

# Energy harvesting with piezoelectric materials for IoT - Review

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**Abstract.** The goal of this paper is to review up to date energy harvesting techniques, while focusing on energy harvesting with piezoelectric materials. A classification of various energy harvesting sources is provided in order to properly locate piezoelectricity. Piezoelectric energy harvesting uses the special material property that exists in many single crystalline materials: the direct piezoelectric effect. Those materials are generating electric potential when mechanical stress is applied. There are two types of mechanical stress suitable for piezoelectric energy harvesting: hitting and vibrating. The hitting method involves the direct transfer of energy to piezoelectric modules, so it generates more power than the vibrating method. This kind of energy harvesting is used to drive low energy consuming devices and is suitable for applications where replacement of battery or maintenance is unpractical, like sensors in the human body, for powering portable devices or it can be used for improvement of a smart building concept. If the piezoelectric transducers are placed in the floor of a crowded area or in shoes, it can theoretically generate 4.9 J/Step; therefore, this energy can be used to replace the chargeable batteries. This review is useful for a proper positioning of this type in the IoT broad context and mainly as an alternate energy source for wearables.

## 1. Introduction

Energy harvesting is the process in which energy is derived from external sources and used to drive the machines directly or the energy is captured and stored for future use [1].

A possible classification is:

- Macro energy harvesting, where the energy sources are renewable like solar, wind, tidal, geothermal etc. This type of energy harvesting is used to reduce oil dependency (energy management solution) [1];
- Micro energy harvesting, where sources are small-scale sources like vibration, motion, heat etc. This type of energy harvesting is used to drive low energy consuming devices (ultra-low-power solutions) [1].

Micro energy harvesting is suitable for the concept of smart building, portable electronics, sensors deployed in remote location or inside the human body (including retinal prosthesis, intraocular pressure monitoring, cochlear implants, subcutaneous glucose monitoring and micro-oxygenator [2]). Piezoelectric energy harvesting is a micro energy harvesting solution and is applicable for those applications which demand low-power electronics and sustainable electrical power [3], where the replacement of the battery or maintenance can be challenging or unpractical.

In this decade, energy consumption in the USA has risen to more than quadrillion BTU (British Thermal Unit) per year, with around 41% of this energy consumption coming from buildings in the residential and commercial sectors [4]. So, smart buildings and clean energy harvesting became a necessity in our days. A building that is aware of its occupancy and power consumption, can help in reducing the overall power consumption. However, the increased number of sensors necessary to realize the smart building concept can lead to extra power draw and complexity in wiring. Therefore, a piezoelectric tile would be a major step

toward realizing the smart building concept, or even be used for pedestrian sidewalks in crowded areas.

Compared with electromagnetic and electrostatic methods, energy harvesting with piezoelectric materials provides higher energy density and higher flexibility of being integrated into a system, and thus has been the most widely studied [5].

The piezoelectric effect is a special material property that exists in many single crystalline materials. There are two types of piezoelectric effect:

- The direct piezoelectric effect is derived from materials generating electric potential when mechanical stress is applied [1];
- The inverse piezoelectric effect implies materials deformation when an electric field is applied [1].

By their type of arrangement, the piezoelectric devices can be classified as:

- Cantilever type: is a simple structure used only for low vibration harvesting [6];
- Cymbal type: produces large output and is used only for micro harvesting [6];
- Stack type: can be used for large loads at large scale harvesting [6];
- Shell type: is more efficient than cantilever type and is used only under torsional loads [6].

Piezoelectric materials can be categorized by their structure characteristics: ceramic, single crystals, polymers and composites (the composite material is a combination of piezoelectric ceramics or single crystals with polymers). For energy harvesting a subgroup of piezoelectrics called “ferroelectrics”, e.g. PZT (lead zirconate titanate) and PMN-PT (the solid solution of lead magnesium niobate and lead titanate) is used. Below Curie temperature, those materials possess spontaneous dipoles, which bestows excellent piezoelectric properties. The difference between ferroelectric single crystals, ceramic or composites and piezoelectric polymers is that the first ones have better piezoelectric properties, but polymers have the ability to sustain much higher strain due to their intrinsic flexibility, making them better suited for application where the device will be subjected to large amount of bending or conforming to a curved mounting surface [5].

