), moderate stratiform rain (MSR), heavy thunderstorms (HT) and Violent. Table 1 shows the raindrop sizes, meteorological experimental terminal velocities [11].

Beard [12] showed that the velocity of raindrops with D ranging from 4 mm to 7 mm can have velocity at 9 m/s - 13 m/s prior to reaching the ground.

By assuming the rain droplet is a sphere, when the air drag force is equal to the gravitational force, terminal velocity is achieved, the terminal velocity equation [31] of a rain droplet is

$$v_t = \sqrt{\frac{8rg\rho_{water}}{3C_d\rho_{air}}}, \quad (1)$$

where r is the radius of the rain droplet, $g = 9.81 \text{ ms}^{-2}$, density of water at 1 atm, $\rho_{water}=999.97\text{kg/m}^3=0.99997\text{g/cm}^3$, $\rho_{air}=1.227 \text{ kg/m}^3$, drag coefficient for a sphere $C_d = 1.225$.

Table 1. Rain fall rate per hour of different types of storms.

Type of Storm	Rate [10]	Largest diameter of a raindrop (mm) [11]	Terminal velocity (ms ⁻¹) [11]
Light rain	2 – 4 mm/hr	2.0	6.49
Moderate rain	5 – 9 mm/hr	2.6	7.57
Heavy rain	10 – 40 mm/hr	5.0	9.09 or 10 [12]
Violent	> 50 mm/hr	N/A	N/A

Note: 1 mm rainfall equals 1 litre of water over an area of one m².

Saikia, *et al.* [13] observed at May 2006 that the raindrop diameter D had the range from 0.5 mm to 4.5 mm. The distribution shows that the mode of raindrop diameter is at 2 mm and the mean was around 2.5 mm. The raindrop size data collected by Mazuki, *et al.* [14] in Kotatabang in Indonesia during 2012 showed that the largest raindrop diameter is about 8.5 mm. The largest raindrop size could be larger in 2016 and in future.

Mass of rain droplet in a

$$m = \rho_{water}V = \rho_{water} \frac{4}{3}\pi \left(\frac{D}{2}\right)^3 \quad (2)$$

Kinetic energy of one rain droplet of diameter D :

$$K = \frac{1}{2}mv_t^2 = \frac{1}{2}\rho_{water} \frac{4}{3}\pi \left(\frac{D}{2}\right)^3 v_t^2 \quad (3)$$

Taking $D = 5 \text{ mm}$ (assume it is the mean diameter) for example, and assume the rain droplet is a sphere, then its volume,

$$V = \frac{4}{3}\pi \left(\frac{0.5}{2}\right)^3 = 0.0654 \text{ cm}^3 \quad (4)$$

Mass of rain droplet in a

$$m = \rho_{water} \times V = 0.065 \text{ g} \quad (5)$$

Kinetic energy of one rain droplet of diameter 5 mm:

$$K = \frac{1}{2}(6.5 \times 10^{-5})(10)^2 = 3.27 \text{ mJ} \quad (6)$$

For instance, according to the World Bank, the average precipitation in depth (mm/yr) in Malaysia

was last measured at 2875 mm in 2011. This means there are

$$7.88 \text{ mm/m}^2/\text{day} = 7.88 \text{ litres/m}^2/\text{day} \\ \cong 7.88 \text{ kg/m}^2/\text{day}$$

$$\rightarrow 7.88 \times 10^3 / 0.065 \text{ drops/m}^2/\text{day} \\ = 1.2 \times 10^5 \text{ drops/m}^2/\text{day}$$

Hence, the area energy density available per day,

$$E_D = 1.2 \times 10^5 \text{ drops/m}^2/\text{day} \times 3.27 \text{ mJ} \\ E_D = 0.395 \text{ kWh/m}^2/\text{day} \text{ or} \\ E_D = 144.7 \text{ kWh/m}^2/\text{year}$$

The available rainfall kinetic energy is not low, though the raindrop kinetic energy density per day is about one twelfth of the average solar power available i.e. approximately 5 kWh/m²/day [15].

For small scale electronics, the available rainfall energy density is more than enough for its energy requirement.

1.2. Working Principles

After impacted by a water drop, the kinetic energy of the water drop is converted into the vibration energy and the electromechanical coupling of the piezoelectric transducer converts this vibration energy to electrical energy (Fig. 1(a)). Fig. 1(b) is the interface circuits, it helps to extract more energy from the piezoelectric transducer. The energy, average power and peak power output of transducer due to the impact of water drop(s) are:

Harvested energy

$$E = \int_0^{T_{total}} \frac{V(t)^2}{R_L} dt \quad (7)$$

Average harvested power,

$$P_{ave} = \frac{E}{T_{total}} \quad (8)$$

Peak harvested power,

$$P_{peak} = \frac{V_{peak}^2}{R_L}, \quad (9)$$

where Q is the total charge transferred from the piezo transducer to the detector, $V(t)$ is the oscillating voltage response recorded by the detector, T_{total} is the total length of time of oscillations due to one or more water drop impacts, V_{peak} is the peak voltage, C_{piezo} is the capacitance of piezo transducer, m is the mass of the water drop, v is the final velocity of the water drop prior to impact, R_L is the load resistor.

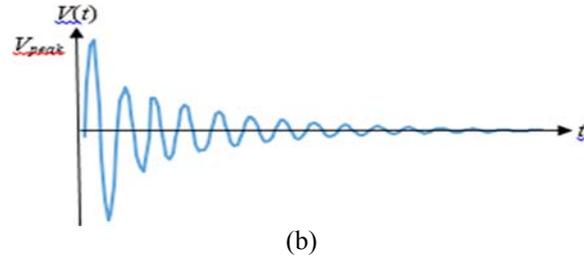
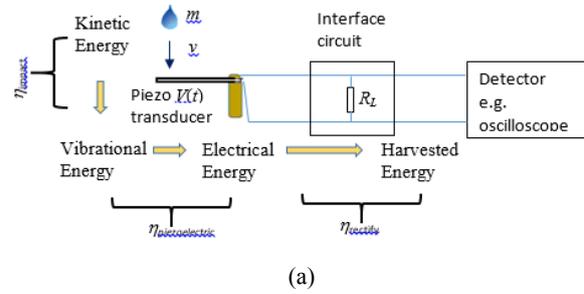


Fig. 1. (a) Diagrams of raindrop energy piezoelectric harvester. (b) Output voltage of piezoelectric upon impact of water drop.

The overall power conversion efficiency consists of three parts i.e.

$$\eta = \eta_{impact} \times \eta_{piezo} \times \eta_{rectify} \quad (10)$$

where η_{impact} is the impact efficiency, η_{piezo} is the piezoelectric efficiency, $\eta_{rectify}$ is the rectify circuit efficiency.

