

Chapter 2

Hybrid Energy Harvesters (HEHs)—A Review

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Abstract In this millennium, the methodologies to harvest existing dissipated powers not only supply input energy to our sophisticated devices, but also contribute the current technological researches and developments. Single harvester generator or harvesting single power source may remain insufficient for the energy feed into the systems like electronic devices, biosensors, human, structural and machine health monitoring, and wireless sensor nodes. To overcome this problem, hybridization of energy harvesters (EHs) takes place to increase the limited energy generation of stand-alone EHs. In this chapter, piezoelectric and electromagnetic generators are compared and classic as well as novel hybrid energy harvester (HEH) designs are reviewed by considering fixed-frequency; broadband including linear, nonlinear and tunable HEHs; multimode; and multisource powered configurations. This review covers two-, three-, four-multi source powered HEHs in micro-, meso- and large-scales. Overall comparisons of classic and novel HEHs are tabulated and discussed in detail in order to guide potential researchers. In the scope of this

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chapter review, it is seen that HEHs generate greater power outputs than its single harvester components. The most promising power and energy generations are 315 mW by four-source powered novel HEH in meso-scale, 215 μ W by tunable broadband classic HEH in microscale and 440 kW h/day by partially three-source powered HEH in large scale. This chapter indicates that HEHs not only increase the output powers and power densities, but also enables endless configurations to maximize harnessing existing power sources.

Keywords Hybrid energy harvesting • Multimode energy harvesting • Multisource energy harvesting • Novel energy harvesters • Microscale energy harvesting • Large-scale energy harvesting

Abbreviation and Acronyms

A-Si	Amorphous Silicon
AGS	Automatic Generating System
DPE	Direct Piezoelectric Effect
EM	Electromagnetic
EMHs	Electromagnetic Energy Harvesters
EHing	Energy Harvesting
HAWT	Horizontal Axis Wind Turbine
HEHs	Hybrid Energy Harvesters
HRTHs	Hybrid Rotary-Translational Harvesters
MEMs	Microelectromechanical Systems
PAGV	Power Augmentation Guide Vane
PE	Piezoelectric
PEHs	Piezoelectric Energy Harvesters
PET	Polyethylene Terephthalate
PV	Photo-voltaic
PZT	Lead Zirconate Titanate
RF	Radio Frequency
SME	Shape Memory Effect
TENG	Triboelectric Nanogenerator
VAWT	Vertical Axis Wind Turbine
WiSH	Wind-Solar Hybrid

2.1 Introduction

Ever since the beginning of the industrial age, being independent from man and animal power sources, especially at greater energy levels, was the greatest innovation. As the time passes by, the more technological improvements occur along

with wireless networks, the more devices are in our lives thus, elevating the quality of life, production and work. In spite of the efforts to decrease the energy input of the electronic devices, this ever increasing demand on energy surprisingly takes us to seek using existing power sources like human movement, known as kinesiology, similar to the energy source before industrial age [1–3]. In this millennium, the methodologies to harvest existing dissipated powers not only supply input energy to our sophisticated devices, but also contribute the current technological researches and developments. Among energy harvesting (EHing) systems, one of the innovative research trend is on hybrid energy harvesters [4, 5].

Obeying the first law of thermodynamics, conservation of energy implies that the existing and dissipated power sources can be scavenged and transduce into usable electrical energy [1]. Up until recently, energy harvester (EH) need is arose by the dominant use of electronic devices, biosensors, human, structural and machine health monitoring, and wireless sensor nodes [6–9]. Single harvester generator or harvesting single power source, also known as stand-alone EH, may produce low output powers to supply energy to the system. For sufficient energy feed to these vast varieties of applications, hybridization of EHs takes place to increase the limited energy generation of stand-alone EHs [10–23].

Harnessing multiple power sources or combining multiple generators for energy extraction in a single unit is called “hybrid energy harvesting or multimodal energy harvesting” [24–27].

In this chapter, piezoelectric (PE) and electromagnetic (EM) generators are compared in Sect. 2.2. Classic HEH designs and novel configurations are reviewed in Sects. 2.3 and 2.4, respectively. Sections 2.3 and 2.4 covers fixed-frequency, broadband HEHs, and their comparisons. Furthermore, Sect. 2.4 includes multi-mode vibration HEHs and multisource powered energy harvesters along with meso-, micro- and large-scale applications. In the final part, HEH performances and evaluations are compared and concluded.

2.2 Comparison of Piezoelectric and Electromagnetic Generators

EM energy harvesters (EMHs) generate power based on faraday’s law of induction, which equates the time derivative of flux to the electromotive force. As the scale shrinks to microscopic level, the decreased coil area results smaller magnetic flux. On the other hand, quasi-static (ultra-low-frequency) movements increase the time intervals. Thus, both factors lead electromotive force to approach to zero. Apart from the fabrication boundaries of coil diameters and turns, theoretically EM harvesters are bound to be limited at low speeds [28]. Thus, EM harvesters perform better at high frequencies and PE harvesters outperform at low frequencies [8]. Additionally, at microscale level, EMH output voltage generally stays lower than the need to power devices [17]. As a result, piezoelectric and electrostatic harvesters

are more suitable for microscale applications, while electrostatic systems hold greater advantage due to the ease of integration to microelectromechanical systems (MEMs) [27].

Similar to EMHs, PE harvesters (PEHs) do not require voltage source while electrostatic generators require separate voltage source and more difficult in practice, and in contrast to EMHs, PEHs produce sufficient output voltage but at low current level [8, 19, 27]. Among these three types of transducers, piezoelectric generators are the simplest ones in terms of required components, transducer geometries and directly converting mechanical energy to voltage output [9]. In addition to PEHs, at macroscopic level, EMHs also provide simplicity in geometry, design and production [19].

In conclusion, PEHs are applicable for micro-, meso- and large-scales, while EMHs are easily manufactured and although they perform better at mesoscale, they are integrable to MEMs. As a result, abundant PE and EM HEH are reviewed and compared in the following sections.

2.3 Classic HEH Systems

While tremendous amounts of multimode energy harvesters (EHs) are possible, there exist such PE and EM combination that takes the greatest research and development interest and turns out to be classic. As listed in Fig. 2.1, these are composed of piezoelectric plate or patch attachment on Euler-Bernoulli beam and either magnetic or coil tip mass is surrounded by respective coil or magnets to achieve faraday law of induction [29].

In this chapter, PE unimorph and bimorph structures; comparison of rectangular and trapezoidal beams; four and two poles magnet configurations and comparisons; serial, parallel and isolated connections of PE and EM transducers in HEHs; fixed-frequency applications; and rarely studied broadband HEH designs are reviewed.

2.3.1 Fixed-Frequency Classic HEHs

Figures 2.1 and 2.2 shows the classic HEH designs and fabrications, respectively. As a brief summary, in 2008, Wischke and Woias researched PE layers on unimorph and bimorph cantilevers with rectangular and trapezoidal layouts in HEH. It is seen that trapezoidal shape is not superior in terms of power generation and its fabrication is more complicated. Since unimorph HEH has greater tip velocity, EM transducer generates greater power. In contrast to unimorph design, bimorph PE part produces greater output than EM part. Upon this contrary output, authors suggest using greater tip mass (magnet) to reduce EM coupling [11]. Becker et al.

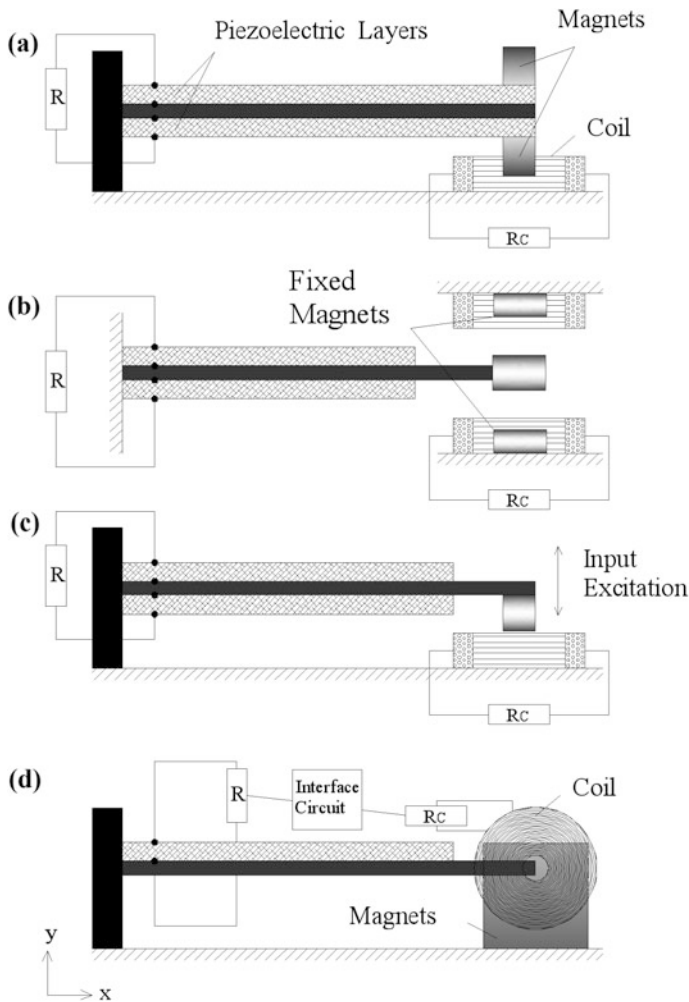
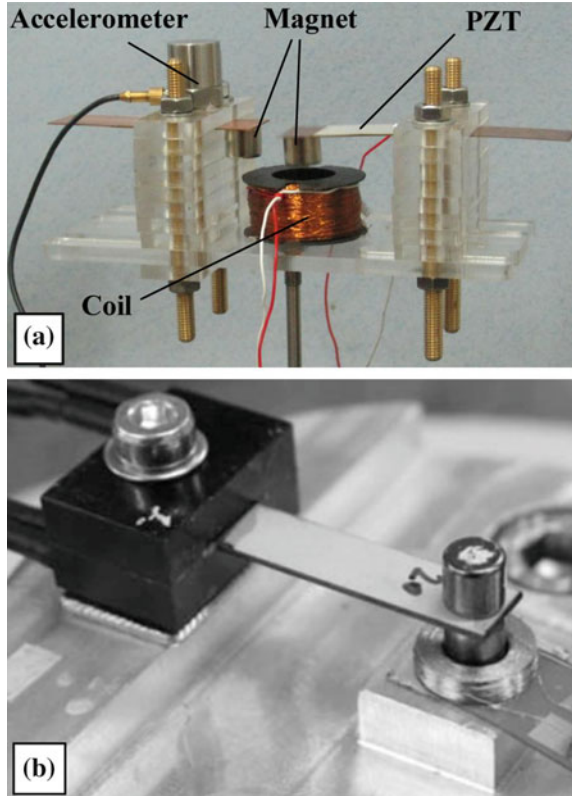


Fig. 2.1 Classic energy HEH configurations are categorized and illustrated. **a** [20, 25, 26, 33–36] and **c** [30, 32, 37] are the most common ones and the tip mass can either be two magnets as in **(a)**, or single magnet surrounded by coils as in **(b)** [4, 15] and **(c)**, or vertical coil surrounded by magnets as in **(d)** [20, 33, 38] as well as modified horizontal arrangement [21]. Along with varying PE length on beam, PE unimorph **(d)** and bimorph **(a, b and c)** cantilever configurations are also possible [11]. Interface circuit is schematically indicated on **(d)**

begin to test HEH prototype in Fig. 2.1c and research further for its adaptation into synchronized switch harvesting interface [30].

Xu et al., both theoretically and experimentally analyzed PE and EM HEH. Theoretical optimum output power is 1.02 mW at 77.8 Hz and experimental value is 0.845 mW at the resonance frequency of 66 Hz under the vibration acceleration of 9.8 m/s^2 . Respective to single PE and EM transducer, output powers are 667 and

Fig. 2.2 Classic HEH prototypes in test setup [25, 39, 40]

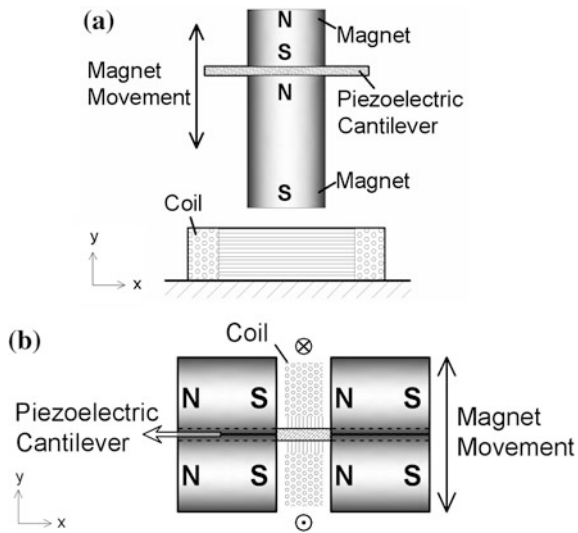


0.32 mW at 9.8 m/s^2 and 66 Hz. Xu et al. proves that presented HEH generates greater power than single EHs [31].

Ali et al., investigated total power outputs of PE and EM harvesters in serial, parallel connection and separately. As seen in Fig. 2.1c, the HEH has approximately 1000 turns and 4 magnets ($25 \times 10 \times 5 \text{ mm}^3$) with opposite polarization at cantilever tip. At the fixed input frequency of 76.2 Hz, total generated power is the highest when PE and EM transducers are isolated. While PEH generates 27.56 mW, EMH generates the lowest power output. Besides, single PEH output power is 3 times greater than serial connected HEH and parallel connected HEH generates 3 times more than single EM transducer [32].