Kolev et al. [7] define two types of piezoelectric devices: piezoelectric generators (PEG) and flexible PEG. The flexible PEG should fulfil specific requirements such as:

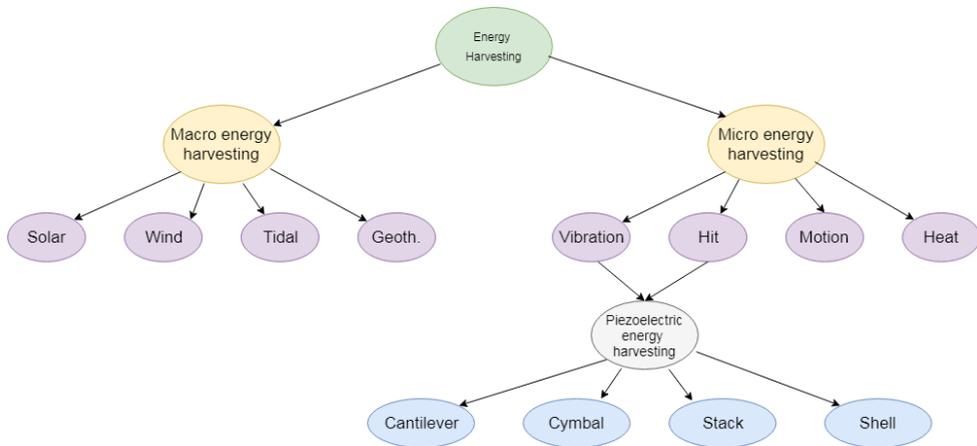
- Ability to follow curves;
- To be light weight and tiny;
- To be able to efficiently convert a deformation into electricity at small activating vibration or forces;
- To be fabricated by low temperature processes, compatible with plastic substrates.

There are two ways of generating power from piezoelectric modules: hitting and vibrating. The hitting method generates more power than the vibrating method because it involves the direct transfer of energy to piezoelectric modules, but it can easily break the modules [8]. Vibrations can be extracted using other methods like inductive or capacitive harvesting, but those require an external voltage source [9].

Applications for piezoelectric energy harvesting:

- Power generating sidewalk: the piezoelectric crystal arrays are laid underneath pavements and the voltage generated can be used to charge the chargeable Lithium batteries [1];
- Power-generating boots or shoes: United States Defense Advance Research Project Agency (DARPA) initiated an innovative project on energy harvesting which attempts to power battlefield equipment by piezoelectric generators embedded in soldiers' boots. However, those energy harvesting sources that put an impact while walking, were abandoned due to the discomfort from additional energy expended by person wearing the shoes [1];

- Gyms and workplaces: machines in the gym can be a source for piezoelectric energy harvesting or at workplaces, energy can be stored in the batteries by laying piezoelectric crystals in the chair [1];
- Mobile keypad and keyboards: the piezoelectric crystals can be laid down under keys of a mobile unit and keyboards, the vibrations created by pressing keys can be used for piezoelectric energy harvesting [1];
- People powered dance clubs: in Europe, certain nightclubs have already begun to power their strobes and stereos by use of piezoelectric crystals [1];
- Energy harvested from the bending of elbow or finger joints and implants in knee joints etc. [8]



**Fig. 1.** Energy harvesting classification

In this paper, an overview of the technologies used for piezoelectric energy harvesting from smart tiles follows.

## 2. Piezoelectric harvested energy balance

In this chapter, it will be analyzed if the piezoelectric energy harvesting can generate enough energy for daily applications.

First, it should be calculated how much energy is needed. The energy consumption for 1 hour of operation of a heart rate meter is 3 J, for respiratory rate meter is also 3 J, for a MP3 player is 350 J, for a mobile phone in standby is 150J and in conversation is 2800 J [10].

According to Rocha et al.[10], vibration-based devices compare well with other potential energy scavenging sources like batteries, fuel cells and solar, temperature and pressure devices, as stressed in Table 1 [11].