Generally, the impact mechanism of a water drop falling onto a solid surface can be divided into three main categories i.e. bouncing, spreading and splashing. The impact of a water drop on the surface of a harvesting device is expected to exhibit a mixture or all of these mechanisms. Various studies show that the dominant impact mechanism of a water drop is one that involved splashing [26]. The impact mechanism is an important factor which will significantly influence the efficiency of conversion of kinetic energy to piezoelectric mechanical energy i.e. η_{impact} of the harvesting device and its power output. On the other hand, η_{piezo} is greatly depending on the electromechanical coupling efficiency (mostly the 31-mode piezoelectric strain coefficient d_{31}) of the piezoelectric material used. As interface circuit plays an important role in helping the harvester device to extract energy from the energy generated in the piezoelectric as a result of impact of water drop, the interface circuit efficiency i.e. $\eta_{rectify}$ is solely affected by the choice of interface circuits.

2. Types of Energy Harvesters

2.1. Raindrop Energy Harvesters

Till recently, there are five types of structures of raindrop kinetic energy piezoelectric harvesters reported, (Fig. 2).

1. Bridge [9, 16, 20]
2. Cantilever [9, 17-25, 28]
3. Membrane [26] – computer simulation only
4. Collecting diaphragm and piezoelectric cantilevers [27] – computer simulation only
5. Edge-anchored PZT plate [31] – computer simulation only

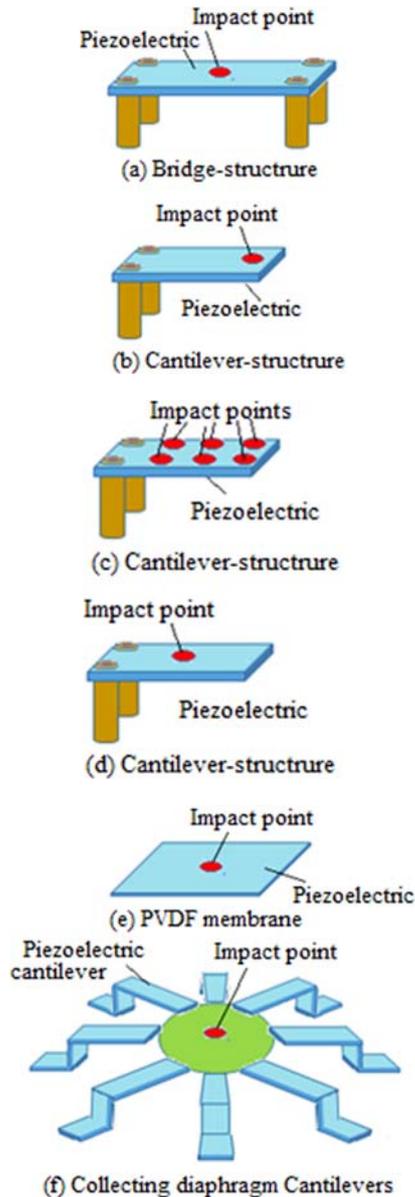


Fig. 2. Different types of raindrop kinetic energy piezoelectric harvesters: (a) Bridge-structure; (b) Cantilever structure with impact point near the free-end; (c) Cantilever structure with six impact points at varies surface locations; (d) Cantilever structure with impact point at the centre; (e) PVDF membrane or PZT edge-anchored plate; (f) Collecting diaphragm cantilevers.

The three piezoelectric materials used were piezopolymer (PVDF), piezoceramic (PZT) and PMMO/GO. [29], the first two were the most widely used materials. The details of all types of harvesters are shown in Table 2.

The first raindrop kinetic energy piezoelectric harvester was proposed by Guigon, *et al.* [16, 30] using polypiezo material, it was a bridge-type structure made of a monostretched PVDF with 25 μm thickness (piezoelectric strain coefficient $d_{31} = 15 \text{ pC N}^{-1}$) and another one was a bistretched PVDF with 9 μm thickness ($d_{31} = 5 \text{ pC N}^{-1}$) (Fig. 2(a)). The area of these two energy harvesters was 10 cm \times 3 mm. With the assumption of that a raindrop, on impact, produces a perfectly inelastic shock. Their numerical simulation shown that a single downpour raindrop of 5 mm in diameter might be able to recover 25 μJ energy and 12 mW of power. Their experimental results showed that the impact of an artificial raindrop of diameter 3 mm and velocity 4.5 ms^{-1} were able to produce 147 nJ energy and 73 μW power. They found that the monostretch 25 μm PVDF was much more effective than the bistretched 9 μm PVDF.

Cantilever piezoelectric beam as shown in Fig. 2(b) is the most general used structure in vibrational based piezoelectric harvesters. In water drop impact energy harvesting application, Vatansever, *et al.* [17] compared the performance of the cantilever harvesters made of PVDF and PZT strips respectively. There were four types harvesters with different piezoelectric materials and number of layers, namely short PVDF, long PVDF, PZT-unimorph, and PZT-bimorph with respective dimensions were 41 \times 16 \times 0.2 mm^3 , 171 \times 22 \times 0.2 mm^3 , 140 \times 15 \times 0.32 mm^3 and 140 \times 15 \times 0.75 mm^3 . The piezoelectric voltage constants of the PVDF and PZT materials in 31-mode (d_{31}) were $216 \times 10^{-3} \text{ VmN}^{-1}$ and $10 \times 10^{-3} \text{ VmN}^{-1}$, respectively. Their results revealed that PVDF harvester outperformed both unimorph and bimorph PZT harvesters, short PVDF was also better than the long PVDF. In their experiment, water drop of mass 7.5 mg and 50 mg were released from the heights ranging from 20 cm to 100 cm. When the tips or free-ends of the cantilevers of the harvesters were impacted by the 50 mg water drop released at the maximum height of 100 cm, the peak voltage generated by the short PVDF harvester was 12 V, whereas the PZT harvester generated less than 2.5 V. They attributed the low voltage output of the PZT energy harvester to the rigidity (and hence low d_{31}) of the ceramic material which hindered the oscillations after impacted by the water drops.

F. Viola, *et al.* [18-19] and Rosario Miceli, *et al.* [20] also conducted experiments on two types of raindrop energy harvesters i.e. bridge-type structure and cantilever-type structure, the difference was that the former was made of PZT and the latter was made of PVDF. The two types of piezoelectric used were the commercial piezoelectric transducers. The dimensions of the bridge-type structure was 25.4 mm \times 93.81 mm \times 90.7874 mm, while the dimensions of the cantilever-type structures were 3.3 mm \times 25 mm - 30 mm and 30 mm \times 12 mm, respectively. In addition, they also studied a cantilever-type harvester with two sets of PVDF transducers arranged in parallel. In their study,

they reported that the single PVDF transducer cantilever structure produced the highest power, the double PVDF transducer cantilever produced lower power; whilst, the power produced by the bridge PZT structure was the lowest. The single PVDF transducer

cantilever structure produced the maximum peak power of $4.5 \mu\text{W}$ when the load resistance was $47 \text{ k}\Omega$, while the same load resistance only produce maximum peak power of $0.9 \mu\text{W}$ for PZT transducer.