As a recent study, Xia et al. not only investigates the classic HEH but also compared the performances of HEH and EMH (Fig. 2.1c). Throughout the experiments best HEH case generated the output power of 2.26 mW with 41% efficiency at 23.3 Hz and 0.4 g input excitation and thus, greater performance compared to EMH alone. HEH not only owns greater output power and efficiency, but also enables broadband operation [33]. In contrast to these findings, Sang and Shan et al. experiments result that HEH has the almost the same resonance frequency with the PEH. Sang et al., considered the valuable Classic HEH

Fig. 2.3 **a** Two-pole and **b** four-pole magnet arrangements on classic HEH designs [20, 34]



configurations and yet, similar to Fig. 2.1c with only difference of having vertical coil placement on both sides of magnet is researched for four different cantilever lengths. HEH with cantilever and PE layer respective sizes of $50 \times 15 \times 1 \text{ mm}^3$ and $30 \times 15 \times 0.5 \text{ mm}^3$, generated 10.7 mW while EM alone was 5.9 mW at 50 Hz with the acceleration of 0.4 g [21]. Supportively, Shan et al. also reported that HEH produced greater output power of 4.25 mW than single PEH of 3.75 mW at 40.5 Hz and optimum loads. Their design is slightly modified version of Fig. 2.1c, d. The U-shaped magnet cage is fixed at the beam end and coil was fixed filling the gap in U-shaped magnets during vibration [16].

Ab Rahman et al. studied two and four pole magnet arrangements on classic HEH in Fig. 2.1a, d, respectively (see Fig. 2.3). It is experimentally proved that each HEH transducer with four-pole magnets produce greater output voltage than two pole HEH. When the input excitation is 1 g, generated output powers of four pole type PE and EM parts were 2.3 and 3.5 mW at 15 Hz, whereas those outputs were 0.5 and 1 mW at 49 Hz for two pole HEH [20, 34]. More detailed comparison of four-, two- and single magnet novel HEH performances are studied by Castagnetti and covered in Sect. 2.4.2 [35].

2.3.2 Broadband Classic HEHs

The ever-demanded ideal EH efficiently performs in wide bandwidth. In order to satisfy this demand, many researches have been conducted and broadband EHing is still one of the popular EHing research subjects. These researches include passive tuning either manually or with linear, non-linear, multi-stable and band-pass harvester structures; and active tuning which may result in negative power outputs due

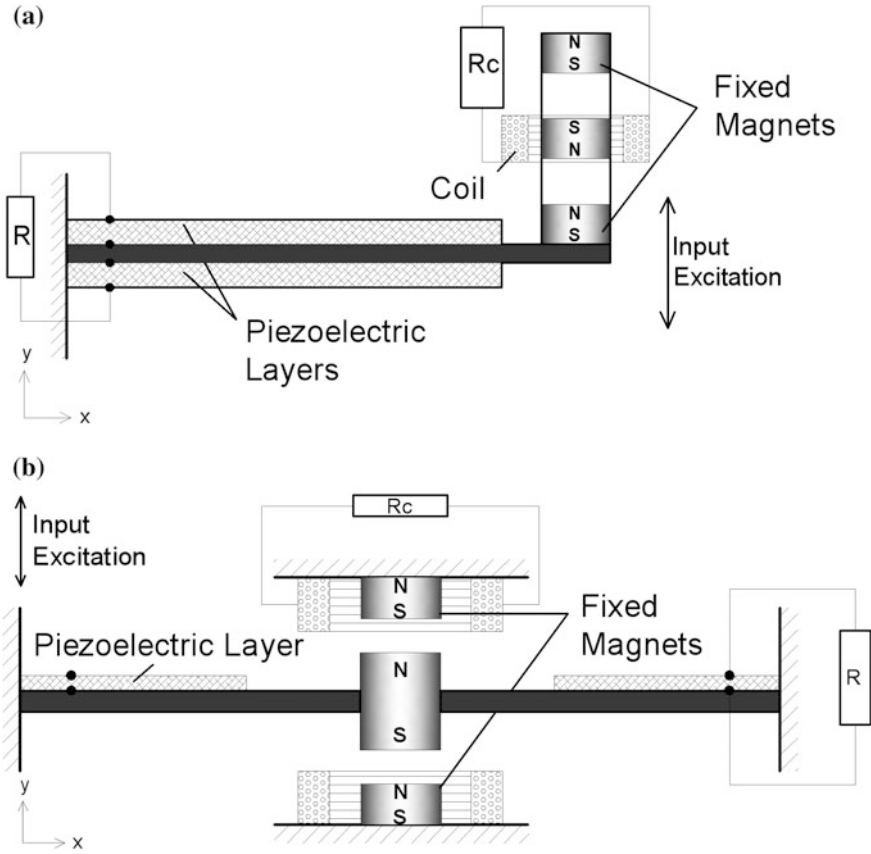


Fig. 2.4 **a** Shan et al. [15] and **b** Ping Li et al. [4] broadband HEH. NdFe35 magnet and PZT-5H ceramics are used as EM and PE transducer components on Shan et al. prototype. Mahmoudi et al. used oppositely aligned magnets and unimorph PE layers in **(b)** configuration [29]

to consumed energy by active parts and advanced electronic networks [26, 36, 37]. Among these efforts, there are some classic HEH design approaches exist. Operation of an EH within wider frequency band is a very significant advantage in EHs. A few studied novel micro scale HEHs are also mentioned in this section for being broadband.

Linear Classic HEH: In 2013, Ping Li et al. designed similar to Fig. 2.4b without fixed magnets. They analyzed their linear HEH performance under white noise excitement to model random vibration. Their sensitivity analysis indicated that the power generation of HEH dominantly affected by vibration frequency, damping ratio, coupling coefficients, which widens the bandwidth and increase power output as increases, and load resistances to achieve HEH impedance matching and maximize power generation. While PE load directly proportional to resonance

frequency of harvester, EM load has almost no effect. The most efficient performances have the mean power levels of 0.44, 1.93, 4.2 mW at 77.5 Hz [17, 38].

Tunable Classic HEH: Wischke et al. focused on frequency tuning method for HEH exactly shown in Fig. 2.1a and the picture of the prototype is on the in Fig. 2.2a. In this technique, voltage is introduced to the PE layer. Applied voltage changes the stiffness of the generator and relatedly, resonance frequency. By matching input frequency with tuned generator's resonance frequency, broadband operation is achieved. Electrode length's effect on tunability is also investigated and found that greater than 10 mm PE beam length, tunable range almost saturates between ~ 50 to 60 Hz. To investigate widest tunable range, fabricated HEH cantilever length was 20 mm with the width of 5 mm. Extractable output powers from EM part is 60 μ W, for PE part with parallel connection is around 200 μ W and with serial connection it is 215 μ W. EM transducer generated minimum of 50 μ W at 56 Hz wide operation band width around the range of 267–323 Hz [25, 39].

Non-linear Classic HEHs: One method to achieve broadband operation is that harvester to be nonlinear so that the frequency response range between half power outputs can be widen [35]. Li et al. summarized nonlinear broadband mechanism such that as nonlinearity increases, resonance frequency decreases and as the acceleration increases, half power bandwidth broadens, whereas resonance frequency decreases [4].

As inspired from classic HEHs in Fig. 2.1b and c, Shan et al. design and materials are illustrated in Fig. 2.4a. In magnet configuration, poles are oppositely aligned so that indirectly exerted force on the suspended magnet can yield nonlinear mono-stable HEH [15]. Two peak powers and modes of HEH are 11.4 mW at 8.373 Hz by EM and 21.6 mW at 14.83 Hz by PE transducers. At half peak power, the device band is around 7–17 Hz [15].

In Addition to HEH in Fig. 2.1c, Xu et al. used same pole magnet aligned in front of the tip magnet (Fig. 2.2a) so that HEH can be nonlinear and operate at larger frequency band. Their nonlinear HEH prototype achieved 5.66 mW power output at 1 g, this result is 247% greater than at 0.5 g and at half power level (3 dB), the frequency band is 83.3% wider than PE transducer alone [40].

Recently, HEH illustrated in Fig. 2.4b is researched by Mahmoudi et al. [29] and Ping Li et al. [4]. Their device mirrors the configuration in Fig. 2.1b; opposite pole magnet arrangement is used by Mahmoudi et al. and same pole magnet arrangement is used by Ping Li et al. While the moving magnet is shared with both symmetrically placed beams having bimorph PE layers by Mahmoudi et al. and lead zirconate titanate (PZT) patches by Ping Li et al. For Mahmoudi et al. HEH, EM and PE parts respectively produce 39 and 61% of the power output. This EM transducer can increase power density by 60% up to 1035 mW/cm³ and bandwidth by 29% (155 to 220 Hz) at 0.9 g with respect to single EMHs [29]. Ping Li et al. deeply studied modeling, tests, effects of nonlinear factors, loads, input frequency and acceleration on amplitude, and found that their HEH design both enhance as wider band with low resonance frequency and greater power output compared to linear HEH designs. In contrast to linear EHs, optimal loads differ with excitation

acceleration. Apart from Ping Li et al. statement, their theoretical and experimental frequency responses show no significant band widening other than shifting the linear resonance frequency from 119 down to 113.5 Hz. Experimental analysis optimum results with respect to input accelerations of 0.2 and 0.45 g are 0.14 and 1.19 mW for EM generator and 0.085 and 0.5 mW for PE generator. The HEH peak power output is 3.6 mW at 0.6 g and ~ 110 Hz having half-power frequency range of ~ 107.5 to 112.5 Hz [4].

As a different vibration source and application on airflow harvesting system example, hybrid aeroelastic vibration EH is modeled by Dias et al. Their system includes an airfoil that is connected to fixed spring and damper at around mid-plane and starting that point, cantilever beam as seen in Fig. 2.1c is connected. Dias et al. propose 2 and 3 degree of freedom system dynamic modeling [41, 42]. Relatedly, novel aeroelastic HEH harvesting incident sunlight is proposed by Chatterjee and Bryant (Fig. 2.16), and their research is covered in Sect. 2.4.3.2. under ‘Two-Multi Source Powered HEHs’ title.

2.3.3 Overall Classic HEHs Comparison

Up to this end, classic HEHs are classified and their performances are reviewed in terms of generated powers by EM and PE parts as well as the whole HEH system. The important factors of classic HEHs are peak power generations, HEH volumes, magnet masses, input excitations, input frequencies and half power band width ranges. Comparison of reviewed performances in Sects. 2.3.1 and 2.3.2, regarding mentioned factors are listed in Table 2.1.

As seen in Table 2.1, among broadband and the whole classic HEHs, the greatest power output of total of 33 mW (21.6 mW by PEH and 11.4 mW by EMH) is achieved by Shan et al. with HEH configuration as illustrated in Fig. 2.4a [15]. Among fixed-frequency HEHs, Ali et al. reached the greatest power output of 27.56 mW [32]. It is then followed by 10.7 mW via Sang et al. HEH [21], both of HEHs share the similar configuration as in Fig. 2.1c, Sang et al. HEH has almost the half device volume of Ali et al. HEH as well as applying below half of the input excitation.

Shan et al. [16] and Ab Rahman et al. [20, 34] HEHs are around similar power generation levels of 4.25, 5.7 and 5.8 mW, respectively. For broadband HEHs to achieve similar power levels, the device volume expands approximately ten times with and exception of Xu et al. nonlinear HEH (Fig. 2.1a) having almost the same device volume with Ab Rahman et al. HEH [40]. Table 2.1 also indicates that four-pole arrangements [20, 34] are always superior to Ab Rahman et al. two-pole arrangement [20].

Finally, the lowest power outputs belongs to Xu et al. [31] and Wischke et al. (Fig. 2.2b) [25, 39]. However, Xu et al. fixed-band HEH volume is also the smallest device volume in Table 2.1, whereas Wischke et al. tunable HEH owns the second biggest device volume.

Table 2.1 The overall comparison of the reviewed classic HEH systems in Sects. 2.3.1 and 2.3.2

Type	References	Input acc.	Input frequency/bandwidth range (Hz)	Volume (mm ³)	Peak power (mW)	Mass (g)
<i>Fixed-frequency classic HEHs</i>						
	[30]	–	130	–	–	–
	[31]	1 g	66	187.2	0.845	–
	[32]	1 g	76.2	5992	PEH:27.56	–
	[33]	0.4 g	23.3		2.26	11
	[21]	0.4 g	50	2975	10.7	~ 15
	[16]	–	40.5	760	4.25	~ 21.5
Four-pole	[34]	1 g	15	2280	PEH: 2.2 EMH: 3.5	–
Four-pole	[20]	1 g	15	2280	PEH: 2.3 EMH: 3.5	–
Two-pole	[20]	1 g	49	1181	PEH: 1 EMH: 0.5	–
<i>Broadband classic HEHs</i>						
Linear	[17, 38]	A*	77.5/~ 70–80	29,810	4.2	–
Tunable	[25, 39]	1 g	299/~ 267–323	31,201	215 μW	–
Nonlinear	[15]	0.5 g	8.373 for EM 14.83 for PE/7–17	20,726	PEH: 21.6 EMH: 11.4	100
Nonlinear	[40]	1 g	~ 45.5/~ 43–47	2257	5.66	9.8
Nonlinear	[29]	0.9 g	93/155–220	40,000	B**	–
Nonlinear	[4]	0.6 g	110/~ 107.5–112.5	18,437	3.6	–

(*) **A**: random acceleration with (0.1 g)²/Hz spectral density of acceleration
(**) **B**: Peak power density of 1035 mW/cm³
Note: Device volumes represent the minimum volume occupied by the harvester components and do not include and remaining device parts and the air gaps in HEHs, and Mass generally stands for the only stated magnet mass in references

2.4 Novel HEH Systems

While stand-alone systems are generally bound to be limited by one power source, multimode designs offer never-ending possibilities. Especially, when multi-source powered EHing concept is included as well as multimode HEHs, designs turn out to be novel. In this section, vibrational HEH novel designs are covered along with multiple vibration source harvesting, two and three multi-source powered harvesting systems in meso, micro and large scales.