**Table 1.** Comparison between portable-energy and power sources [11]

Power Source	Power ( $\mu\text{W}/\text{cm}^3$ )	Energy ( $\text{J}/\text{cm}^3$ )	Power /yr ( $\mu\text{W}/\text{cm}^3/\text{yr}$ )	Need of secondary Storage	Need of Voltage regulation	Commercially available
Primary battery	N/A	2880	90	No	No	Yes
Secondary battery	N/A	1080	34	N/A	No	Yes
Micro fuel cell	N/A	3500	110	Maybe	Maybe	No
Ultra capacitor	$3 \cdot 10^6$	50-100	1.6-3.2	No	Yes	Yes
Heat engine	$10^6$	3346	106	Yes	Yes	No
Radioactive (Ni)	0.54	1.640	0.52	Yes	Yes	No
Solar (outside)	$15000^1$	N/A	N/A	Usually	Maybe	Yes
Solar (inside)	$10^1$	N/A	N/A	Usually	Maybe	Yes
Temperature	$40^{1,2}$	N/A	N/A	Usually	Maybe	Soon
Human power	330	N/A	N/A	Yes	Yes	No
Air flow	$380^3$	N/A	N/A	Yes	Yes	No
Pressure variation	$17^4$	N/A	N/A	Yes	Yes	No
Vibrations	375	N/A	N/A	Yes	Yes	No

- 1 – Measured in power per square centimeter, rather than power per cubic centimeter.
- 2 – Demonstrated from a  $5^\circ\text{C}$  temperature differential.
- 3 – Assumes an air velocity of 5 m/s and 5 percent conversion efficiency.
- 4 – Based on  $1\text{cm}^3$  closed volume of helium undergoing a  $10^\circ\text{C}$  change once a day.

Rocha et al. [10], show that, mathematically, the piezoelectric charge coefficients predict, for small stress levels, the surface charge density originated by external stress. In the charge mode and under conditions approaching a short circuit, the generated charge density is given by

$$D = \frac{Q}{A} = d_{3n} \cdot F_n, n = 1, 2, 3 \tag{1}$$

where  $D$  is the surface charge density developed,  $Q$  is the charge developed,  $A$  is the conductive electrode area,  $d_{3n}$  is the appropriate piezoelectric coefficient for the axis of applied stress, and  $F_n$  is the stress applied in the relevant direction. The mechanical axis  $n$  of applied stress, by convention, is 1 for length direction, 2 for width direction and 3 for thickness direction.

Krinshna and Vignesh [6] have analyzed energy generation in crystal, energy generated in steps, energy stored and discharge time.

Voltage generated in crystal is [6]:

$$E = g_{31} \cdot t \cdot P \tag{2}$$

where  $g_{31}$  is the voltage sensitivity of PZT ( $10 \times 10^{-3}$  Vm),  $t$  is the thickness of one crystal (0.5 mm) and  $P$  is the pressure exerted on the PZT crystal.

The pressure is the force exerted by human walk / area of one crystal. The exerted force by human (at weight of 50 kg) walk is 490.5 N (i.e.  $50 \times 9.81$ ), so the pressure is [6]:

$$P = \frac{490.5}{\pi \cdot 2.5 \cdot 2.5 \cdot 10^{-2} \cdot 10^{-2}} = 0.249 \text{ N/m}^2 \tag{3}$$

Thus, the voltage being generated in theoretical calculation is [6]:

$$E = 10 \cdot 10^{-3} \cdot 0.5 \cdot 10^{-3} \cdot 0.249 \cdot 10^6 = 1.245 \text{ V} \tag{4}$$

The energy generated in steps is [6]:

$$E = 490.5 \cdot 0.01 = 4.9 \text{ J / Step} \tag{5}$$

Since some of them may pass by pressing single foot in rush, the theoretical energy should be calculated by half, so 2.455 J is generated in one foot step [6].

To determine the energy generated in kWh, the following calculations are made [6]:

$$E = 2.455 \text{ J/Step} \cdot (0.240 \text{ m}^2 / 0.01 \text{ m}) \cdot 1 \text{ kWh} / 3.6 \cdot 10^6 \text{ J} = 0.0000164 \text{ kWh} \tag{6}$$

For instance, consider 1000000 people using the floor, the energy generated will be 1.64 kWh/day but the energy storage has some losses in voltage drops.

For energy stored, Krinshna and Vignesh [6] performed an experiment for 1 hour by applying continuous uniform load on the floor setups according to the desired power output. So, for a load of 60 kg, the voltage stored was 0.56 V and the time required to charge a 12 V battery is 21 hours and for a load of 85 kg, the voltage stored was 0.8 V and the time required to charge a 12 V battery is 15 hours.