Table 2. Information of various types of piezoelectric harvester for harvesting raindrop kinetic energy.

Single drop Peak Voltage/Power (Load Resistance)	Dimensions (length \times width \times thickness)	Types of Piezoelectric	Type of harvester structures	Authors (Year)
$D=3 \text{ mm} - 17.62 \text{ V}$, $D=1.6 \text{ mm} - 4.68 \text{ V}$	$10 \text{ cm} \times 3 \text{ mm} \times 25 \mu\text{m}$ (and $9 \mu\text{m}$)	PVDF membrane	Bridge	R. Guigon, <i>et al.</i> [16] (2008)
12 V , 2.2 V	$16 \times 4 \times 0.2 \text{ mm}^3$ -short $140 \times 15 \times (0.32 \text{ or } 0.75) \text{ mm}^3$	PVDF PZT	Cantilever	D. Vatansever, <i>et al.</i> [17] (2011)
N/A	$1 \text{ m} \times 1 \text{ m}$	PVDF	Piezoelectric membrane	C. Perera, <i>et al.</i> [26] (2011)
$0.9 \mu\text{W}$ ($47 \text{ k}\Omega$) $4.5 \mu\text{W}$ ($47 \text{ k}\Omega$) $1.75 \mu\text{W}$ ($68 \text{ k}\Omega$) (for 2 parallel PVDF)	$25.4 \times 3.81 \times 0.78 \text{ mm}^3$ $2.5 - 3.0 \text{ cm} \times 0.33 \text{ cm}$	PZT PVDF	Bridge Cantilever	F. Viola, <i>et al.</i> [18] (2013)
6 V ($5 \text{ M}\Omega$)	$3 \text{ cm} \times 0.33 \text{ cm}$	PVDF	Cantilever	F. Viola, <i>et al.</i> [19] (2014)
$0.12 \mu\text{W}$ ($82 \text{ k}\Omega$) $5 \mu\text{W}$ ($47 \text{ k}\Omega$)	$30 \text{ mm} \times 12 \text{ mm}$ N/A	PZT PVDF	Bridge Cantilever	Rosario Miceli, <i>et al.</i> [20] (2014)
$1.55 \text{ V}/0.16 \text{ mW}$ ($15 \text{ k}\Omega$) [22]	$46.355 \text{ mm} \times 38.1 \text{ mm} \times 0.33 \text{ mm}$	PZT Bimorph	Cantilever	V. K. Wong, <i>et al.</i> [21, 22] (2014)
$V_{peak} = 1.003 \text{ V}$ $V_{peak} = 3.52 \text{ V}$	$30 \text{ mm} \times 4 \text{ mm} \times 25 \mu\text{m}$ ($25 \mu\text{m}$ is the best)	PVDF	Cantilever Bridge	C. H. Wong [9] (2014)
$V_{pk-to-pk} = 0.8 \text{ V}$ ($10 \text{ k}\Omega$), $23 \mu\text{W}$	$20 \text{ mm} \times 8 \text{ mm} \times 0.58 \text{ mm}$	5 layer of PZT thick films	Cantilever	M. Al Ahmad [23] (2014)
N/A	$80 \text{ mm} \times 28 \text{ mm}$	PVDF	Leaf cantilever	S. Gart, <i>et al.</i> [28] (2015)
$2.3 \mu\text{W}$ ($2.2 \text{ M}\Omega$)	$25 \times 13 \times 3 \text{ mm}^3$	PVDF	Cantilever	Ilyas [25] (2015)

C. H. Wong [9] also compared two different types of energy harvester i.e. bridge-type and cantilever-type structures, the only difference was both harvesters were made of PVDF in their experiments. In his experiment, the highest output voltage of the two types of harvesters when impacted by a drop of diameter 5.77 mm from the height of 1 m were 3.502 V and 1.003 V , respectively. The results indicated that the bridge-type harvester were better than cantilever-type harvester when both were made from the same piezoelectric material as well as with the same dimensions.

Ahmad [23] examined the five-layer PZT clamped-free cantilever energy harvester, the dimensions of the cantilever was $25 \text{ mm} \times 3 \text{ mm} \times 0.58 \text{ mm}$. Two sets of different experiments were conducted for impacting the cantilever at two different drop intensity, namely one at 75 drops/s drop intensity and the other was at 200 drops/s . The mass of a water drop was 0.23 g with drop speed of 3.43 m/s . From their experiment, $0.3 \mu\text{J/drop}$ energy was harvested at 75 drops/s drop

intensity while at moderate drop intensity of 200 drops/s , the energy output of the harvester yield a total energy of $400 \mu\text{J}$. At 200 drops/s drop intensity, the instantaneous power was measured to be of $192 \mu\text{W}$ with a load of $10 \text{ k}\Omega$. Apart from that, they also investigated how the proof mass affects the output voltage when the cantilever was impacted with different water drop mass.

Gart, *et al.* [28] studied how falling raindrops affected cantilever beam which was made of polycarbonate and PVDF with different surface properties, length, width and impact velocity. From the numerical and experimental results of the beam made of the two types of materials, they found that wettable beams experienced higher bending energy. The wettable PVDF cantilever with dimensions of $8 \text{ mm} \times 28 \text{ mm}$ harvested greater electric energy, especially at higher impact velocities. For a water drop of radius 1.73 mm , at its maximum speed, the electrical energy generated by the piezoelectric cantilever was 23 nJ .

Most of the studies of the energy harvesters were done on impacting the dry surface harvesters by water drops, but in reality, this is not possible. V. K. Wong [21] studied the dynamics of a PZT bimorph cantilever beam, the dimensions of the cantilever was $46\text{ mm}\times 33\text{ mm}\times 127\text{ }\mu\text{m}$. They impacted the free-end of the cantilever beam with and without the presence of water layer. The rms voltage produced without water layer was numerically and experimentally found to be larger than that of rms voltage produced with water layer. This indicated that the power output of the cantilever beam was lower at the presence of water layer. In another experiment [22], they utilized six syringes connected to six solenoid valves to produce 4.5 mm diameter water drops. The water drops were produced one by one at a controlled rain rate to impact different surface locations of the cantilever beam, as shown in Fig. 2(c). The three different rain rates were light stratiform rain (LSR), moderate stratiform rain (MSR) and heavy thundershower (HT). The voltage produced was largest when the water drop was impacted close to the free-end of the cantilever and was lowest when the impact location located near the fix-end of the cantilever. This is because, larger strain was produced when water drop impacted locations close to the free-end of the cantilever and hence more energy was converted. The average power for three different rain rates, LSR, MSR and HT were $0.52\text{ }\mu\text{W}$, $1.01\text{ }\mu\text{W}$ and $1.84\text{ }\mu\text{W}$. From the investigation of different resistive loads, $15\text{ k}\Omega$ were found to generate maximum peak power of 0.16 mW .

