Chapter 1
Ambient Energy Sources: Mechanical, Light, and Thermal

1.1 Toward a New World Based on Green Energy

In the recent past, the growing presence of renewable-energy research in academic journals and industrial companies has led to an increase in its contribution: 19% to global energy consumption and 22% to U.S. electricity generation in 2012 and 2013, respectively. National renewable-energy markets are expected to continue growing strongly in the coming decade and beyond for many reasons. First of all, clean energy comes from unlimited and natural resources, e.g., the movement of wind and water, and the heat and light of the Sun. Secondly, it reduces global warming and pollution, and improves environmental quality. Furthermore, it creates jobs and enhances economies.

Although ambient mechanical and thermal energy are classified as the largest forms of renewable energy among those available, they are also considered to provide desired power for low-power electronic devices by using piezoelectric and pyroelectric materials. Ambient mechanical and thermal energy are produced naturally and non-naturally; for example, ambient mechanical energy is produced naturally from different sources, such as hydroelectricity, ocean or river waves, and wind. It is also produced non-naturally due to the forced motion of objects, such as human and machine motion. Conversely, thermal energy is generated naturally from sun rays or geothermal waves, and non-naturally from artificial light and microwaves.[1,2]

Converting mechanical vibrations to a usable form of energy has been the topic of many recent investigations. The ultimate goal is to convert ambient or aeroelastic vibrations to operate low-power electronic devices, such as micro-electro-mechanical systems (MEMS), structural health monitoring (SHM) sensors, and wireless sensor nodes (WSNs), or replacing small batteries that have a finite life span or would require difficult and expensive maintenance.[3,4] Even though the total market for energy-harvesting devices, including everything from wristwatches to wireless sensors, will increase over

$4 billion in 2021, ninety percent of WSNs cannot be enabled without energy-harvesting technology.[5] Figure 1.1 shows the percentage of the WSN market, as published by Frost and Sullivan in 2006.[6]

The transduction mechanisms used to transform mechanical vibrations to electric power include electromagnetic (EM), electrostatic, and piezoelectric mechanisms. They can harvest energy over a wide range of frequencies. Piezoelectric conversion has attracted significant interest due to its ease of application. Figure 1.2 shows the basic method to convert ambient energy harvesting into a useable form of energy. The power consumption and energy autonomy of some low-power electronic devices is presented in Table 1.1,

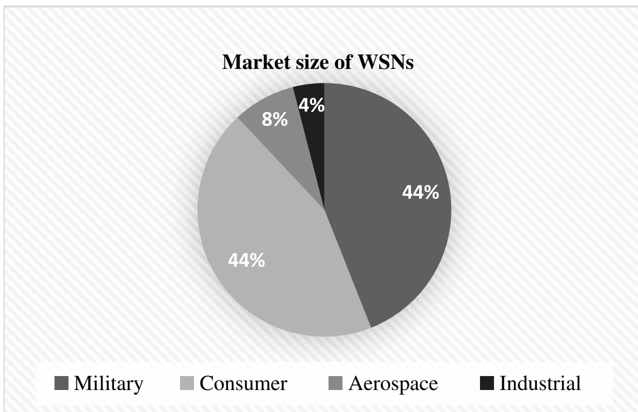


Figure 1.1 The percentage distribution of the WSN market.

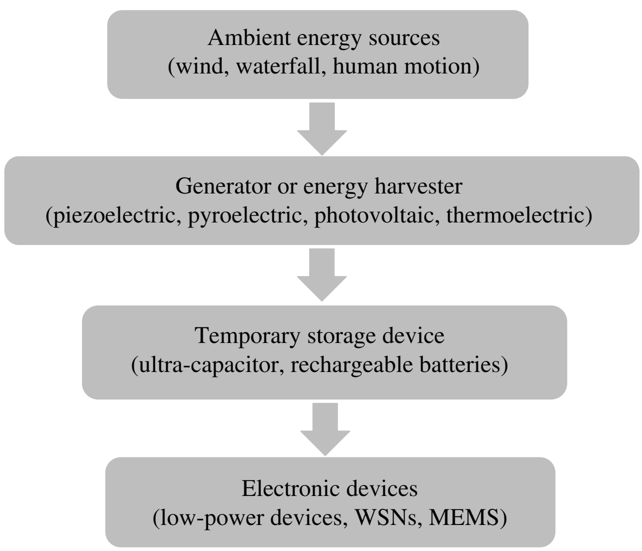


Figure 1.2 Energy-harvesting process as an alternative for low-power electronic devices.