They also made some calculations of discharge time [6]. Peukertw's law expresses the capacity of a battery in terms of the rate at which it is discharged from former [6]:

$$t = H \cdot \left(\frac{C}{I \cdot H}\right)^k \tag{7}$$

where  $t$  is the time consumed by 30W bulb,  $H = 0.36$  A,  $I = (40 \text{ W} / 12 \text{ V}) = 3.33$  A,  $k=1.44$  for lead acid battery. So,

$$t = 0.36 \cdot \left(\frac{7.2}{3.33 \cdot 0.36}\right)^{1.44} = 4.75 \text{ hours} \tag{8}$$

In the experiment, they discharge the 12 V battery, 7.2 Ah using 40W bulb and the experimental time consumed for the discharge of the battery took 4.5 hours [6].

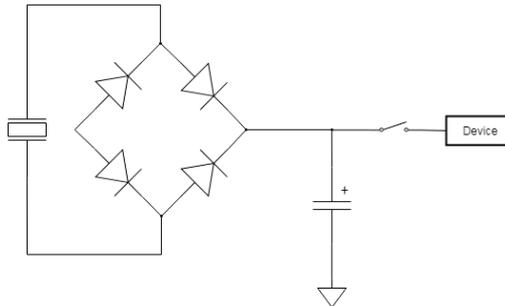
So, the value of  $t$  is 4.75 hours from calculations and in practical experiment is 4.5 hours. Of course, the discharge time depends on the type of equipment used. In table 2, it is shown the charge consumed by electrical equipments in watts and the time taken by 12 V lead acid battery to discharge in hours for different electrical equipments.

**Table 2.** Calculation of discharge time for various electrical equipment [6]

Electrical equipment used	Charge consumed [W]	Discharge time [hours]
Halogen bulb	72	2.04
	53	3.17
	43	4.28
	28	7.94
CFL (Compact Fluorescent)	23	10.54
	20	12.89
	15	19.51
	10	34.98
LED (Led Emitting Diode)	20	12.89
	14	21.55
	12	26.90
	8	48.23

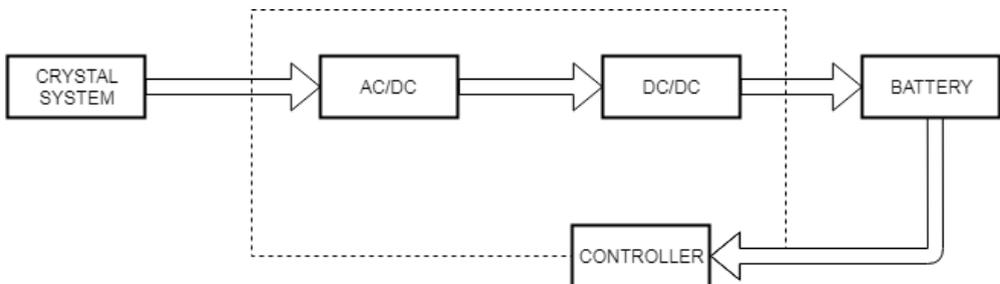
### 3. Electric circuits

There are a few implementations for the electronic circuit of piezoelectric energy harvester. The implementation from Figure 2 [1] use an AC-DC converter (a simple diode rectifier), followed by a storage capacitor which gets charged when the switch is open. When the switch is closed, the capacitor discharges through the device.



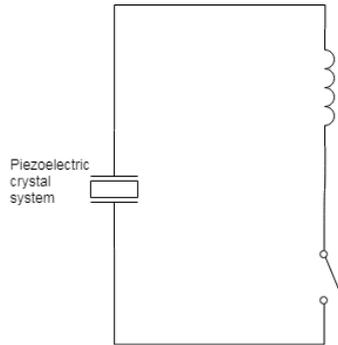
**Fig. 2.** Energy harvesting circuit [1]

The energy harvesting capacity from the circuit from Figure 2 is not appreciable, so Dikshit et al. [1] improved the circuit by adding a DC-DC converter after the bridge rectifier (Figure 3).



**Fig. 3.** Energy harvesting block diagram [1]

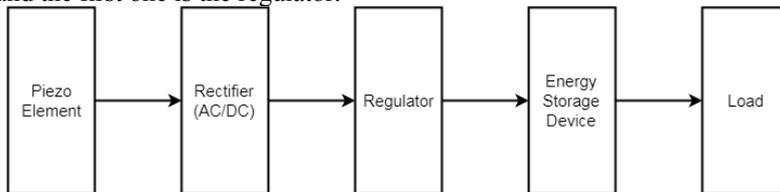
The same authors presented in their article a non-linear processing technique “Synchronized Switch Harvesting on Inductor” (SSHI) [1] – Figure 4.