Ilyas, *et al.* [25] developed a cantilever-structure energy harvester which composed of four different layers i.e. silicon, polyamide, Al and PVDF with the dimension of $25\times 13\times 3\text{ mm}^3$. They tried to find the optimum thickness of the electrode layer and the PVDF layer for obtaining a maximum displacement upon impacted by a water drop. They found that when PVDF thickness was $150\text{ }\mu\text{m}$ and Al thickness was $35\text{ }\mu\text{m}$, a maximum displacement of $2800\text{ }\mu\text{m}$ was obtained. They connected different load resistances ranging from $1\text{ M}\Omega$ - $4.7\text{ M}\Omega$ to the piezoelectric transducer. They found the total mean power were generally below $2.5\text{ }\mu\text{W}$ and a maximum energy harvested was around 85 nJ when the energy harvester was subjected to the impact of a water droplet of radius of 2 mm and velocity 2.13 ms^{-1} . With the optimal load resistance of $2.2\text{ M}\Omega$, the maximum efficiency was found to be around 0.11% at $v = 2.13\text{ ms}^{-1}$. By employing the information gather from their experimental results, they calculated the mean output power of a theoretical harvester array model under the rainfall of 32 mm (32 L per m^3) with 80% active harvesting area. Within the duration of 300 s , the highest mean output power at different drop velocity for a 1 m^2 , 10 m^2 and 100 m^2 harvester arrays were calculated to be $150\text{ }\mu\text{W}$ (2.13 ms^{-1}), 160 mW (2.13 ms^{-1}) and 3.5 W (9.62 ms^{-1}), respectively.

Apart from cantilever-structure and bridge-structure, Perera [26] proposed a $1\text{ m}\times 1\text{ m}$ PVDF piezoelectric membrane as shown in Fig. 2(e). They performed simulations for impacts of varies drop sizes of the rain at different rain rates such as LSR, MSR and HT. The largest energy harvested was $2.72\times 10^{-32}\text{ J}$ and highest power output was $2.23\times 10^{-29}\text{ W}$ for the impact of the largest drop size during the HT rain.

Fig. 2(f) shows a new piezoelectric harvester theoretical model presented by C. H. Wong [27] i.e. a collecting diaphragm and PVDF piezoelectric cantilevers energy harvester which consists of five layers i.e. silicon, polyimide, aluminium bottom, PVDF and Al top. They performed simulation for varies thickness layers with finite element method. In their work, thickness of PVDF ranging from 120 to $200\text{ }\mu\text{m}$ and thickness of Al ranging from 20 – $40\text{ }\mu\text{m}$ were investigated. The max-displacement was obtained when a pressure of 13.718 MPa was applied on the center of the harvester.

Miao and Jia [31] studied the strain distribution of a $50\text{ mm}\times 50\text{ mm}$ edge-anchored piezoelectric plate made of PZT-5H when impacted by 5 mm raindrop at various locations. Their simulation using COSMOS Multiphysics software indicated that multiple arrays of small edge-anchored plates would be significantly better than a single large plate anchored at far edges.

Valentini, *et al.* [29] deposited the poly(methyl methacrylate)/graphene oxide (PMMA/GO) film on top of a glass substrate to make the energy harvester. The PMMA/GO is a type of piezoelectric, output power of 6 nW was generated when impacted by a $5\text{ }\mu\text{g}$ water drop released from a height of 0.2 m . Different from all of the previous energy harvesters, this piezoelectric transducer worked in 33-mode.

2.2. Hybrid Energy Harvesters

As solar energy is more sustainable energy source, photovoltaic (PV) or solar cell becomes the most popular renewable energy systems in the last two decades. However, the main setback for solar energy is its seasonal availability i.e. during monsoon seasons, the power output is greatly degraded due to cloud covering. Moreover, the operational condition of the ideal silicon-based solar cell is best at a relatively cold and sunny environment rather than the humid and hot climate region. Hybrid systems that complement each other should be a good option, for instance, a hybrid rain energy and solar energy harvesters in which rain energy harvesters to cover for the heavy rainfall when solar cell energy output is low and wind turbines during the windy and cloudy days.

The team of E. Siores, *et al.* [32] in University of Bolton's Institute of Materials Research and Innovation (IMRI) has developed a hybrid piezoelectric-photovoltaic device at the form of films and fibres, which was able to harvest raindrop, wind and solar energy. The hybrid films and hybrid fibres

were created by depositing the organic solar cell on a PVDF film and the fibres respectively. At one sun intensity, the open circuit voltage and short circuit current of 0.43 V and 4.48 mA/cm², respectively, were obtained from the flexible hybrid film. The hybrid film also generated a peak power of 85 μ W at wind speed of 10 m/s [33]. They did not conduct experiments to test the conversion efficiency of their hybrid energy harvesters for harvesting the water drop kinetic energy.

3. Performances of Raindrop Impact Piezoelectric Energy Harvesters

Most of the power harvested from the raindrop kinetic energy piezoelectric energy harvester are at the range of μ W [18, 20, 23, 25]. C. H. Wong [9] shows that bridge-type harvester converted more power than

cantilever-type energy harvester, both are made of PVDF. The experiment conducted by V. K. Wong [22] found that their piezoelectric cantilever made of PZT was able to obtain 0.16 mW per drop. This is the highest harvested power per drop ever reported. However, it is still at least two order magnitude smaller if compare to the 12 mW peak power simulated by Guigon, *et al.* [30] using bridge-type harvester.

Output peak power is not a good parameter for comparison between different energy harvesters. Instead, the best parameter for the comparison is the energy conversion efficiency (η_E) of the energy harvester (Table 3). However, none of the published papers to date, except Miao and Jia [31] have quantified the conversion efficiencies of their devices. Due to lacking of certain information, it is only possible to compute the energy conversion efficiency of a few of the harvesters.

Table 3. Energy conversion efficiency of various types of piezoelectric raindrop kinetic energy harvester.