Table 1.1 Selected battery-operated systems.[7]

Device type	Power consumption	Energy autonomy
Smartphone	1 W	5 h
MP3 player	50 mW	15 h
Hearing aid	1 mW	5 days
Wireless sensor node (WSN)	100 μW	Lifetime
Cardiac pacemaker	50 μW	7 years
Quartz watch	5 μW	5 years

Table 1.2 Ambient- and harvested-power characteristics of various energy sources.[7]

Source	Harvested Power
Ambient light	
Indoor	10 μW/cm^2
Outdoor	10 mW/cm^2
Vibration/motion	
Human	4 μW/cm^2
Industrial	100 μW/cm^2
Thermal energy	
Human	25 μW/cm^2
Industrial	1–10 μW/cm^2
Radio frequency	
GSM	0.1 μW/cm^2
Wifi	1 μW/cm^2

whereas a comparison of harvested power per cm^2 for different energy sources is listed in Table 1.2.[7,8]

1.2 Vibration-to-Electricity Conversion

Energy from vibration and movement provides energy harvesters (EHs) with enough mechanical energy to be converted into electrical energy. The following qualities are advantages of mechanical energy: available almost anywhere and anytime (e.g., human motion or air/water flow), higher electrical energy values than light or thermal energy sources, and available over a wide frequency spectrum range.[9] The frequency of the mechanical excitation depends on the source: less than 10 Hz for human movements and typically over 30 Hz for machinery vibrations. Table 1.3 includes many vibration sources measured in terms of the frequency and acceleration magnitude of the fundamental vibration mode.[10] There are three main mechanisms of mechanical–electrical energy-conversion systems: electrostatic, electromagnetic, and piezoelectric (there is also magnetostrictive transduction, which is commonly used with magnetically polarized materials).

Table 1.3 Ambient- and harvested-power characteristics of various energy sources.[10]

Vibration source	A (m/s^2)	f_{peak} (Hz)
Car-engine compartment	12	200
Base of three-axis machine tool	10	70
Blender casing	6.4	121
Clothes dryer	3.5	121
Person nervously tapping their heel	3	1
Car instrument panel	3	13
Door frame just after door closes	3	125
Small microwave oven	2.5	121
HVAC vents in office building	0.2–1.5	60
Windows next to a busy road	0.7	100
CD on notebook computer	0.6	75
Second-story floor of busy office	0.2	100

1.2.1 Electrostatic energy harvesting

Electrostatic devices are structures with variable capacitors that produce surface charges from a relative mechanical-vibration motion between two plates, which changes the capacitance between the maximum and minimum value. Surface charges will then move from the capacitor to a storage device or to the load as the capacitance decreases. In this case, the mechanical vibration motion between two plates is converted to electrical energy in the device. Electrostatic EHs are generally classified according to the three types shown in Fig. 1.3: in-plane overlap, which varies the overlap area between electrodes; in-plane gap closing, which varies the gap between electrodes; and out-of-plane gap closing, which varies the gap between two large electrode plates.[11]

1.2.2 Electromagnetic energy harvesting

Harvesting electromagnetic energy from an ambient system can also provide the desired electrical energy for micro-power devices. Electromagnetic EHs are essentially built from permanent magnets to produce a strong magnetic field, and coils are used as a conductor. As an example, when a permanent

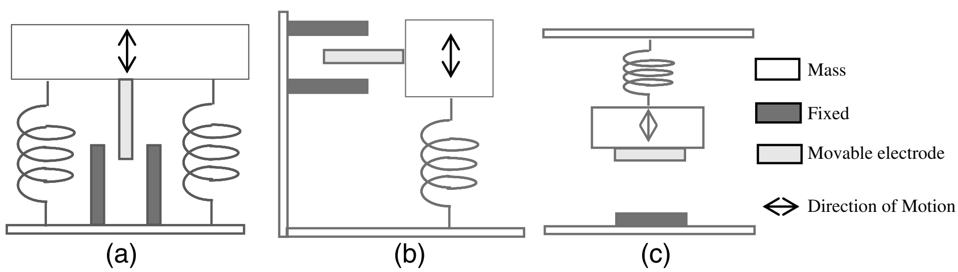


Figure 1.3 Electrostatic energy-harvesting process: (a) in-plane overlap, (b) in-plane gap closing, and (c) out-of-plane gap closing.[11]

magnet moves relative to the fixed coil, it produces an electromotive force or a magnetic field in the coil. The changes in the magnetic field with respect to time produces a magnetic flux, which leads to the establishment of a net current in the wire and an output voltage in the voltmeter, as shown in Fig. 1.4.[12–14]