2.4.1 Fixed-Frequency Single-Source Powered HEHs

As a preliminary study, Reuschel et al. proposed axial flux and radial flux arrangements, where set of opposite pole magnets aligned radially in a radial coil house, designing EMH and PE cantilever modeling for the proposed arrangements. They announce to combine both transducers and analyze HEH as a whole system [43].

Harvesting from human motion is a demanded research subject especially to power personal electronics. Wei and Ramasamy studied harvesting kinesiology and it is shown that the HEH is suitable to feed personal electronics and charged mobile phone in experiments. The mechanical harvesting part composed of flywheel and in each footfall, it runs the shaft connected to one-third of diameter of the actual wheel. Two piezoelectric configurations researched for shoe insole and it is seen that rolled piezoelectric plate is placed in shoe sole. It is seen that though this HEH is slow to charge mobile phone for being able to charge about 10% in 30 min, it is also found that starting from half-fully charged phone. The user can end up with 70% of charge with HEH, whereas without any harvester, charge level would be 16%. Authors assume the potential over one-million personal usages of their harvester. In this case, they foreseen the total power generation of 60,000 kW h [1].

Halim et al. unique components turns classic HEH into novel one. The main harvester body is almost same with the illustration in Fig. 2.4 on the right. Novel parts are the parabolic top of the tip mass, which is intended to move vertically by the non-magnetic ball action during horizontal input excitations (see Fig. 2.5). This mechanism also leads vertical PE bimorph displacement at center and EM induction with magnet attachment. This design is aimed to harvest human motion, thus shaken manually by hand at around 5 Hz during experiments. Resulted frequency responses of EM and PE transducers show that the first mode is at 816 Hz for both parts. Optimum power generation performances are 0.64 mW for EM part and 0.98 mW for PE part of HEH system [14].

2.4.2 Broadband Single-Source Powered HEHs

Linear Novel HEHs: Castagnetti's novel HEH is one of the most innovative one as well possessing 60 Hz-bandwidth. The design concept is composed of Belleville springs (B1 and B2 in Fig. 2.6b and c) and three different case of EM part for having a single magnet as in Fig. 2.6a, 2 magnets (Fig. 2.6c) and four magnets configurations. The vertical frame in (a) is shown horizontally in (c), denoted by "F". Experiments conducted for three cases of HEHs at 1 g and 19.62 m/s^2 . Input acceleration of 19.62 m/s^2 yield greater power outputs at resonance frequency. Among HEHs, the generated power of four-magnet HEH is 2 times of two-pole magnet HEH and 8 times of single magnet HEH. The four-magnet HEH

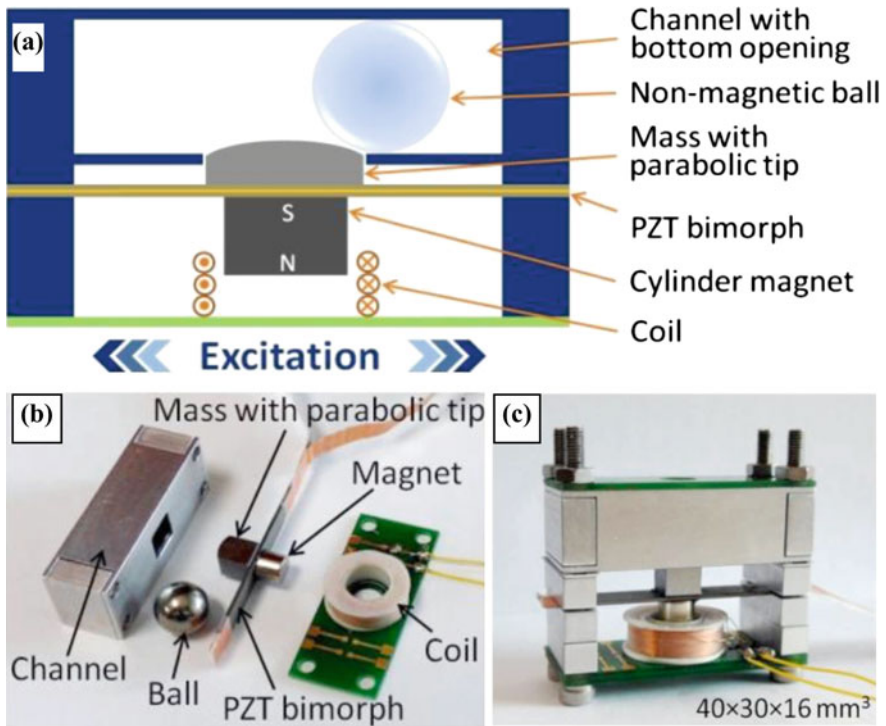
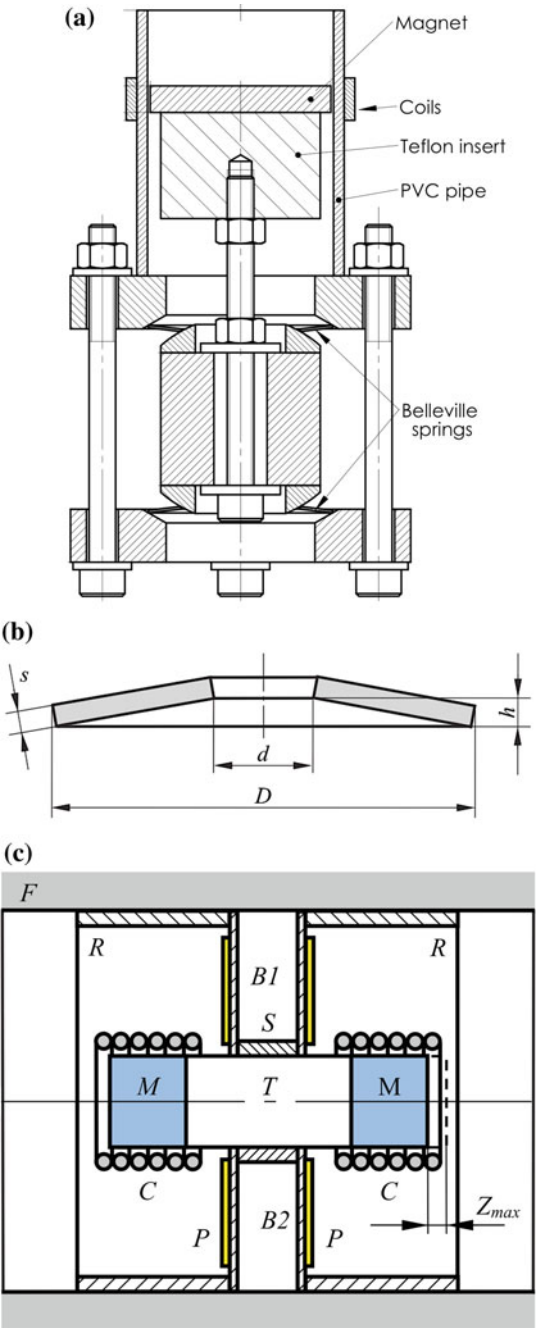


Fig. 2.5 **a** Halim et al. novel HEH design schematic representation, **b** listed fabricated components, and **c** assembled prototype [14]

configuration produced the greater power of 15.31 mW and enables broadband operation from 120 to 180 Hz at 2 g. Castagnetti also reported their HEH is superior than commercial products like Perpetuum in terms of power generation and band-width [35].

Non-linear Novel HEHs: Karami and Inman presented mono and bistable non-linear thus, broadband novel HEH, as seen in Fig. 2.7. As the horizontal input excitation is applied, then, the tip magnet moves harmonically. This oscillation yields EM and PE energy generation. HEH magnets are aligned with opposite polarization and these magnets' distance is arranged such that the HEH can perform as mono or bistable but nonlinear unless the gap is set to 50 mm in order to see linear system performance. Additionally, the system behaves as linear at low input base excitation and nonlinear at greater acceleration inputs. The best power output results are close to 35 μW for EM transducer and 1.5 mW for PE part at 1.7 m/s^2 . It is worth to mentioned that linear dynamics of these HEH systems at low excitations [44, 45] are overcome by Leadnham and Erturk's M-shaped PEH design [46].

Fig. 2.6 **a** The technical drawing of the Castagnetti’s HEH prototype, **b** Belleville spring scheme, and **c** HEH scheme with two magnets [35]



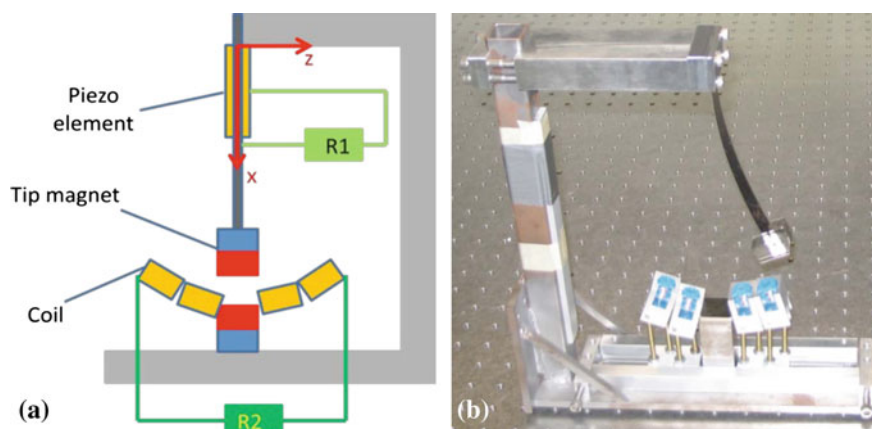


Fig. 2.7 Karami and Inman's design illustration and prototype [44, 45]

2.4.3 Multimode and Multisource Powered HEHs

The term “multimode EH” refers larger literature than “hybrid EH”. Further, multimode and multisource power terms are used in title to imply that novel researches of the extreme levels of hybridization of harvesters, multi-vibrational power source types (Sect. 2.4.3.1) and multi-power source inputs (Sects. 2.4.3.2, 2.4.3.3 and 2.4.3.4) are reviewed in this part.

2.4.3.1 Hybrid Rotary-Translational Harvesters (HRTBs)

The characteristics of motion highly affect the harvester design. Unlike the excitement types so far, two axes translational and rotary motions are the realistic cases of vibration inputs as in kinesiology and rotary machines. All these and chaotic or random and varying excitations lead broadband methods, among these, manual tuning is preferably employed for simplicity. However, as an alternative, different types of random motions can be scavenged without active physical input and it is known as “automatic generating system (AGS)” under the Kinetic brand. One classic commonly known commercial example is SEIKO wristwatches. Harmonic movement of the rotor drives the gear train and eventually almost 100 times of the eccentric mass rotational speed is converted to run the EM generator (at 5–15 krpm for 50 ms). In 1988, the device average power output range was 5–10 μW and in 1996 it was 10 μW when worn, 1 mW when shaken with a maximum capacity of 10 mW [47–51]. Sasaki et al. researched this HRTB and analyzed damping, self excited rotation and swinging motions as indicated in Fig. 2.8b. Electric load connection on generator causes rotor axis damping to increase up to some limit for self-excited rotation mode. This electromechanical damping limit is a