Authors	Type of harvester structures	Water drop D or m or h or v	Harvested energy /Kinetic energy, E/E_k	Energy Conversion Efficiency $\eta_E = E/E_k \times 100$ (%)
R. Guigon, <i>et al.</i> [16]	Bridge (PVDF)	$D = 3$ mm, $v = 4.5$ ms ⁻¹	147 nJ / 0.143 mJ	0.1 %
		$D = 1.6$ mm $v = 3.2$ ms ⁻¹	16 nJ / 0.011 mJ	0.146 %
V. K. Wong, <i>et al.</i> [21, 22] (2014)	Cantilever (bimorph PZT)	LSR		0.33 %
		MSR	*6.5 μ J/1.96 mJ	0.32 %
		HT $m = 47.7$ mg $v = 3.7$ ms ⁻¹	*12.625 μ J/3.92 mJ *23 μ J/5.88 mJ	0.39 %
M. Al Ahmad [23]	Cantilever (5 layer PZT)	$m = 0.23$ g $v = 3.43$ ms ⁻¹	0.08 μ J / 1.353 mJ (75 drop /s)	0.006 %
			1.739 μ J/1.353 mJ (at 200 drop/s intensity)	0.128 %
S. Gart, <i>et al.</i> [28]	leaf cantilever (PVDF)	$D = 2 \times 1.73$ mm	23 nJ / 62 μ J	0.037 %
Ilyas, <i>et al.</i> [25]	Cantilever (PVDF)	$D = 4$ mm, $v = 2.13$ ms ⁻¹ $E = 0.5 \times (0.0335) \times v^2$ $= 27.4$ μ J – 76 μ J	85 nJ / 76 μ J	0.11 %

Note: D is the diameter of a raindrop and h is the released height of the raindrop and “*” means the harvested energy was the total energy as a result of water drop impacts at various location of the harvester, the value should be at least two times lesser than the energy compare to when all of the water drops impacts were on the free-end of the harvester.

For a single drop impacted near the free-end of the cantilever-type or the centre of the bridge-type energy harvester, the efficiency η_E for cantilever-type harvester made of PZT was the highest i.e. approximately 0.39 % [22] (η_E should be more than double of this value if all of the water drops were impacted near the free-end of the cantilever), which is an order magnitude higher than the efficiency of the cantilever-type harvester made of PVDF [28] i.e. 0.037 %; whilst the highest efficiency for bridge-type harvester made of PVDF was approximately 0.146 %

[16]. It shows that PZT-made energy harvester had a higher energy conversion efficiency, despite the fact that, Vatansever, *et al.* [17], Viola, *et al.* [18] and Rosario Miceli, *et al.* [20] all showed that PVDF outperformed PZT in harvesting raindrop kinetic energy application. The reason could be due to the PZT used in [22] had a piezoelectric constant d_{31} of -190 pC N⁻¹ (or 25.9×10^{-3} Vm N⁻¹), while it was 10×10^{-3} Vm N⁻¹ in the case of Vatansever, *et al.* [17]. Other reasons could be due to the differences in dimension and number of piezoelectric layers used.

Ilyas, *et al.* [25] obtained 0.11 % efficiency using a PVDF cantilever, the efficiency could be few times higher if the water drop was impacted near the free-end instead of the centre of the piezoelectric cantilever. This can be seen by the peak voltage generated by impacts of water drops at various location in the experiment of V. K. Wong, *et al.* [22].

At moderate rain rate i.e. 200 drops/s, Ahmad [23] demonstrated that when the oscillations due to two consecutive impacts superimposed, the energy output and the efficiency could be raised to 1.739 $\mu\text{J}/\text{drop}$ and 0.128 %, respectively. This is a lot higher than the single drop impact efficiency of 0.006 % [23]. The overall conversion efficiency η_E for an energy harvester could also be affected by the mass and terminal velocity (or kinetic energy) of the water drop, for example, in the experiment of Guigon, *et al.* [16], the efficiency of their bridge-type harvester when impacted by raindrop with K.E. of 0.011 mJ was 0.146 %, whilst when impacted by a raindrop with K. E. of 0.143 mJ was 0.1 %. The loss was due to splash, which was 46 %.

As shown in Fig. 3 are the plots of the two-types of area power density i.e. single drop maximum peak power density (P_{Dpeak}) [16, 18-23, 31].

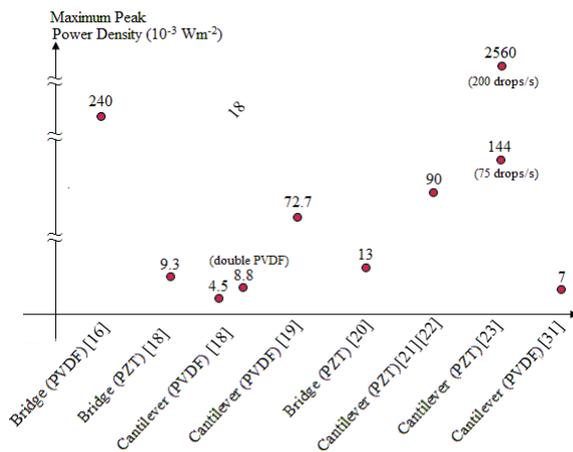


Fig. 3. Graph of maximum peak power density P_{Dpeak} of various types of raindrop kinetic energy piezoelectric harvesters [16, 18-23, 31].

Most of the papers calculated the single drop impact maximum peak power density P_{Dpeak} of their piezoelectric transducers. All of the raindrop energy harvester to date, has a very small P_{Dpeak} . The highest P_{Dpeak} was achieved by the PVDF bridge-type energy harvester 0.24 W/m^2 or $240 \times 10^{-3} \text{ W}/\text{m}^2$ [16] followed by the PZT cantilever-type energy harvester studied by Ahmad [23], which was $144 \times 10^{-3} \text{ W}/\text{m}^2$ (the author claimed that their power density was $4950 \times 10^{-3} \text{ W}/\text{m}^2$). At 200 drops/s drop intensity, their peak power density was $2560 \times 10^{-3} \text{ W}/\text{m}^2$. Practically, the average power density P_{Dave} is a better indicator of performance of an energy harvester per unit area due to the fact that the location where raindrops impinged is not always at the free-end. For example, at MSR rain

rate, P_{Dave} of $0.57 \times 10^{-3} \text{ W}/\text{m}^2$ (P_{ave} was 1.01 μW) was lower than P_{Dpeak} of $90 \times 10^{-3} \text{ W}/\text{m}^2$ [22]. Power density is also affected by rain rate, for example, LSR rain rate P_{Dave} was lower i.e. $0.29 \times 10^{-3} \text{ W}/\text{m}^2$ [22] (P_{ave} was 0.52 μW).

Note: $P_{Dpeak} = P_{Speak} / A$, $P_{Dave} = P_{ave} / A$, P_{Speak} is the maximum peak power generated when the piezoelectric transducer was impacted by a single water drop at the location near the free-end of a cantilever or the centre of the bridge-type piezoelectric transducer, P_{ave} is the average power generated when the piezoelectric transducers was impacted by multiple water drops at a certain rain rate or drop intensity and at different surface location of the piezoelectric transducer; and A is the top surface area of the piezoelectric transducer.