**Fig. 4.** SSHI [1]

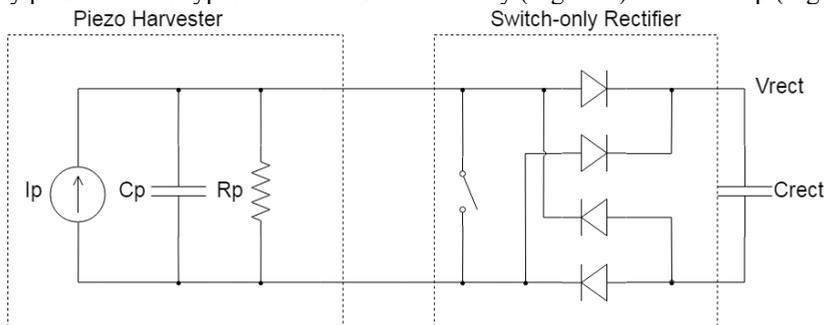
The technique involves a piezoelectric element, a switching device composed of a switch, and an inductor connected in series. When the maximum displacement occurs in the transducer, the switch closes and the capacitance of the piezoelectric element and inductor together constitute an oscillator. When the voltage on the piezoelectric element has been reversed, the switch opens. This technique increases the energy harvesting capacity [1]. The SSHI technique can be combined with “Synchronous Inversion and Charge Extraction” (SECE) technique and the result is “Synchronous Inversion and Charge Extraction” (SICE) interface circuit which can achieve high power gain and is independent of loading impedance [12].

Huidong et al. [5] present another approach (Figure 5). The difference between this concept and the first one is the regulator.

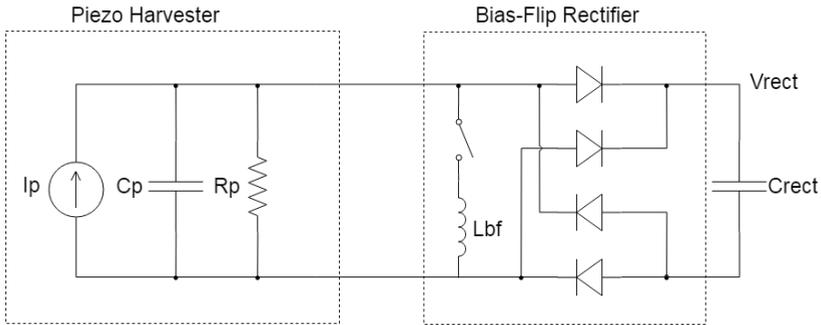


**Fig. 5.** Energy harvesting block diagram [5]

They presented two types of rectifiers: switch-only (Figure 6) and bias-flip (Figure 7).



**Fig. 6.** Piezoelectric harvester and Switch-only Rectifier [5]



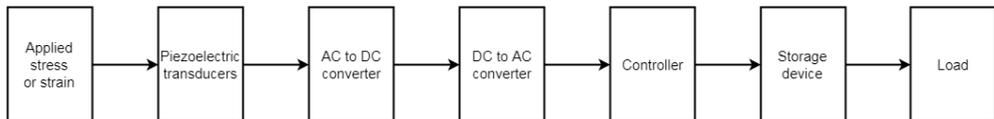
**Fig. 7.** Piezoelectric harvester and Bias-Flip Rectifier [5]

For the switch-only rectifier, the capacitance of the piezoelectric material  $C_p$  is discharged when the switch connected in parallel with the piezoelectric harvester is ON and it is fully charged when the switch is OFF. Such a design enabled the rectifier to utilize both half-cycles of the input current [3]. This circuit provides 2 x power compared to commonly used full-bridge rectifiers, but almost a half of the charge is lost during every half-cycle.

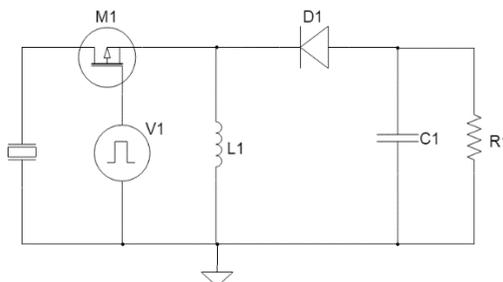
The bias-flip rectifier has an inductor in series with the switch, which can store the energy with external magnetic field and flip the voltage across the piezoelectric element, making it unnecessary to fully discharge  $C_p$  before it could be charged again. The switch is turned ON when the direction of  $I_p$  is changed and turned OFF when the current in the inductor is zero [3]. This circuit provides more than 4 x power than a traditional full-bridge rectifier.