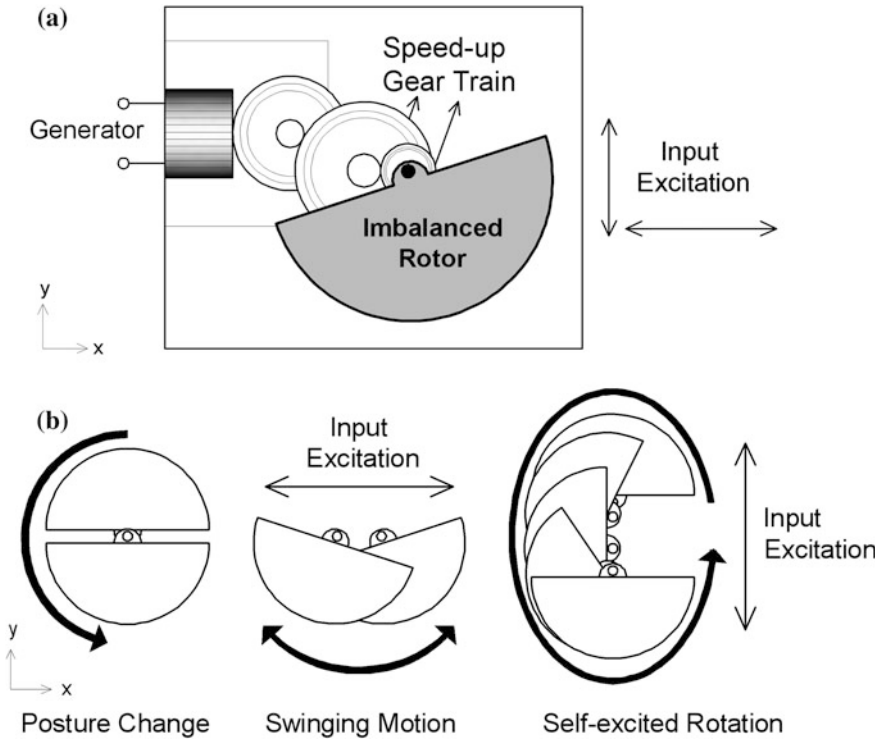
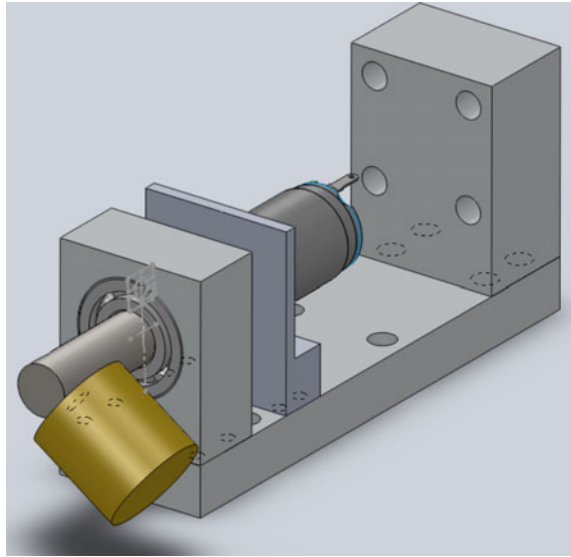


Fig. 2.8 Schematic AGS mechanism and harvested multi-motions [48, 49]

bit greater than 10^{-4} Nms/rad. Self excited rotation reaches its maximum value of 10 mW at this point and as damping increases further, sudden decline in power generation occurs down to 1 mW and the mode turns into swinging motion. This indicated that power generation in self-excited rotation is 10 times greater than swinging mode. In the light of these findings, AGS is better at low frequency and large amplitude inputs like walking or running [48].

For medical implants, this HRTH is experimentally tested on the right ventricular wall of the dog's heart. Test results are 13 μ J per heartbeat, and 80 mJ in 30 min (44 μ W), yet never further tested to feed aimed application of heart-pace since less power is produced than needed 200 mJ per half an hour. This design's feasibility on pacemakers further studied: This harvester mechanism is placed on the surface of a human chest and performance tested in office activity. In 8 h, multi-mode harvester generated 0.5 μ W, which is much less than pacemaker battery recharge feed [50]. Related to Sasaki et al. conclusion on AGS, high amplitude is necessary for greater power outputs. Hence, office environment does not provide this vibration input as in running. However, generated power in office is sufficient enough to run wristwatches.

Fig. 2.9 HRTH with magnetic pendulum and DC motor components [51]



Karami and Inman, investigated, modeled and simulated nonlinear HRTH in order to enlarge operation bandwidth. This design has magnetic pendulum as an eccentric mass connected to DC motor shaft and generates power from DC motor as the magnet oscillates (Fig. 2.9). In case of full rotation is passed, the resulted vibration is either two period vibration or chaotic. As the vertical base acceleration increases from 1 g up to 1000 g, power output rises from 10 mW to 1 W. While the base frequency increases up to 10 Hz, the output power is almost the same around 1 mW, after 20 Hz, logarithmically increases maximum of 0.5 mW, which is the saturation value at 90 Hz. The multiplicity of these findings gave maximum power generation of about 70 mW. The analytic calculations of power generations are much higher than the alternative proposed HRTHs, which is highly favorable in applications like tires and wind turbine blades [51].

Jung Kim Min et al. are especially designed HRTH for low frequency and structural applications. The complete HRTH design is shown in Figs. 2.10 and 2.11c as Case 3. The whole system is separately analyzed and tested for three cases of harvester components. The first case (Fig. 2.11a) is EM transducer where same pole magnet movement results in EM induction. In case 2 (Fig. 2.11b), as the beam oscillates, it is transformed into rotational motion and similar to Karami and Inman design, this rotation input yields power generation by DC motor. When all the harvesting mechanisms are gathered, there exists another implementation for the permanent magnets to oscillate in boundary limits so that the efficiency can be increased and since the beam is not fixed or not able to complete full rotation. Therefore, In case 3, the mechanical stoppers are added to both oscillation radial clockwise and counter-clockwise directions as seen in Fig. 2.11. In experiments, all cases are tested at constant input excitation of 0.03 g and the frequency is shifted

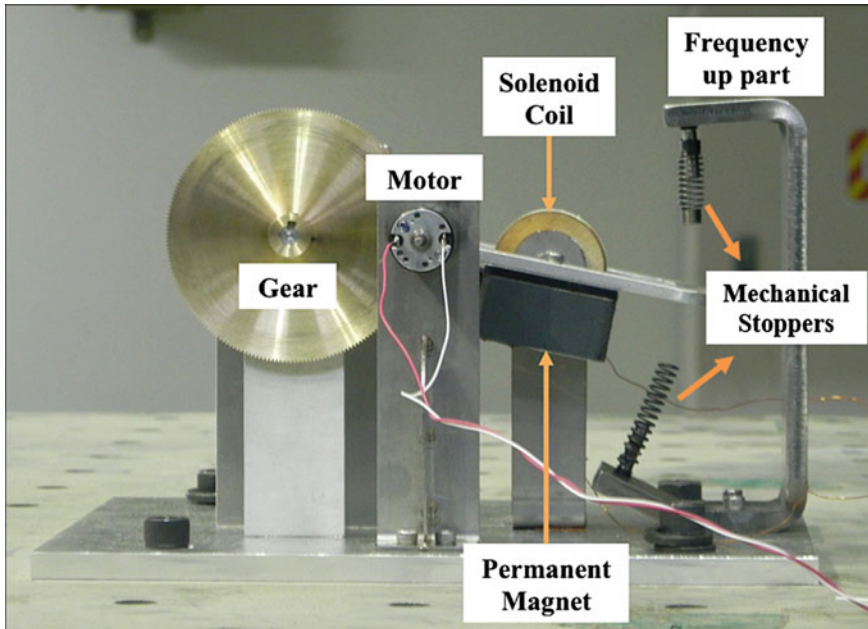


Fig. 2.10 Jung Kim Min et al. test HARTH prototype, it is analyzed in three cases [52]

from 0.5 to 5 Hz. Frequency response showed that the resonance frequency of all cases is almost at 1 Hz and output power of the system in Case 2 that is power generated by the motor with the gear ratio of 10:1, overwhelms the generation in Case 1. As a result, the harvester power generation of 37 mW is mostly contributed by the second case [52].

Larkin and Tadesse's novel design is composed of 3 HEH cantilevers in Fig. 2.1a mounted onto rotation center and a circular coil house (Fig. 2.12). The 3 HEH cantilever acts as eccentric mass and in addition to operation modes are shown at the bottom of Fig. 2.8, PE beams allow harvesting perpendicular translational forces. To sum up, the operation modes are rotational, and translational in both vertical and horizontal axes in 1–10 Hz with a maximum of 30 Hz operation range. Combined PE generator output power was 332 μW at 5 Hz and 0.8 g input excitation, and 1.25 mW at 20.6 Hz and 0.6 g vibration input. Other experiments cover testing at two body levels (wrist and ankle) when the device is placed horizontally (normal to gravitational axis, Fig. 2.12d and f) and vertically (in line with gravitational axis for walking, walk with spinning and jogging, Fig. 2.12e). The best performances respective to EM and PE generators are 17 at mW vertical placement on the wrist, and 759 μW at ankle while jogging. For both transduction mechanisms, lowest performances are observed for horizontal placement on the wrist with walking alone. The reason for vertical placement to produce greater powers is that the gravitational force effect on the eccentric mass set which increases its rotational

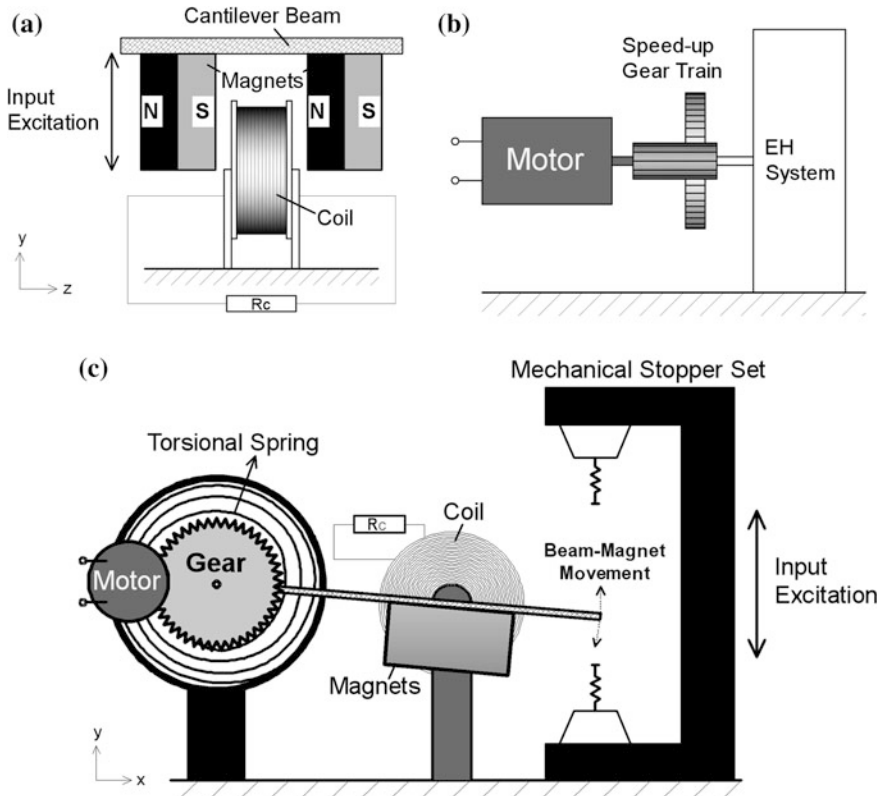


Fig. 2.11 The tested three cases of HRTH. **a** Case 1 represents EMH part, **b** Case 2 illustrates transformed beam oscillation as rotational input yields power generation by DC motor, and **c** Case 3 shows the schematic Fig. 2.2 of the whole HRTH system [52]

speed [24, 54]. Similar to AGS mechanism and Larkin and Tadesse's novel HRTH, Zhong et al. multi-source powered HEH (Figs. 2.17 and 2.18) is covered in Sect. 2.4.3.2.

In addition to combination of multiple transducers for EHing in HEHs concept, the other phenomenon is to harvest multiple power sources with either single or multiple generators and the former is known as “hybrid power systems or multi source power systems” [55]. In the following parts, multi source systems will be investigated in three parts so that the number of different power sources can be classified.

2.4.3.2 Two-Multi Source Powered HEHs

Gambier et al. presented combined solar and PE transducers as a multi-source HEH. In addition to HEH, they also investigate thermoelectric generator and suggest

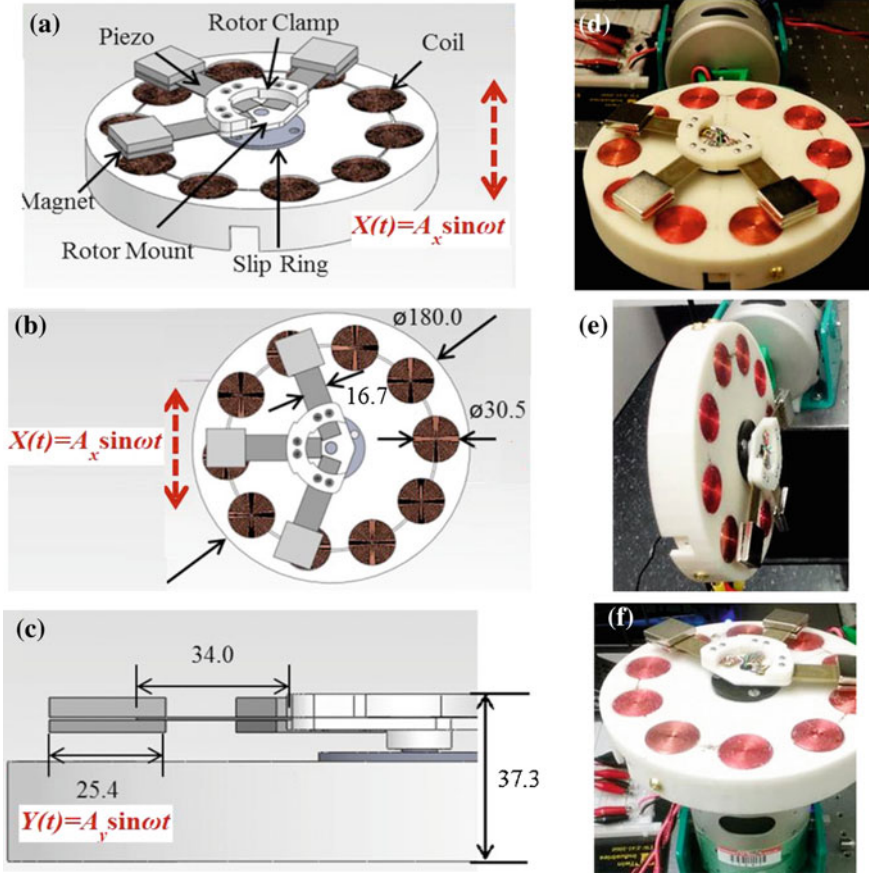


Fig. 2.12 Larkin and Tadesse's novel HRTH schematic design in (a), (b) and (c) [53], and the tested prototype vertical (e) and horizontal (d and f) arrangements [24, 54]

combining these three generators as a HEH. HEH design is composed of flexible solar (PowerFilm, Inc.), piezoceramic (QuickPack QP10n, Mide TC) generators and thin-film battery (MEC102, Infinite Power Solutions, Inc.) supported by metallic substrates, Kapton layers with implanted flexible copper electrodes for electrical isolation and epoxy layers having high-shear strength, as seen in Fig. 2.13. Single layer solar transducer dimensions are $93 \times 25 \times 0.178 \text{ mm}^3$ and cantilever volume including piezoceramic is $93 \times 25 \times 1.5 \text{ mm}^3$. Tests are conducted independently and together with solar and vibrational EHs. Three levels of illumination intensities are used as 124, 223, 311 and 437 W/m^2 . As expected, highest irradiance of 437 W/m^2 resulted the maximum output power of 30 mW, while it is 12.5 mW at 223 W/m^2 . Frequency swept from 0 to 500 Hz to catch the device resonance frequency and after that, measured output powers at 56.4 Hz are 0.4 and 0.49 mW with respect to the base excitations of 0.1 and 0.5 g.