4. Interfacing Circuit

Generally, there is a need for the harvested energy to be stored in the storage devices such as battery or capacitors. In order to do that, an AC-to-DC converter such as a full-bridge rectifier circuit is needed to act as an interface circuit. In piezoelectric vibration-powered generators, the full-bridge rectifier circuit [34-35] as the so-called “standard circuit” (Fig. 4) was the most commonly used circuit.

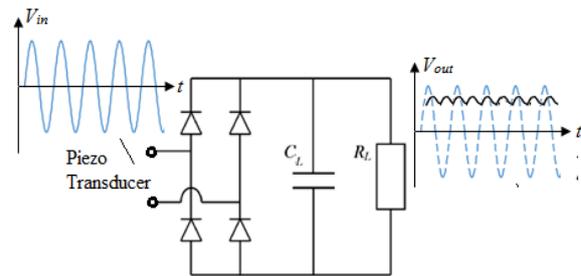


Fig. 4. Standard interface circuit i.e. full-bridge rectifier AC-to-DC converter with capacitor and load resistor.

4.1. Buck-Boost Converter Circuits

It is almost impossible to always match the circuit impedance with the optimum load required when standard circuit was used. Hence, DC-to-DC converter (Fig. 5) which converts and regulates voltage level is essential to provide a fix output voltage to the energy storage device and a fix optimum impedance to the transducer regardless the actual circuit load connected. Among the DC-to-DC converters, buck-boost converter [36-38] which controls its output voltage level based on the duty circle of the switching transistor is a good candidate. Leteuer, *et al.* claimed that an 84 % high efficiency and maximum harvester power of 1.5 mW was achieved by the buck-boost converter that can track the dependence of power generator with acceleration and vibration frequency of piezoelectric device [36].

Made, *et al.* [38] investigated buck boost circuit in discontinuous conduction mode circuit (DCM). The converter operated in DCM was able to isolate its input and output impedance, hence provide a constraint input impedance that was matched with the optimal load of the energy harvester. The efficiency was higher because of the switch-based rectifier provided lower voltage drop than traditional diode-based rectifier. The input impedance was governed by the switching frequency and duty cycle and also the inductor size. This adjustable input impedance of the Buck Boost circuit allowed optimum piezoelectric energy harvesting based on impedance matching principle.

However, the optimal load will vary with change of frequency of transducer for raindrop application. Ottman, *et al.* [39] presented a more complex DC-to-DC converters based on current sensing. Experimentally they showed that the use of the adaptive dc-dc converter increased power transfer by over 400 % as compared to when the standard circuit was employed. The drawback is that this method is more energy consuming.



Fig. 5. Interface circuits consisting of AC-to-DC converter and DC-to-DC converter.

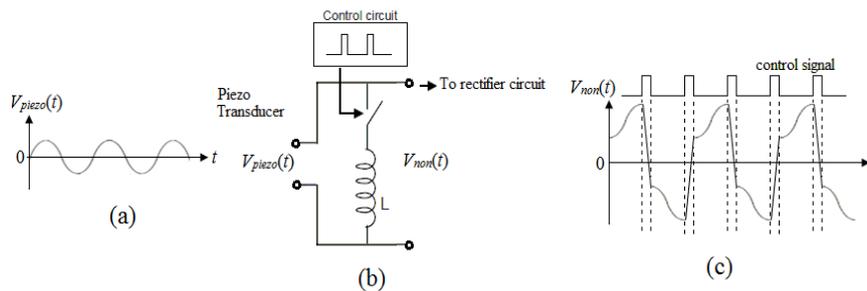


Fig. 7. (a) Input voltage waveform $V_{piezo}(t)$ of piezo transducer under periodic mechanical vibration; (b) Non-linear circuit; (c) Output voltage waveform $V_{non}(t)$ of the non-linear circuit and control signal.

Lallart and Guyomar [42] developed a Synchronized Switch Harvesting on Inductor (SSHI) with an efficiency of 160 % over standard rectifier.

Ramadass and Chandrakasan [43] presented a bias-flip rectifier using on chip and off-chip diodes and inductors of different values. The output power obtained was in the range of μW . Using off-chip diodes, they managed to extract 4 times higher power. When on-chip diodes were used, the improvement in power extraction increases to above 7 times.

Using displacement sensor, the synchronized charge extraction technique with inductor connected either in series or parallel to the piezo transducer was proposed by Lefeuvre, *et al.* [44], resulting in the increase of the harvested power by at least factor of 4, and reach maximum of 15 compare to standard interface circuit.

4.2. Synchronized Switch Harvesting on Inductor (SSHI) Circuits

The main constraint of the standard circuit (Fig. 6) is that a rather large portion of charge generated by the transducer has been used to charge up its own internal capacitor, leaving only a small portion to be delivered to the external capacitor C_L . This loss in charge reduces the amount of electrical energy that can be harnessed and hence the rectifying efficiency of the standard circuit.

To further improve the rectifying efficiency of the bridge-type rectifying circuit, a non-linear circuit which could extract charge synchronously was proposed. As depicted in Fig. 7, the charge generated is extracted whenever the piezoelectric voltage reached the maximum point or minimum point. This discharging process is controlled by a switch which was connected to a control circuit [40-41].

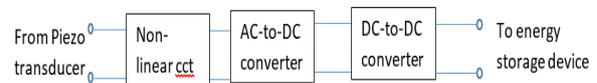


Fig. 6. Interface circuits consisting of AC-to-DC converter and DC-to-DC converter and a non-linear circuit, the non-linear circuit can be placed before or after the AC-to-DC converter.

Other type of interface circuit is the rectifier free piezoelectric energy harvester (Fig. 8) proposed by Kwon, *et al.* [45], the efficiency achieved was 71 %.

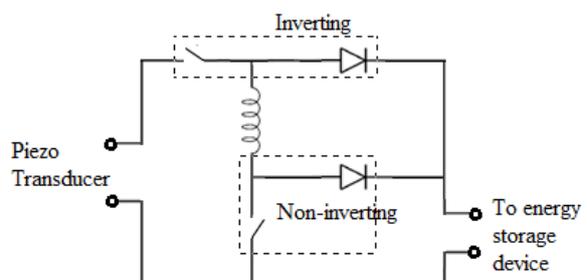


Fig. 8. Rectifier-free piezoelectric energy harvesting circuit [45].

For low input piezoelectric amplitude voltage i.e. less than 1 V, Peters, *et al.* [46] suggested two stage concept including a negative voltage converter (passive stage) and only one active diode. The efficiency was over 90 % and the power consumption was measured to be 266 nW.