After rectification, the voltage generated from the piezoelectric element needs to be regulated for the external load. The authors presented a few types of voltage regulators [5]. The first type is a step-down converter which regulates high inputs voltages to low output voltages. A commercial example of a step-down converter is LTC1474 from LT. Here the capacitor reached a preset value, it discharge into the step-down converter providing a stabilized output voltage for the load circuit. Another type of voltage regulator presented is an offline forward-switching converter which has a much higher efficiency than the linear regulators when the difference between input and output voltage is large.

Mostafa et al. [13] present another approach (Figure 8 and Figure 9).



**Fig. 8.** Block diagram for energy harvesting [13]



**Fig. 9.** Piezoelectric energy harvesting circuit [13]

A basic converter (Buck-Boost converter) needs a MOSFET switch, a diode and an inductor. For temporary storage and to reduce the ripple, a capacitor is used. A PWM signal controls the MOSFET switch. The circuit is design to convert the voltage either higher or lower than input voltage depending on duty cycle. If the duty cycle is between 1% and 50%, the output is less than the input voltage [13].

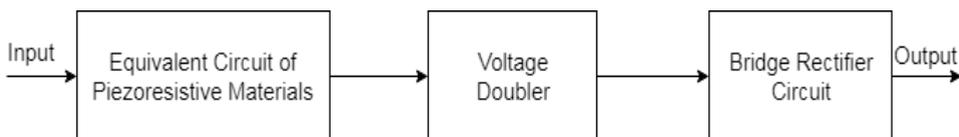
The input and output voltage relationship is:

$$V_{out} = \frac{D}{1 - D} \cdot V_{in} \tag{9}$$

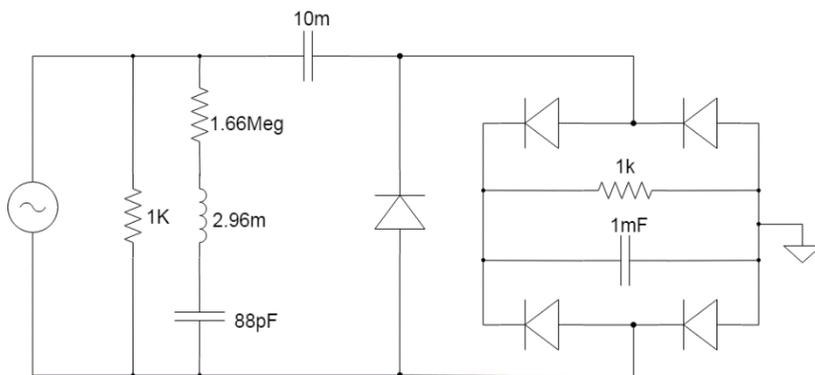
where  $D$  is the duty cycle,  $V_{out}$  is the output voltage and  $V_{in}$  is the input voltage.

When the switch is ON, the inductor (L1) is charging, while when the switch is OFF, the inductor starts discharging energy to the storage capacitor (C1).

Chowdhury et al. [14] use another approach of piezoelectric energy harvesting. Theirs concept is presented in Figure 10 and Figure 11.



**Fig. 10.** Piezoelectric energy harvesting block diagram



**Fig. 11.** Piezoelectric energy harvesting electronic circuit

The piezoelectric element was represented electrically as a current source in parallel with a capacitor, inductor and resistor. The current source (represented by a voltage source in parallel with a resistor) provides current proportional to the input vibration amplitude. The output of the piezoelectric device needs to be rectified before it can be used to power circuits. Full-bridge rectifiers and voltage doublers are commonly used as rectifier circuits to convert the AC output of a piezoelectric harvester into a DC voltage [14].

If the input voltage is a 10 V sine wave, the voltage doubler rises the output of the first stage to almost 20V in the next stage. Then the full wave bridge converts the doubled sine wave into an almost DC voltage of 17 V and this voltage is used to charge the battery [14].

## 4. Optimization

The output voltage obtained from a single piezoelectric crystal is in the millivolts range, while the power is in the microwatt range. In order to achieve higher voltages, some authors recommend arranging the piezoelectric crystals in series [1], but most of the authors recommend a parallel connection. A parallel connection scheme provides a higher output current and a lower impedance to better match the impedance of electrical devices [5].