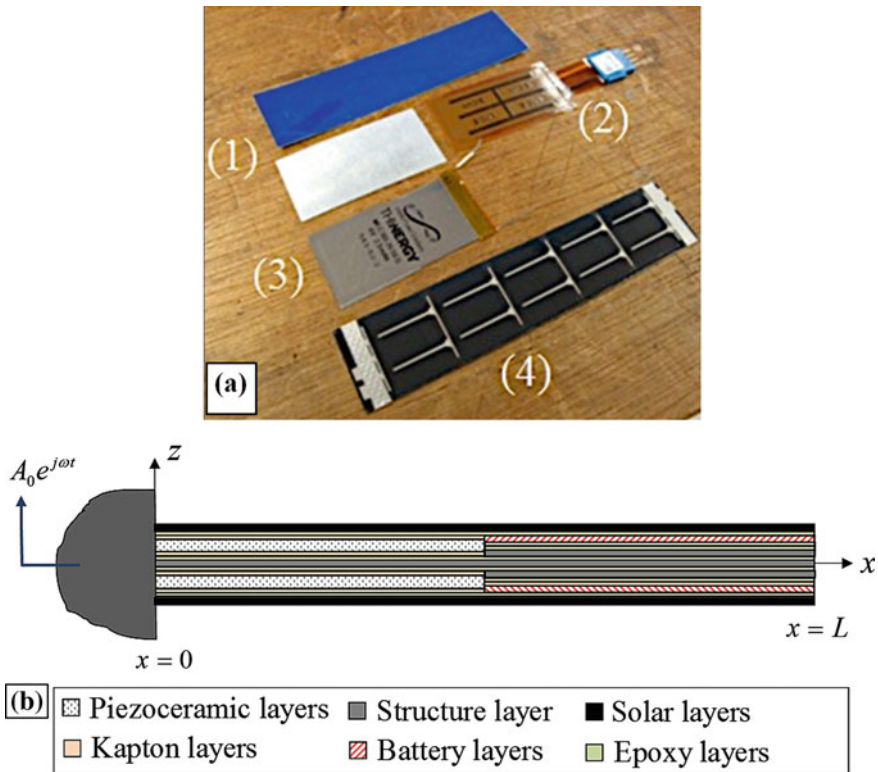


Fig. 2.13 Gambier et al. novel HEH combined with flexible thin-film batteries. **a** Aluminum structure layer (1), piezoceramic in Kapton material (2), flexible battery (3) and flexible solar layer (4), and **b** HEH scheme after integration of the layers [56]

At illumination exposure at 223 W/m^2 single solar generator charges 1 mA h of a thin-film battery in 20 min and 1.3 mA h in 26 min, whereas it takes 8 h for 1 mA h and 3 h for 0.38 mA h of capacity with PEH at base excitation of 0.5 g and 56.4 Hz [56].

Novelty of Hehr et al. research is that both vibrational and radio frequency (RF) inputs are harvested upon the same solenoid coil in EMH. As seen in Fig. 2.14, EMH dimensions are 50.8 mm diameter and 95.3 mm length with neodymium magnet of 38.1 mm diameter and 12.5 mm length. Designed harvester has the first resonance frequency of 12.5 Hz , which is experimentally validated at 3.5 and 5 g acceleration amplitudes. Coil diameter of 40.5 mm (coil set 1 and 2) is selected in order to keep the center frequency of band at 2.45 GHz and its equivalent wavelength is 122.4 mm so that HEH can function for industrial, scientific and medical radio band of 2.4 GHz . Throughout experiments, electromagnetic resonance was measured as 2.46 GHz . For the helical antenna, grounding copper ring diameter is 39 mm . For maximum voltage output, coil sets are

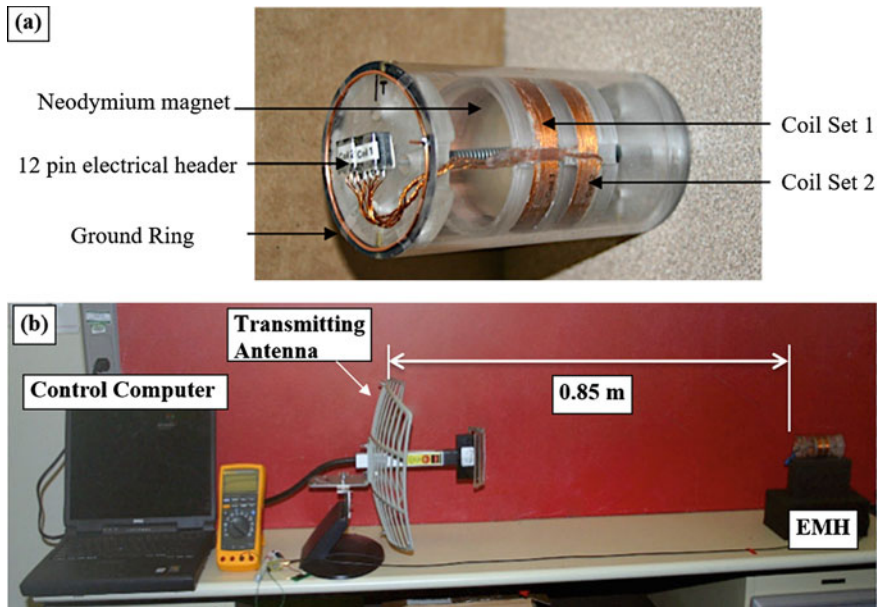


Fig. 2.14 **a** Kinetic and RF EM generator and **b** RF EHing test set-up with the same multi source powered harvester upon coil part alone [57]

connected in series for vibrational EHing and in parallel for RF EHing in the axial orientation to the source antenna as seen in the bottom in Fig. 2.14. The interesting finding was that the voltage differences between 1.52 V for coil 1 only and 1.32 V for coil 1 and 2 connected in parallel. Hehr et al. explains the reason as the indication of RF interface between the coils. At 1 g and 12.5 Hz, EM generator output energy is 1 J in ~ 90 s namely, ~ 11 mW. At 2.46 GHz, RF generator produces 70 mJ of energy in 100 s in other words, 0.7 mW [57].

Collado and Georgiadis also comprised unusual two energy sources of solar and electromagnetic waves in a single device. Novelty of their research is not limited to these harvesting sources but also include the HEH design in Fig. 2.15, developed low cost and efficient solar cells, maximized power point tracking and low power DC/DC converter to fix DC voltage. Collado and Georgiadis's novel HEH design is based on broadband monopole rectifying antenna on flexible polyethylene terephthalate (PET) substrate structure and on top of the antenna, flexible hydrogenated amorphous silicon (A-Si) solar panel is thin solar cell arrays are implemented (Fig. 2.15). The antenna alone is the copper layer of $35\ \mu\text{m}$ covering a PET substrate of $75\ \mu\text{m}$. In contrast to Hehr et al., authors aimed to harvest broadband range of 800 MHz to 6 GHz so that dissipated wide range of standard communication bands can be harvested. Solar array integration was chosen such that the RF harvesting performance will not be affected. Thus the experiments conducted at a distance of 3.45 m from the transmitter, which transmits RF power less than

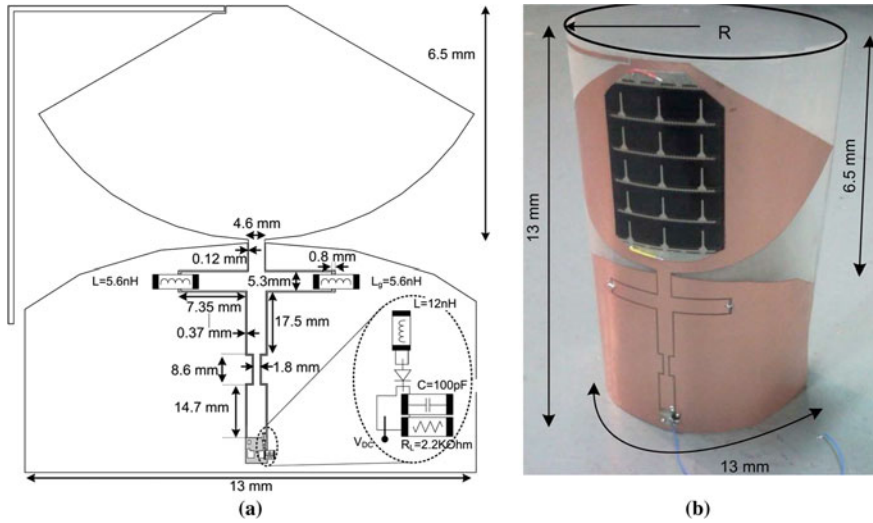


Fig. 2.15 **a** HEH design with dimensions and implemented dual band rectifier and **b** broadband rectenna on PET substrate [58, 59]

20 dBm for the rectenna of radius (R) of 70 and 100 mm and with and without the solar cell integration. For solar and RF HEH, the illumination was set almost to standard global solar irradiance of 100 and 15 mW/cm² for shade simulation. With respect to the stated illuminations, the voltage outputs of the solar array are 4.06 V and 3.90 mV. It is seen that EH with and without solar cells generates similar voltage trend and amount just as the radius of 10 and 7 mm prototypes resulted, yet 10 mm radii prototype generates slightly higher voltage at 850 and 1850 MHz. Collado and Georgiadis concluded that the best performance of the HEH is able to generate 56 mW [58, 59].

Resembling Gambier et al. novel multi source powered HEH [56], Chatterjee and Bryant's HEH harnesses solar and wind flow or vibration type kinetic powers. Only Chatterjee and Bryant state possible application of HEHs on mobile robots. As shown in Fig. 2.16, the PE patches are laminated underneath flexible thin film solar ribbon with very low aspect ratio. HEH is fixed in both ends and during longitudinal tension; transverse wind flow is induced to form aeroelastic vibration. In spite of setting the test set up, in Chatterjee and Bryant's paper, authors only proposed theoretical modeling and tuning via changing the longitudinal tension. They concluded that the transverse matrix methods is superior over Bokaikan method, where as the stress is reduced, the power generation of PE patches also reduces while being almost ineffective on mode shapes, yet effective on the mode shape of the structure without the PE patches [60].

Similar to AGS mechanism and Larkin and Tadesse's novel HIRTH, Zhong et al. combined planar rotary disk EMH with triboelectric nanogenerator (TENG) in order to harvest hand induced rotating kinesiology (see Fig. 2.17).

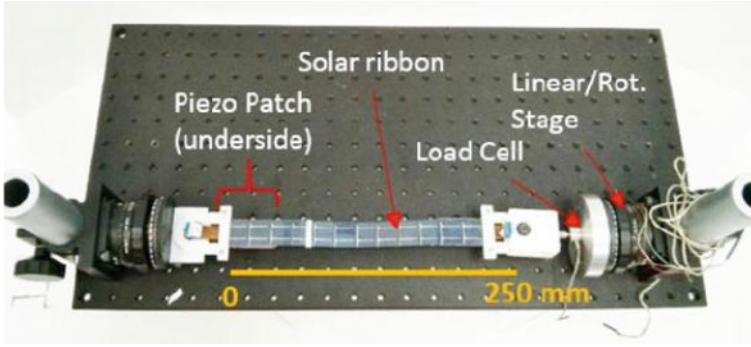


Fig. 2.16 Test setup of the solar and vibrational HEH [60]

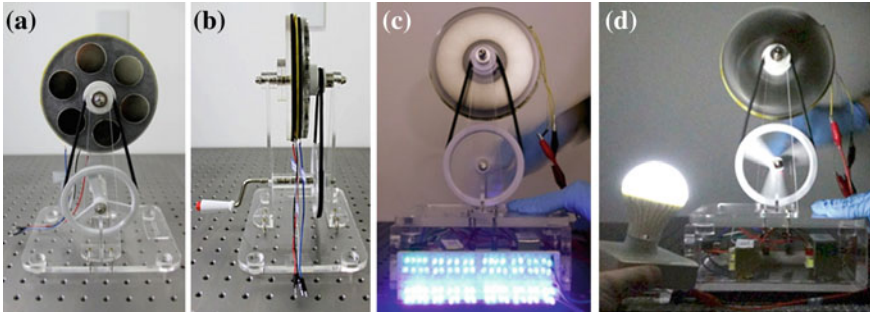


Fig. 2.17 Assembled prototype used in tests (a and b). Hand motion induced to HEH and lights 40 LEDs (c), and a globe light (d) [61]

During experiments, hand induced rotation supplied to HEH and successfully lit 40 LEDs and a globe light with a maximum illumination up to 1700 lux (Figs. 2.17 and 2.18). At a rate of 200 rpm, HEH generates ~ 8.4 mW by EM part and 8.4 mW by TENG part. Under optimum loads of 1 and 2 k Ω , respective power generations by EM and TENG transducers are 50 and 17 mW [61].