An improved version of two-stage rectifier was presented by Li, *et al.* [47], the second stage was replaced by a comparator controlled active diode rectifier works, resulting in a wider input range i.e. amplitude of 0.45 till 1.8 V. the peak power conversion efficiency and power conversion efficiency achieved were 96 % and 90 %, respectively. The power consumption was 197 nW.

4.3. Pre-bias Circuit

Electrical energy is generated when the external force is damped by the piezoelectric transducers. However, limited by the intrinsic shunt capacitance, the transducer operated with a resistive load is often hard to provide sufficient damping force [49].

Compared to an optimised purely resistive load, which were the circuit utilized by most of the energy harvesters reported [16-30], Dicken, *et al.* [48] showed that it is possible to increase the damping force of the piezoelectric transducers by a circuit they designed.

They designed a dedicated circuit that was able to synchronously discharge the generated charge to the load at the maximum or minimum point of each cycle and immediately followed by a pre-charge step. With assumption that the charge oscillation is in phase with the vibration of the piezo cantilever, the processes are illustrated in Fig. 9. The charging circuit they used comprised of a H-bridge with an inductor. Pre-charging caused the piezo cantilever to bend in a larger amplitude and, hence, larger output voltage. The net energy output, $E_{pre} = \text{discharge energy} - \text{energy to charge piezo to } V_B$

$$E_{pre} = \frac{1}{2}C \left[\eta_d (V_B + \Delta V)^2 - \frac{V_B^2}{\eta_c} \right] \quad (11)$$

E_{pre} is larger than the energy output without pre-biased i.e. $E = \frac{1}{2}C[\eta_d(\Delta V)^2]$.

They showed that by using the pre-biasing circuit, the efficiency of the piezoelectric transducer could be improved by at least 2 times and at most to be more than 10 times. Their circuit was designed for an undampable oscillating source only, it does not work for the raindrop energy harvest which provides a damped oscillating source.

5. Issues and Outlook

From the authors literature review, the efficiency of the raindrop kinetic energy piezoelectric harvester is still too low to be commercially implemented.

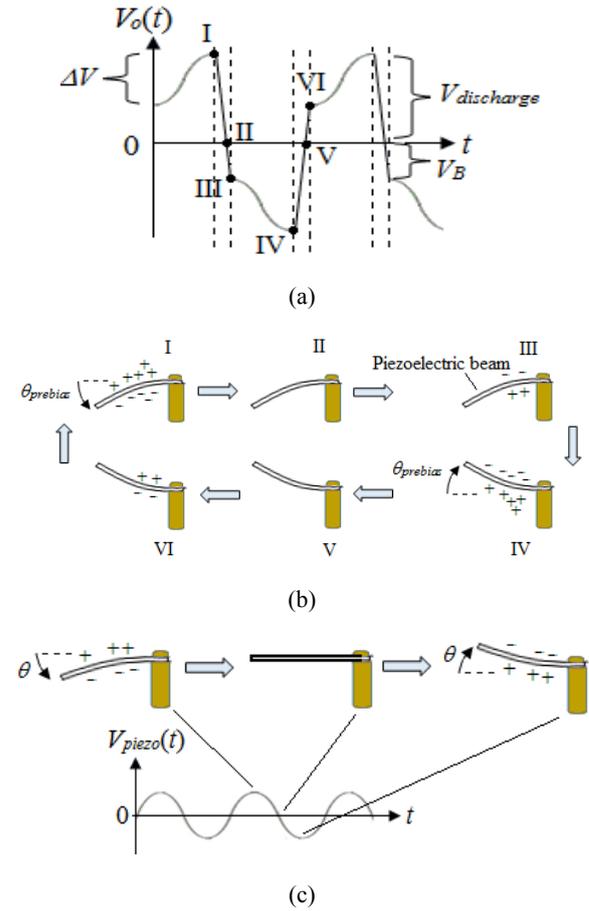


Fig. 9. (a) Pre-biasing circuit output voltage $V_o(t)$, the piezo cantilever is synchronous discharged ($V_{discharge}$) from point I till point II, followed by pre-biased of potential difference V_B to point III; the cantilever bended upward producing highest negative voltage at point IV; it is synchronous discharged again till point V followed by another pre-bias process, the processes are repeated. (b) The movements of cantilever and charges corresponding to the processes I - VI. (c) The movements of cantilever and charges without pre-biasing circuit and the transducer output voltage $V_{piezo}(t)$. The amplitude of deflection in terms of angle for pre-bias process $\theta_{prebias}$ is larger than θ .

However, the simulation result of Guigon, *et al.* [30] showed that the peak power could reach 12 mW and the efficiency at 2.5 % ((25 μ J)/1 mJ). Besides, in the studies of piezoelectric energy harvesting from constant vibration sources, Shu, *et al.* [52] indicated that the 46 % conversion efficiency can potentially be achieved. This means there are still rooms for improvements. The areas of improvements and some important issues:

5.1. Optimization of Impact Efficiency

Problem of splash becomes an important impact mechanism when the raindrop size and kinetic energy becomes large [9, 16] and this could greatly reduce the impact efficiency, η_{impact} . Studies by Sikalo, *et al.* [53-54] showed that water drop impact mechanism depends on angle of impact, surface material

properties, and etc. This implies that the impact efficiency can be significantly enhanced by engineering the harvester surface properties and profile.

The energy harvested of a piezoelectric cantilever beam is affected by type of surface. A hydrophilic surface which caused the water drop to stick better on the surface of the piezoelectric cantilever, could increase the power output [28]. Conversely, water accumulation on the cantilever surface caused power output to decrease [21], thus, a new design must consider having a stickier surface and yet preventing water accumulation on the surface of the harvester.

5.2. Optimization of Piezoelectric Efficiency

As depicted in Fig. 10, the strain of a rectangle shape piezoelectric beam structure is not uniform along the whole length, it is largest at the fix-end and linearly reduced to the free-end [55]. As the electric charge generated in piezoelectric beam is directly proportional to the strain the transducer undergone, the energy generated or piezoelectric efficiency (η_{piezo}) would be small.

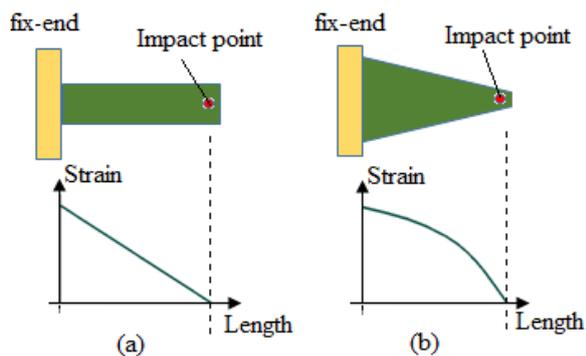


Fig. 10. Piezoelectric cantilever of different shapes and their corresponding strain versus length graph [55].