The output voltage of a piezoelectric energy harvesting system depends on the type of crystal used. In Table 3 [5] are presented some piezoelectric materials with different dimensions and their output power generated by different force.

Table 3 specifies that the piezoelectric ceramics provide a higher power output than others materials, but are less capable of sustaining large strain, while the piezoelectric polymers provide the smallest power output, but have the biggest flexibility and smallest coupling coefficients. The piezoelectric single crystals have better power density than the other piezoelectric materials, but they are very expensive. If our application uses PZT ceramics at low frequency, we need a large PZT element or a large excitation (PZT ceramic-based harvesters are normally used at 50 Hz or higher). Because piezoelectric polymers are flexible, they respond faster than the other piezoelectric materials, so can be used in very low frequency applications (<10 Hz).

**Table 3.** Some piezoelectric energy harvesters and their performances [5]

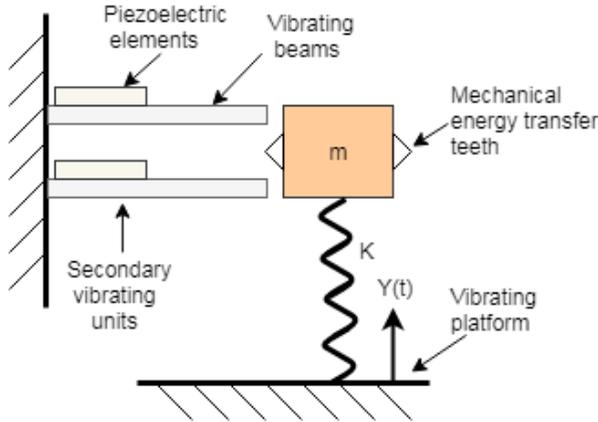
Material type	Peak power [ $\mu$ W]	Volume	Frequency [Hz]	Excitation (acceleration, force or pressure)
PVDF	2	28 modules of 16.5 x 9.5 x 0.15 cm <sup>3</sup> film	2	0.1 or 0.2 G
PVDF	0.0005	30 x 12 x 0.005 mm <sup>3</sup>	2	3-point bending at 3 N
PVDF	610	72 x 16 x 0.41 mm <sup>3</sup>	3	Wind speed of 4 m/s
PVDF	2.75	10.94 x 22 x 0.354 mm <sup>3</sup>	104	1 G
PVDF	2	20 x 16.1 x 0.2 mm <sup>3</sup>	146	Acoustic pressure: 9 Pa
PZT ceramic	47	25 x 10 x 0.8 mm <sup>3</sup> bimorph	1	Shook by hand, Ball hits piezo beams
PZT ceramic	265	1 x 1 x 2 cm <sup>3</sup>	1	900 N
PZT ceramic	2000	45 x 20 x 0.3 mm <sup>3</sup>	20	1 N
PZT ceramic	40	31.8 x 6.4 x 0.3 mm <sup>3</sup>	36	0.2 G
PZT ceramic	30000	63.5 x 60.3 x 0.27 mm <sup>3</sup>	50	
PZT ceramic	39000	1 cm <sup>3</sup>	100	7.8 N
PZT ceramic	52000	1.5 cm <sup>3</sup>	100	70 N
PZT ceramic	60	1 cm <sup>3</sup>	100	0.23 G
PZT ceramic		1 cm <sup>3</sup>	120	0.25 G
PZT ceramic	1800		2580	2 G

PZT ceramic	144	90.4 x 14.5 x 0.79 mm <sup>3</sup>	2.5	
PZT fiber	750		180	
PZT fiber	120000	2.2 cm <sup>3</sup>		Dropping a 33.5 g steel ball from 10 cm
PMN-PZT single crystal	14.7	20 x 5 x 0.5 mm <sup>3</sup>	1744	
PMN-PT single crystal	3700	25 x 5 x 1 mm <sup>3</sup>	102	3.2 G
PMN-PT single crystal	6.7	1.7 x 1.7 x 0.00084 cm <sup>3</sup>	0.3	Bending motion at a strain of 0.36 %

The output energy also depends on number of transducers used. If it is used a large number of transducers, the more potential there is for energy to be harvested before the transducers become overloaded, but it decreases the sensitivity of the tile, or the amount of energy produced per load. Therefore, it is an optimum number of transducers to be employed for maximum energy harvesting from a target weight [4]. Sharpes et al. [4] have found that for a child (32 kg) the optimum number of transducers is 4, for an average adult (82 kg) is 8 transducers and for a 115 kg adult, the optimum number is 14 transducers. However, a tile optimized for a child can make more energy per step at low weights, but has a much lower maximum possible energy production compared to a tile optimized for an adult [4]. Another observation in their article is that after a certain minimum weight, the floor tile will produce a constant amount of energy per step, regardless of the load [4].