Microscale Examples: Yu et al. investigated the combination of solar panels for low illumination and MEM vibrational EH. Similar to Collado and Georgiadis, Yu et al. also selected A-Si solar panel with a surface area of 9.6 cm² since it is suitable for indoor light (fluorescent or LED). When authors' five-parameter modeling simulations of solar power generations are compared with the experiments, their modeling is closer to the experimental measurements and thus, more accurate than traditional models. The maximum power output is 110 μ W at 530 lux. Microscopic scale vibrational EH is composed of five PZT beam array connected in series with a silicon proof mass (Fig. 2.19a). The peak power output is 66.75 μ W at 234.5 Hz and 5 m/s² [62].

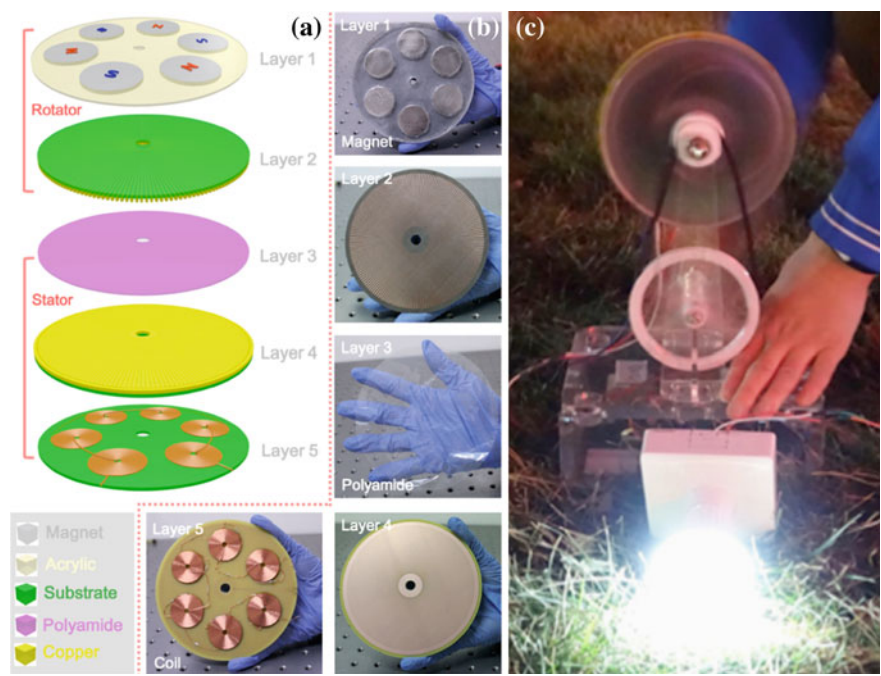


Fig. 2.18 **a** and **b** the first layer consists 6 magnets on a 5 mm thick circular acrylic disk with 140 mm in diameter. Likewise, 6 coil sets are aligned to the magnets on last layer. 2–4 layers are TENG parts: *second* and *fourth* layers are the combination of the copper strips that are integrated on a flexible substrate. The *third* polyamide layer is sandwiched in between these layers. **c** The prototype picture in use and HEH runs the globe light [61]

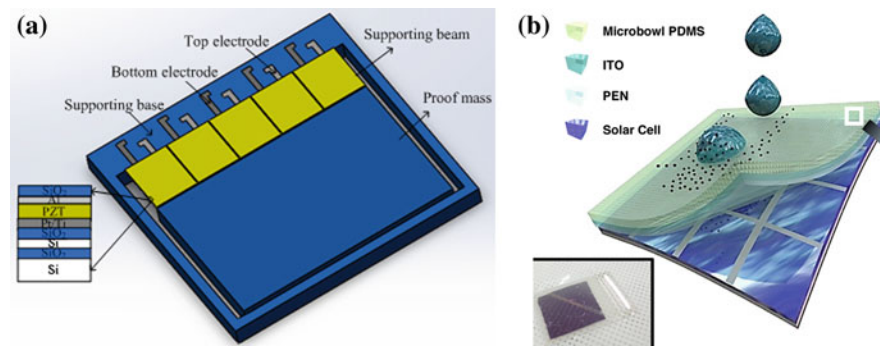


Fig. 2.19 **a** Yu et al. vibrational HEH structure without solar panels [62] and **b** Jeon et al. self cleaning rain drop and solar powered HEH [63]

Jeon et al. not only propose a novel multi source powered HEH but also solves the cleaning need of the solar cells and thus, keep its efficiency stable by the second power source of raindrops. In addition contact electrification by mechanic input, water solid interactions are also enough to harness energy via TENGs. Transparent and superhydrophobic TENGs with small contact angle allows water droplets to remove particles on the surface as well providing light to transmit and reach to the solar cells. In Fig. 2.19b, transparent superhydrophobic PDMS and ITO-PEN substrate layers on solar cells, and the prototype (below) are demonstrated. Throughout the experiments conducted with distilled water, raw tap water, actual rain, 0.01 and 1 M NaCl solutions. The resulted power generation is in the same order of the tested solutions regarding the highest to lowest power generation. While in the real rain case the output power is decreased, it is almost negligible especially the standard deviations are considered. Jeon et al. multi-function HEH generated maximum power output of $0.27 \mu\text{W}$ [63].

Novelty of Zakharov et al. study is to harness thermal energy via PE transducer due to the resulted mechanical deformation. Their design couples shape memory effect (SME) and direct piezoelectric effect (DPE). However, proposed novel harvester is partially HEH since the direct main source is thermal and the second source is indirect mechanical deformation, caused by the thermal input (Fig. 2.20) [64]. NiTi wire connected to fixed support and the tip of the cantilever shrinks during heating and bend the bulk PZT ceramic plate, and also reach the initial state as it is cooled down as shown in Fig. 2.20a. SME and DPE structure with 0.2 cm^3 of active materials energy generations are $90 \mu\text{J}$ over a temperature increase of 35°C and $60 \mu\text{J}$ while cooling [64].

Large Scale Examples: Dr. Tong's research team installed HEH consists of surrounding novel power augmentation guide vane (PAGV), vertical axis wind turbine (VAWT) and solar panel at the top so that the LED outdoor light can be driven.

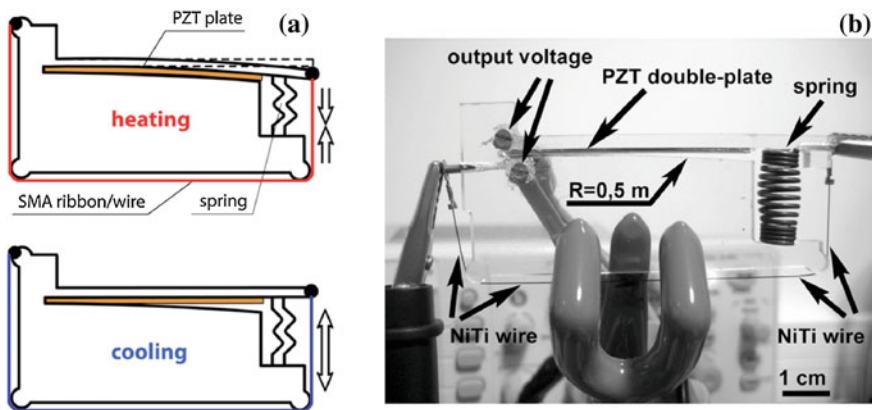


Fig. 2.20 a Zakharov et al. partially hybrid EH working principle scheme and b prototype picture along with the heat source (for the video record during operation, please visit www.youtube.com/watch?v=uS0z4ZEBeyw) [64]



Fig. 2.21 Eco-GreenergyTM Wind-Solar Outdoor Lighting System in Kuala Lumpur Campus, University of Mala [65, 66]

The developed system runs against low wind speeds due to PAGV integration (Fig. 2.21) [65, 66].

De et al. also studied wind-solar hybrid EH. Their so-called “WiSH” system consists horizontal axis wind turbine (HAWT) having 500 W rotor and solar PV panels with 250 W capacity so that the energy production can be increased during low wind speed regimes in India. HAWTs have two types; having 3 blades and 4 blades. Each blade weighs about 600 g and to achieve this low weight and high strength, they are made of carbon fiber composite. Performance curves gained from mobile testing indicated that fabricated 4-blade HAWT is more efficient than 3-bladed one. Prototypes of WiSH systems are installed in Kodihalli Campus, India for field tests (Fig. 2.22). Both 4 bladed HAWTs are parallel and 30 m-high. With the help of industrial partnership of ARES, prototypes developed up to 1–5 kW capacity and further produced 50 units of these WiSH systems [67].

2.4.3.3 Three-Multi Source Powered HEHs

In edition to Porcarelli et al. novel device comprising solar, airflow and hydrogen micro fuel cell EHs (Fig. 2.23), their [68] and Chung et al. researches [69] lie in the early studies about powering wireless sensor nodes by fuel cells.

Simulations for power generation of solar and wind EHs are compared with the experimental results. Solar cells are tested for the irradiation levels of 8000; 24,000; 40,000; and 80,000 lux. In the same order with light intensities, the photo-voltaic (PV) cell maximum output powers are 0.075, 0.13, 0.28, and 0.45 mW. Airflow energy is harvested by meso-scale plastic four bladed HAWT, 6.3 cm in diameter and 7.5 cm in length. Flow EH is tested for the flow speeds of 8.5, 15 and 16 km/h

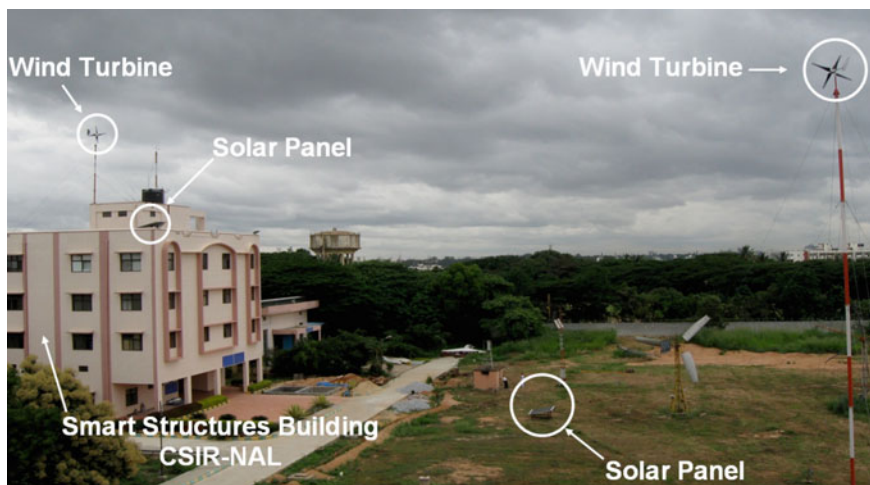


Fig. 2.22 De et al. WiSH prototypes under field test. For controlled conditions, HAWTs are 30 m above the ground level and parallel to each other [67]

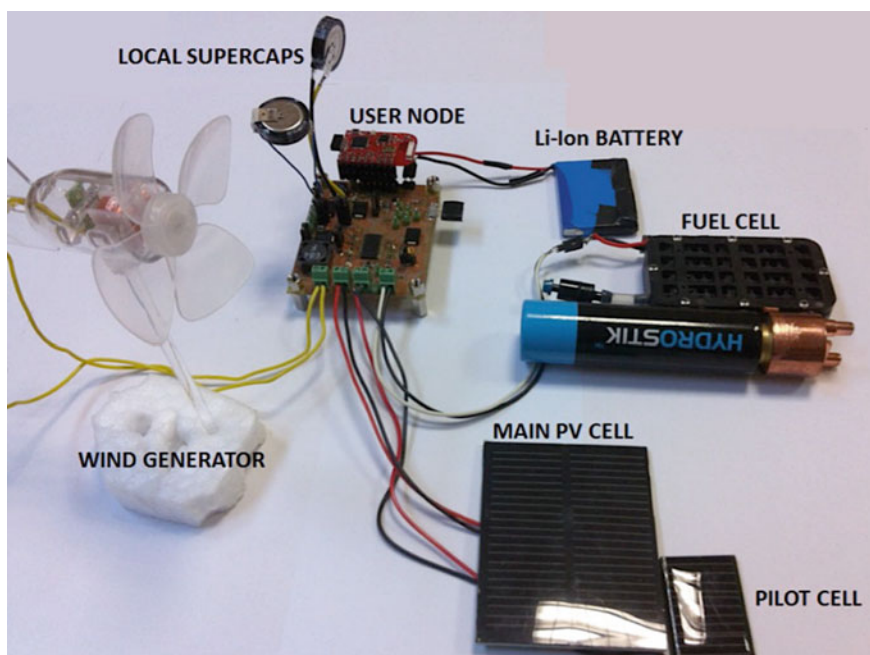


Fig. 2.23 Porcarelli et al. three-multi source powered HEH: solar, airflow and hydrogen micro fuel cell harvesters, battery and harvester circuitry are shown [68]

and the respective wind generator maximum output powers are 3.1, 5, and 7.7 mW. Solar cell and wind harvester experimental results are very close to simulation findings. As a final component, fuel cell EH with 3.61 cm^2 area, power generation is around 1 mW [68].