As suggested by Rosario Miceli [20] and S. Roundy, *et al.* [55], to maximize energy, the geometries must be designed so as to produce as uniform and as large a strain as possible. Trapezium shape piezoelectric beam suggested by [20, 55] can produce a more uniform strain on the piezoelectric beam and thus larger energy output. Rosario Miceli, *et al.* [20] also suggested that energy output can be increase by pressed the cantilever against a suitably shaped profile. Therefore, an optimum shape of a piezo transducer or shaped profile should be developed for raindrop energy harvester.

Properties of piezoelectric is a key factor that dictates the low η_{piezo} for a piezoelectric energy harvester, thus, new ways have to be found to overcome this limitation. Apart from searching for new piezo material that could have a high piezoelectric coefficient, the pre-biasing technique developed by Dicken, *et al.* [48] to enhance the damping force of the piezoelectric transducers could also be a good choice

to increase the conversion efficiency. Although their circuit was only designed for an un-dampable oscillating source that it would not work for the raindrop energy harvester which provides a damped oscillating source, new circuit based on the same concept could still be developed.

A more important issue is the power generated per unit area (P_D), P_D of rain harvesters are very low. As illustrated by V. K. Wong, *et al.* [22], power output due to water drop impact decreased gradually from the free-end of the cantilever to the fix end. The piezoelectric cantilever beam [9, 17-25, 28] has one fix-end; the bridge-type harvester [9, 16, 20] has two fix-end and the fix-end of the device of C. H. Wong [27] are all around the circumference. The new type of harvester should be designed in such a way that there is no fix-end(s).

Instead electricity generation via the direct impact of raindrops on the piezoelectric transducer, another approach is to generate electricity indirectly using piezoelectric watermill or turbine. Since the falling speed of the raindrops had reached their terminal velocity far before hitting the ground, and the kinetic energy of the raindrops are proportional to the square of their terminal velocity, it makes no difference in the energy output between harvesting rainfall on ground level or at a higher elevation. Furthermore, raindrops can be collected at an elevated platform by using a water tank. In this indirect electricity generation, the rain water which possess of gravitational energy can be released and streamed onto the arm of the piezoelectric turbine [31, 56] to make it rotate. As shown in Fig. 11, the rotation causes the bending of attached piezoelectric cantilevers, resulting in electricity generation.

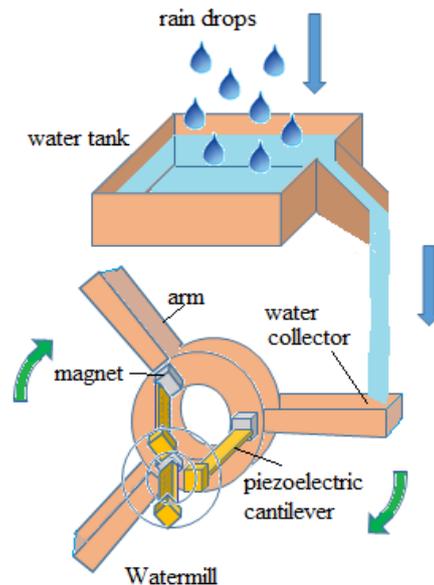


Fig. 11. Water tank acts as a water reservoir in collecting the rainwater and channel the rain water to fall onto a water collector of the watermill. The transfer of momentum causes the watermill to rotate and in turn bends the piezoelectric cantilevers via magnetic coupling (in non-contact mode), resulting in electricity generation.

The process allows a larger instantaneous driving force on the piezoelectric cantilever than that of direct impact of one single raindrop at one time, which allows electrical operation at a higher efficiency. It has been estimated that the piezoelectric watermill driven by rain water stream from a water tank can yield an average energy densities in the order of 10 W/m³ to 100 W/m³ [56].

5.3. Optimization of Rectifying Efficiency

Although studies indicated that a right interface circuit could increase the energy output of a piezoelectric harvester based on non-damping vibration source e.g. car engine vibration, the suitability and the efficiencies of these circuits [34-48] with energy harvesting based on damping source i.e. water drop impact remain unknown. From the reviewed papers, the interface circuits of all of the water drop energy harvesters were simply resistive loads. Efforts on optimizing the circuit efficiency $\eta_{rectify}$ were only done on finding the optimum load resistance, but studies on interface circuits suggested in [34-48] are still lacking. Therefore, extensive investigations should be made to test the suitability and efficiency for water drop energy harvesters.

5.4. Hybrid System

As the energies available in an environment varies with time, climate, and etc., integrating more than one type of structure or material into one hybrid system so that the more types of energy resources such as raindrops, wind, thermal changes and sun light can be utilized anytime and anywhere has already becoming a new trend in the field of energy harvesting research [57-63, 69]. Electrostatic energy [65-70] of rain or water drop, which is not harvested by the piezoelectric energy harvesters, should also be given consideration. The future direction of hybrid system should be in enhancing the efficiency of the hybrid energy harvester and developing innovative methods to harvest more types of energies within one hybrid system.

6. Conclusions

This paper has done a comprehensive review on various types of raindrop kinetic energy piezoelectric energy harvesters as well as different types of interface circuits. The performance of the harvesters in terms of their conversion efficiency, power output and power density were also discussed.

From the published works, the power output of these piezoelectric harvesters were in the range of μ W, which is only suitable to be used to power some low-power devices in applications where the power requirements are not so demanding, wireless sensor,

for instant. The area power density of the harvesters are very low, even the highest power density, achieved by PVDF bridge-structure [16] was found to be only 0.24 W/m².

The highest energy conversion efficiency was from the PZT cantilever-structure energy harvester [22]. In contrast with the findings [9, 17-18, 20] that bridge-structure and PVDF outperformed cantilever-structure and PZT. However, due to lacking of information of some of the reviewed papers, the harvesters which could potentially have a higher conversion efficiency are still unknown. Therefore, it is still inconclusive on which combinations of piezoelectric material and type of structure that could be joined to become the best system to provide the highest conversion efficiency. More works have to be done to verify this.

Generally, the conversion efficiency is found to be quite low, registering less than 1 %. However, simulation done by Guigon, *et al.* [30] showed that a conversion efficiency of 2.5 % should be achievable. Moreover, the studies of piezoelectric energy harvesting from constant vibration sources [52] indicated that the efficiency as high as 46 % is also attainable.

Optimizing the conversion efficiency and power density can be done by searching of the best piezoelectric material, the transducer shapes and size, and interface circuit to increase energy output and to reduce loss e.g. splash of water drop. Apart from these, innovative methods should be developed to integrate more types of energy harvesters into one hybrid renewable energy system.

The study in piezoelectric energy harvesting from raindrop impact using piezoelectric has proved to be a promising approach, but it is still in its embryonic stage, the field is wide open with many opportunities for research.

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ADVANCES IN SENSORS: REVIEWS 3

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