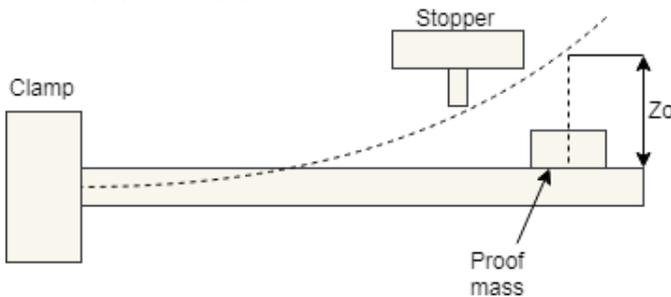
The efficiency of the piezoelectric element can be improved by matching the resonance frequency ( $f_r$ ) of the piezoelectric energy harvester with the input frequency ( $f_i$ ). There are three ways to do that: lowering  $f_r$  towards  $f_i$ , up-converting  $f_i$  and broadening the bandwidth of the harvester [5].

- The most frequently method for lowering  $f_r$  towards  $f_i$  is the use of a proof mass, which can be attached to the free end of a piezoelectric cantilever, the center of a piezoelectric diaphragm or two-point-supported beam.
- For up-converting  $f_i$ , Li et al. mentioned two methods:
  - i) The first one implies a design (Figure 12 [5]) where the spring-mass system is the primary vibrating system, responding at the input frequency of the host structure and the secondary system is an array of piezoelectric cantilevers that harvests the mechanical energy. As the mass vibrates, the mechanical energy transferring teeth hit and leave the piezoelectric cantilever periodically, causing them to vibrate at their natural resonance frequency [5].



**Fig. 12.** System for up-converting  $f_i$

- ii) The second method involve a cantilever that carries a coil for electromagnetic power generation and has a magnetic tip and two magnets. One of them is at the top of the housing of the device as the upper resonator, which vibrates with the host structure, and the other is positioned near the magnetic tip of the cantilever to interact with the coil for energy conversion. The top magnet catches the cantilever at a certain point of its vibration and the releases it at another point. After the release, the cantilever would start resonating at its own resonance frequency, which is higher than the vibration frequency of the host structure [5].
- To broaden the bandwidth of the system, a stopper carried by a slider that is positioned above the cantilever beam and close to the proof mass can be used (Figure 13 [5]). As the cantilever beam oscillates at amplitude greater than  $Z_0$ , it engages the stopper and the contact point becomes a new fixed point of the beam, which gives the portion of the beam beyond this point a higher effective stiffness than that of the rest of the beam, thus extending the resonance over a wider span of the frequency spectrum [5].



**Fig. 13.** System for broadening the bandwidth

If the application needs a large bandwidth, the energy harvesting technique should combine two methods: piezoelectric and electromagnetic. The system consists of a flexible strip, over which the piezoelectric crystals are mounted and at one end of the strip, a magnet is mounted inside a stationary coil. When the intensity of vibration is high, the source is piezoelectric and when the intensity of vibration is small, the magnet moves inside the stationary coil. This motion generate an electromagnetic flux and the output voltage is obtained [1]. Ziniu et al. [15] demonstrate that the beginning frequency of the lowest bang

gap can be reduced by increasing the length of resonators, while broadening band gaps are reduced by rising the filling ratio of the piezoelectric patches.

## 5. Conclusion

Nowadays, the need for development of energy harvesting system is evident; furthermore, the development of piezoelectric energy harvesting is essential because it can be used in places where changing the battery or maintenance can be difficult. Using piezoelectric devices in floor tiles, we can barely generate 16.4  $\mu\text{Wh}/\text{step}$ , but thinking on a large scale, it can power low energy consuming devices if the system is installed in crowded areas. In this article, different configurations of electronic circuits and optimization methods were presented, thus the piezoelectric devices can be used in a wide range of applications.

This paper compares different piezoelectric energy harvesting systems both in terms of the circuit configuration and the materials used. It is an alignment of concerns, achievements and trends in the field.

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