Zheng et al. are researched a pretty novel application of single improved dual mode TENG in such a way to harness raindrop and wind energies, and combined it with solar EHing. The very similar structure is in Jean et al. HEH as demonstrated in Fig. 2.19b. Zheng et al. also used the transparent superhydrophobic TENG with a 40 cm^2 surface area on silicon-based solar cells. TENG's transparency is validated by spectra transmittance test as being more transparent even than a 3 mm-thick commercial glass. Moreover, separation of polytetrafluoroethylene and nylon layers by PET spacer border enhances dual mode of TENG (fabrication and experiments of HEH components are given in detail in Zheng et al. article). These dual modes are: water contact TENG as rain EH and the wind contact TENG as wind EH. The tests are set as such: Rainy day conditions are considered (13.6 and 20 mL/s dripping rates) and the incident angle between raindrops and TENG surface is 45° , with a distance of 40 cm from the rain shower. Common daily wind speeds of 1.7; 2.7; 4.1 and 4.9 m/s are flowed from a faucet and the solar irradiation is set to 100 mW/cm^2 . At 20 mL/s dripping rate, water TENG, water contact TENG and HEH drive 10, 20 and 50 LEDs, respectively. Experiments have shown that the dual-mode TENG (water and water contact TENGs are in series) voltage and current densities are greater than water contact TENG that is greater than water TENG alone. Generated power of the prototype is limited but since the size can be expanded, generated powers in per square meter of the HEH surface area are more representative as in current densities, thus, for HEH it is 86 mW/m^2 at a dripping rate of 13.6 mL/s and in the absence of solar and rain sources, it is 8 mW/m^2 from wind at a speed of 2.7 m/s [70].

Microscale Examples: Chung et al. combined thermal, mechanical and magnetic powers in such a novel way. As mentioned in two-multi source powered HEHs title for Zakharov et al. 2015-design, in 2012, Chung et al. also used indirect source of magnetism to harness direct thermal power source. So, Chung et al. device is partially three-source powered HEH. As seen in the prototype picture in Fig. 2.24a, main body is copper-beryllium spring and the PE cantilever is both fixed to glass frame and attached to the spring. Design has two types of magnets: Moving gadolinium soft-magnet on top of spring and fixed neodymium-iron-boron hard-magnet on frame. The working principle of this novel HEH demonstrated in Fig. 2.24b and c: As the soft magnet is cooled below Curie temperature, it gains ferromagnetic property and almost attaches to the fixed hard magnet (b), which bends the spring and PEH. Worth to mention that magnets never really touch due to the distance between them in y direction. As the topside is cooled down (15°C) and heated (27°C), magnetic attraction incidence and withdrawal of the magnetic attraction leads spring, thus, PE beam oscillation and power generation. Second working mode is classic vibrational spring-proof mass energy generation on PEHs. Final creative additional working mode is the oscillation of the soft magnet on spring due to the induced AC magnetic field in z direction (c) [69].

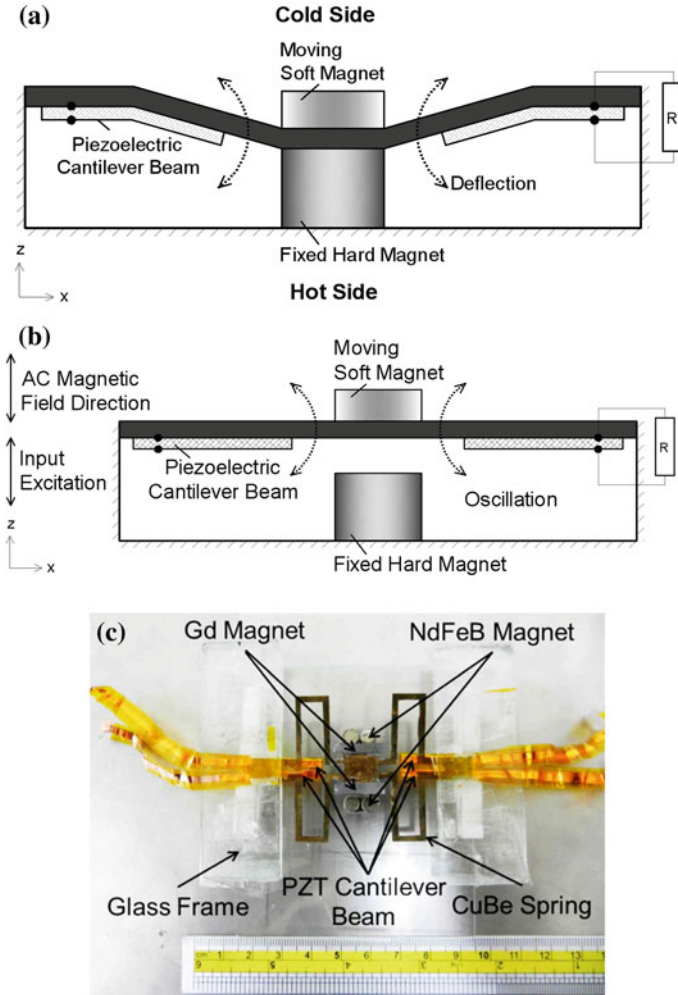


Fig. 2.24 **a** Temperature-difference-driven thermal and **b** vibrational and magnetic field induced schematic working principles. **c** Chung et al. fabricated prototype [69]

Chung et al. experiments resulted as: For temperature-difference-driven thermal EHing, a 25 °C difference lead minimum and maximum of 15 and 70 peak-to-peak voltages, respectively. Generated peak-to-peak voltage outputs are 175 and 20 mV with respect to the input excitation of 1 mm at 46 Hz, and AC magnetic field of ± 3.5 Oe at 43 Hz. The preliminary results clearly indicate that the vibrational energy generation is undoubtedly greater than other working modes [69]. Almost the same research team; Chen et al. took further to analyze their novel design (Fig. 2.25) [71].

Chen et al. simplified their previous study by using gadolinium soft-magnet as a fixed beam on PZT sheet and silicon clamps and keeping the same fixed neodymium-iron-boron hard-magnet on frame. Experimental measurements are

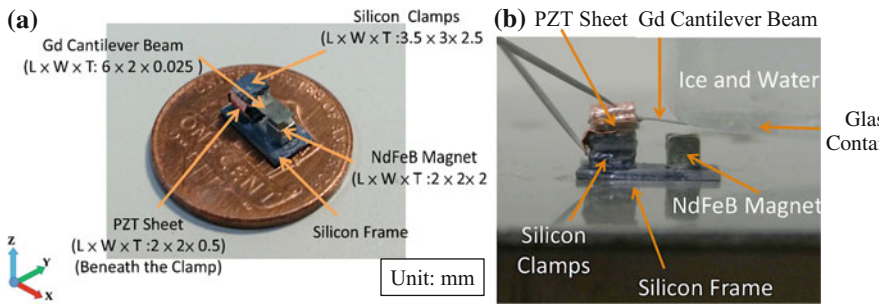


Fig. 2.25 Chen et al. simplified recent magnetic-piezoelectric thermal HEH prototype with dimensions (a) and during experiments with ice water (b) [71]

37 mV of peak-to-peak voltage and 1.98 mV RMS voltage at 20 °C temperature difference for the temperature range of 6.7 to 26.7 °C. The maximum output power is and average power density is ~ 1.37 nW with an average of ~ 3.96 pW with the breakthrough HEH volume of about 0.063 cm^3 [71].

Large Scale Examples: Chong et al. presented VAWT, solar energy converter and rainwater collection systems integration with PAGV. Since the rainwater collection system is not an EH, it is only for storage purpose and indirectly saving energy from the reduced pumping need [72, 73] so their design is partially three-source powered HEH. Nevertheless, as Mithra et al. suggested in their research, it is also possible to harness energy from rainwater by increasing its kinetic energy from falling and the use of turbines [55]. As seen in their patent scheme in Fig. 2.26a–c, the wind turbine ‘A’ is placed in the middle of the structure with rudder ‘C’, PAGV ‘B’ has sloped upper ‘D’ and lower ‘E’ wall ducts, and surrounded by the protective mesh ‘M’. The upper wall duct also acts as a collector of the rain shower and at the same time, having solar energy converter (PV and/or solar thermal panel or solar concentrator system) ‘F’ on the upper surface. The captured rainwater after filter ‘N’ flows through the passage ‘G’ and reach to the storage ‘K’, which has thermal insulation at the base ‘L’ so that heat transfer into building can be blocked. VAWT power drive shaft ‘H’ is connected to the generator ‘I’ via mechanical drive box ‘J’. Their design is open to many modifications and one is illustrated in Fig. 2.26b. Tests conducted with and without 3-blade Sistan rotor having 0.5 m diameter and 0.25 m height, surrounded by the PAGV having 30 m diameter. Pilot-scale test set up height from the PAGV to base is 12 m. It is reported that PAGV amplifies the wind speed by ~ 1.8 times (46 rpm for pilot tests) and VAWT gains direct flow angle. It is seen that PAVG integration increases energy generation by 1.25 times. It is estimated that for the system on a 220 m high skyscraper, energy generations of the wind energy harvester system is approximately 157 and 58.4 MW h/year, solar panels with a 650 m^2 active area is 280 kW h/day, and monthly the energy saving for 220 m pumped domestic water is 79 kW h. Ultimately, Chong et al. research suggests the annual total saved and generated energy is 160 MW h and by

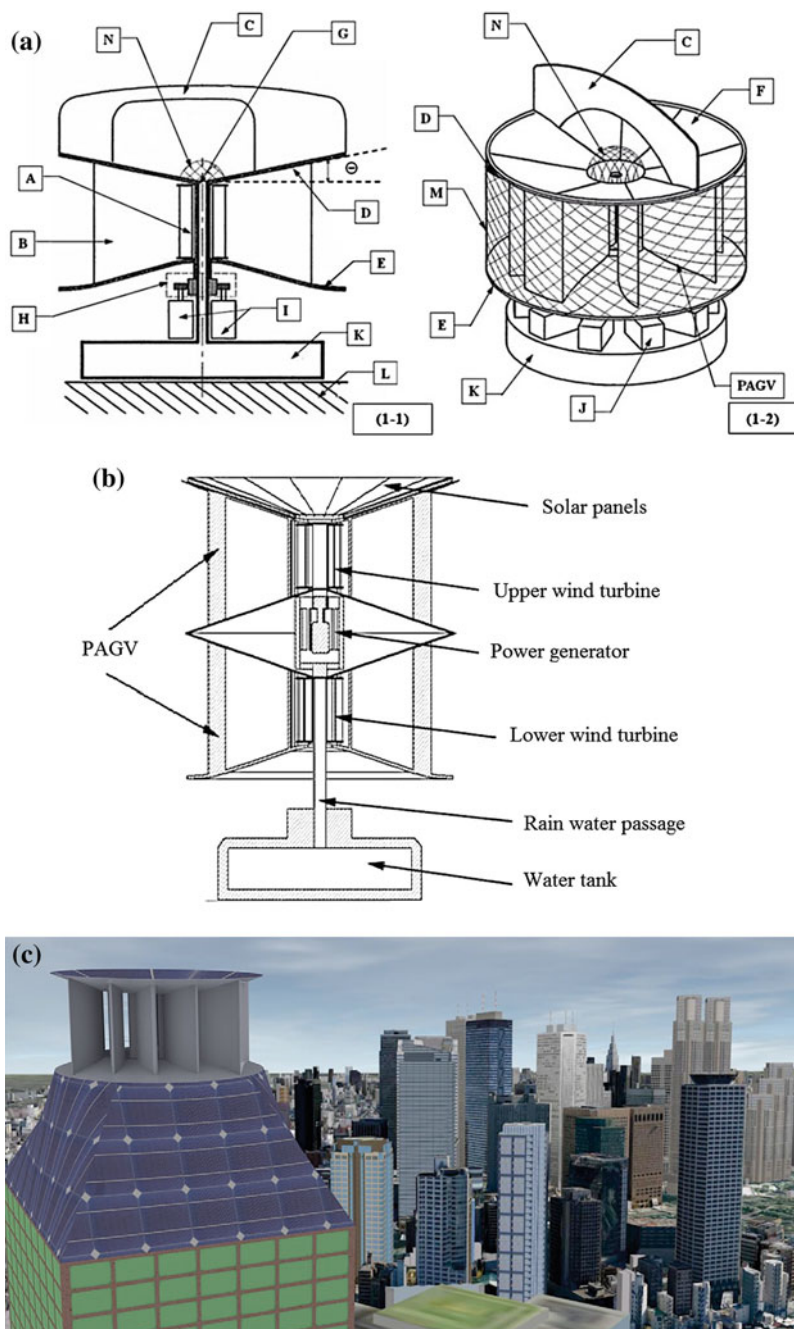


Fig. 2.26 **a** Patented and proposed design's referred figure and **b** proposed modified design, and **c** artistic demonstration of HEH on the high rise building in Tokyo, Japan [72, 73]

considering 2.8 MW h of energy consumption per house, one skyscraper application can help to supply energy for 57 houses [72, 73].

Relatedly, Donnie holds a patent of the similar HEH application. Patented HEH has solar panels on the outer rotating large blades, harvesting wind energy and the inner part has either acoustic piezoelectric or electrostatic energy harvester in order to harness entered wind's remaining kinetic energy [74].

Sathiyamoorthy and Bharathib proposed the idea of combining PEH integration roads, rotational solar panel and two-blade VAWT between two-way roads to gain turbulence, and thus, rotational motion input. This configuration aims to feed streetlights but they also suggested HEH implementation on rooftop to supply electricity for households. Proposed VAWT is applicable at low levels for energy generation, in other words, suitable for residential structures. The novelty lies on the sun-tracking module that does not require any sensor or controller. It works as a pendulum clock and as the hanging wheel oscillates, it rotates the escapement wheel and the center shaft. Gear mechanism, reduce the clockwise rotation of the shaft and reduced shaft is connected to solar panel and tracking sun's direction from east to west. PEH is selected as PZT (lead zirconium titanate) and connected in series. Measured maximum output power and peak-to-peak voltage of solar panel and PE are 10 W and 12 V, respectively. Authors propose wind turbine analytic modeling but do not mention the value of the potential power generation [75].

Mithra et al. combined the classic rainwater, solar and wind harvesting systems. Rainwater harvesting starts from the collection of the rainfall on the roof of a three-floor, ~ 9 m high building to the header tank. The water falls from the conduits, which increase pressure thus, velocity. At the base the falling water meets the turbine and its shaft is connected to alternator's rotor. After the rainwater hits the turbine blades it is collected and stored for further use, while the generated power is used to feed first of all power electronics and then, power systems. Based on this plot scale findings, the desired real-life application's evaluated electricity production is stated as 1.53 kW h for 7 m high normal house and 290 kWh for 98 m skyscrapers. Classic Solar PV arrays and wind turbine to harvest wind energy are suggested to meet domestic power consumption. Nonetheless, Mithra et al. have not stated pilot scale tests along with rainwater system. The combination of mentioned generation systems are concluded as: The rainwater and wind power generations are rectified by AC-DC converters and the PV power alone is converted to fix DC voltage by chopper. The control unit combines these three different generated energies as a hybrid system [55].

2.4.3.4 Four-Multi Source Powered HEH

After Porcarelli et al. another attempt to research solar, wind and fuel cell EHs are studied by Saini et al. with an additional novel segment of electrolyzer (Fig. 2.27). Saini et al. uses solar, airflow, water, and produced hydrogen and oxygen as a result of electrolysis. HEH solar module is $95 \times 135 \times 30 \text{ mm}^3$ in dimension, 89 g of weight and the maximum PV power generation is $\sim 190 \text{ mW}$ when exposed to single 75 W lamp at 90° . Six blade HAWT and the maximum output power is 400 mW.

Table 2.2 The overall comparison of fixed-frequency and broadband single-source powered HEHs and multimode HRTs in Sects. 2.4.1 and 2.4.2

Type	References	Input power sources/types	Working modes	Input acc.	Input properties	Volume/surface A.	Peak output power voltage, power density	Mass
<i>Fixed-frequency single-source powered HEHs</i>								
	[1]	Mechanical: foot fall	Rotary Generator, PEH	–	~5 Hz*	–	0.06 kW h, 10 V	–
	[14]	Mechanical: hand motion	Ball driven PEH, EMH	–	~5 Hz**	19 cm ³	PEH: 0.98 mW, 20 V EMH: 0.64 mW, 0.65 V HEH: 84.4 μW/cm ³	–
<i>Broadband single-source powered HEHs</i>								
Linear	[35]	Mechanical	PE and EM	2 g	~150/120–180 Hz	884 cm ³	4 magnet HEH: 15.31 mW, 1.75 V	–
Nonlinear	[44, 45]	Mechanical	PE and EM	1.7 m/s ²	~12 Hz	819 mm ³	PEH: 1.5 mW EMH: 35 mW	48 g
<i>Multimode: hybrid rotary-translational harvesters</i>								
	[47–51]	Mechanical: wrist motion	Mechanical: rotary-translational AGS	–	5–15 krpm	in the wristwatch	1–10 mW	–
	[50]	Mechanical: dog's heart		–	–	–	44 μW	–
		Mechanical: on chest		–	–	–	0.5 μW	–

(continued)

Table 2.2 (continued)

Type	References	Input power sources/types	Working modes	Input acc.	Input properties	Volume/surface A.	Peak output power voltage, power density	Mass
	[51]	Mechanical	Rotary-translational generator, DC motor	1–1000 g	10–90 Hz		10 mW to 1 W, (avg: 70 mW)	–
	[52]	Mechanical	Rotary-translational DC motor, EMH	0.03 g	1 Hz	~1000 cm ³	37 mW, 0.27 V	–
	[24, 54]	Mechanical: walking, jogging	Mechanical: rotary-translational PEH and EM	–	Jogging: PEH on ankle, EMH on wrist	958 cm ³	PEH: 759 μW, EMH: 17 mW	–

(*) Standard walking and running human motion frequency value [14]

(**) Input frequency is 5 Hz in horizontal axis, but the HEH resonance frequency is 816 Hz

Table 2.3 The overall comparison of multisource powered EHs. Classified according to micro-, meso- and large scales

# of source	References	Input power sources	Working modes	Input acc.	Input properties	Volume/surface A.	Peak output power voltage, power density	Mass (g)
<i>Microscale</i>								
Two	[62]	Solar, vibration	PV, PE	0.5 g	Solar: 530 lux, PE: 234.5 Hz	1096 mm ²	Solar: 110 μ W, PE: 66.75 μ W	–
Two	[63]	Raindrop, solar	TENG, PV	–	Solar: 150 mW/cm ²	13.4 mm ²	0.27 μ W	–
Two	[64]	Thermal, (mechanical)	Thermally-driven PE, (SME, DPE)	–	Temp increase: 35 °C	200 mm ³	Temp rise: 90 μ J Cooling: 60 μ J	–
Three	[69]	Thermal, magnetic field, vibration	Thermally-driven PE, Magnetic field induced PE, Vibration induced PE	–	T: 25 °C, PE: 1 mm at 46 Hz, AC magnetic field: $\pm$ 3.5 Oe at 43 Hz	49 cm ³	Thermally-driven PE: 35 V	–
Three	[71]	Thermal, (magnetic field, vibration)	Thermally driven PE, (Magnetic Field driven PE, Vibration)	–	T: 20 °C	63 mm ³	$\sim$ 1.37 nW, 1.98 V, 21.7 nW/cm ³	–
<i>Mesoscale</i>								
Two	[56]	Solar, vibration	PV, PE	0.5 g	Solar: 437 W/m ² , PE: 56.4 Hz	3488 mm ³	Solar: 30 mW, PE: 0.49 mW	–
Two	[57]	RF, vibration	RF, EM	5 g	RF: 2.46 GHz, RF wavelength: 122 mm, EM: 12.5 Hz	773 cm ³	RF: 0.7 mW, 1.52 V, EM: 11 mW, 4.5 V	–
Two	[58, 59]	RF, solar	RF, PV	–	RF: 800 MHz-6 GHz Solar: 100 mW/cm ²	4084 mm ³	HEH: 56 mW, Solar: 4.06 V	–

(continued)

Table 2.3 (continued)

# of source	References	Input power sources	Working modes	Input acc.	Input properties	Volume/surface A.	Peak output power voltage, power density	Mass (g)
Two	[61]	Mechanical: hand-induced	TENG, EM	–	200 rpm	77 cm ³	TENG: 17 mW, EM: 50 mW	–
Three	[68]	Solar, airflow, fuel cell	PV, HAWT, hydrogen fuel cell	–	PV: 80,000 lux, Wind speed: 16 km/h	HAWT: 234 cm ³ , Fuel cell: 361 mm ³	PV: 0.45 mW	–
							HAWT: 7.7 mW	
							Fuel cell: ~1 mW, 1.23 V, 2.5 A, 282 mW/cm ²	
Three	[70]	Solar, raindrop, airflow	A-Si Solar cells, TENG	–	Solar: 100 mW/cm ² Rain: 13.6 mL/s Wind speed: 2.7 m/s	40 cm ²	HEH: 344 μW, 86 mW/m ²	–
Four	[2]	Solar, airflow, water, fuel cell	PV, wind mill, electrolyzer, hydrogen & Oxygen fuel cell	–	75 W lamp at 90°	1234 cm ³	Solar: 190 mW	573
							Wind: 400 mW,	
							HEH: 315 mW, 3 V, 105 mA	
Large-scale								
Two	[65, 66]	Solar, airflow	PV, HAWT	–	–	Outdoor-light Size	Enough to drive LED street-light	–
Two	[67]	Solar, wind	PV, HAWT	–	8.5 m/s	30 m-high	up to 1–5 kW	–
Three	[72, 73]	Solar, airflow, (rainwater collection)	PV or Solar Thermal Panel or Solar Concentrator System, VAWT	–	–	Pilot scale: 10,603 m ³	VAWT: 157 kW h/day PV: 280 kW h/day Pumping: 2.6 kW h/day	–

(continued)

Table 2.3 (continued)

# of source	References	Input power sources	Working modes	Input acc.	Input properties	Volume/ surface A.	Peak output power voltage, power density	Mass (g)
Three	[75]	Solar, airflow, road traffic	PV, VAWT, PE	–	–	Actual: on 220 m high skyscraper Actual on two-way roads and houses	Solar: 10 W, PE: 12 V	–
Three	[55]	Solar, airflow, rainwater	PV, Wind turbine, Turbine	–	–	Pilot: three-floor, ~9 m high building Actual: 98 m skyscrapers	290 kWh	–

Table 2.2 covers fixed-frequency and broadband single-source powered HEHs and multimode HRTs in Sects. 2.4.1, 2.4.2 and 2.4.3.1. Table 2.3 emphasizes micro-, meso-, and large-scale based comparisons of two-, three- and four-multisource powered HEHs in Sects. 2.4.3.2, 2.4.3.3 and 2.4.3.4. The given device volume and surface areas are the conservative values of the HEHs, and generally belong to transducer parts and active surface areas. The overall novel HEHs comparisons are evaluated in Sect. 2.5.

2.5 Conclusions

The need to achieve greater power generation leads researchers to investigate hybridization of EHing transduction mechanisms, working modes and source powers. As indicated in literature [10–23], in the scope of this chapter review, it is seen that HEHs generate greater power outputs than their single harvester components.

Among classic HEHs, Table 2.1 shows that Shan et al. HEH holds the greatest power output of 33 mW along with broadband performance in the range of 7 to 17 Hz [16]. Regarding the device volume, Ali et al. holds greater power density than Shan et al. [32]. Once PE and EM power generations are compared, generally, EM power generations are lower than PE parts with an only exception of Ab Rahman et al. HEH with four pole magnet arrangement [20, 34]. Apart from Wischke et al. microscale HEH, Xu et al. device [31] has the lowest energy generation with the minimum volume of 187.2 [31].

In novel HEH class, the most promising power generations are proposed by Yu et al. [62] in microscale, Saini et al. [2] and Karami and Inman [51] in meso-scale, and Chang et al. [72, 73] in large scale HEHs. Broadband technique significantly increases output power and density in nonlinear designs [44, 45]. In case of linear HEHs, Halim et al. novel design suppresses power density of Castagnetti's HEH [35] about 5 times, but not the bandwidth [14]. Within HRTs, best performance is achieved by Karami and Inman with an average power output of 70 mW and maximum of 1 W when exposed to 1000 g [51]. However, Jung et al. managed to produce 37 mW at low excitation as much as 0.03 g [52]. At almost the same device size with Jung et al. Larkin and Tadesse gained more than 17 mW during jogging activity on wrist placement [24, 54] (see Table 2.2). In micro-scale HEH class, Wischke et al. managed to gain the highest output power of 215 μ W via tuning in broadband operation, yet the total harvester volume is much greater [25, 39] than remaining prototypes. The closest result of 177 μ W is reached by Yu et al. by solar and vibration powered HEH with a surface area of ~ 1 cm² [62]. The smallest size prototype with 13.4 mm² surface area is fabricated and tested by Jeon et al. and it produces 0.27 μ W of output power [63]. Comparison of mesoscale novel HEHs emphasize that four-source powered HEH produces the greatest power output of 315 mW, whereas occupying the greatest volume [2]. It is seen that two-multisource powered HEHs produce greater power than three-multisource

powered ones without an exception. Collado and Georgiadis proved that RF and solar HEH are able to harness 56 mW of power with a small volume of 4 cm³ [58, 59]. Regardless of the device size, Zhong et al. hand induced hybrid TENG and EM harvester generates total of 67 mW of power [61]. Lastly, large-scale HEHs result the best when implemented on high buildings such as skyscrapers. The greatest energy generation is estimated for solar and airflow harvesting along with rainwater storage, which saves pumping cost and eventually serves a total of 440 kW h of surplus energy daily [72, 73] (Table 2.3).

Among overall reviewed classic and novel HEHs, the peak power of 1 W is achieved by Karami and Inman at an extreme excitation of 1000 g, yet reasonable daily conditions are enough for the generation of 315 mW by Saini et al. four-source powered novel HEH. Regarding the size of HEHs, Collado and Georgiadis' two-source powered HEH generates the highest output power of 56 mW. The most promising power generations are achieved by Saini et al. four-source powered novel HEH in meso-scale, Wischke et al. tunable broadband classic HEH in microscale and Chong et al. proposed partially three-source powered HEH arrangement in large scale. In conclusion, HEHs not only increase the output powers and power densities, but also enable endless configurations to maximize harnessing existing power sources.

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