1.2.3 Piezoelectric energy harvesting

Many materials (natural and synthetic) exhibit piezoelectricity. Crystals that acquire a charge when compressed, twisted, or distorted are said to be piezoelectric. This phenomenon provides a convenient transducer effect between mechanical and electrical oscillations. The generation of an electric potential in certain nonconducting and noncentrosymmetric materials under mechanical stress, e.g., pressure or vibration, can work in either d_{33} mode or d_{31} mode, as shown in Fig. 1.5.[11,15]

In d_{31} mode, a piezoelectric material is polarized in the direction perpendicular to the lateral force, as shown in Fig. 1.5(a). In d_{33} mode, the material is polarized in the direction parallel to the applied force, as shown in Fig. 1.5(b). A piezoelectric cantilever beam in d_{31} mode is commonly used because it produces high lateral stress under external pressure or force.

Piezoelectric materials can be divided into four different categories: polycrystalline ceramics, single crystals, polymers, and composites. In single-crystal materials, positive and negative ions are organized in a periodic

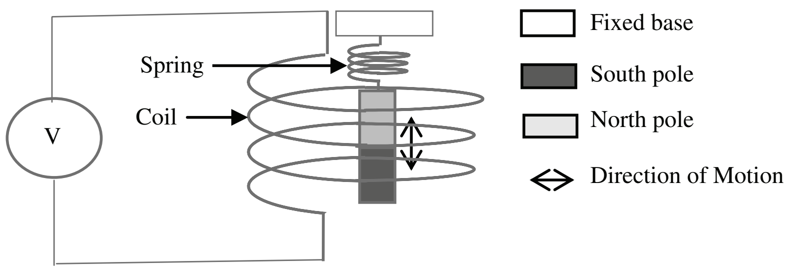
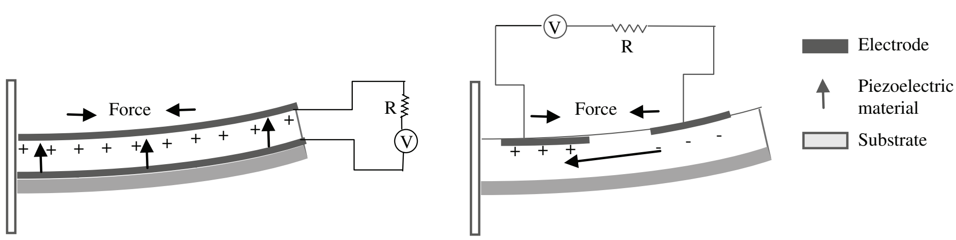


Figure 1.4 Electromagnetic energy-harvesting process where a moving magnet vibrates with respect to a fixed coil.[11]



(a) (b)

Figure 1.5 Two types of piezoelectric energy harvesters: (a) d_{31} and (b) d_{33}.

fashion throughout the entire material, except for the occasional crystalline defects. One of the most widely used (in sensors and actuators) piezoelectric single crystals is a solid solution of lead magnesium niobate–lead titanate (PMN-PT). In contrast, ceramics, such as lead zirconate titanate (PZT), are polycrystalline materials, and polyvinylidene fluoride (PVDF) is a polymer material. In conclusion, piezoelectric energy harvesters offer many advantages, including high reliability, high energy-conversion efficiency, high output voltage with low current level, and high output impedance.

1.2.4 Magnetostrictive energy harvesting

Magnetostrictive materials have specific properties that show a coupling relationship between strain and stress mechanical quantities, and magnetic and induction field strength. Magnetostrictive materials have a constitutive relationship that directly couples mechanical and/or thermal variables to magnetic variables, and they are used to build actuators or sensors.[16] Magnetostrictive materials include several common kinds, such as iron and nickel, and they have different advantages, including ultra-high coupling coefficients, high flexibility, being suited to high frequency vibration, and no depolarization problem.[16] Magnetostrictive harvesters are divided into two main categories: direct force or force-driven, and inertial or velocity-driven, as shown in Fig. 1.6. The figure includes two conceptual implementations of the mechanical part. Figure 1.6(a) shows where active material is used between the source of the vibrations and a reference frame.[11] The magnetostrictive rod is bound to a rigid frame and undergoes a time-variable, uniform vertical force (z axis). A z-axis-directed compressive stress then appears, and the material generates a time-variable magnetization. Figure 1.6(b) is suitable when a vibrating frame is available.[12] Here, one end of a magnetostrictive cantilever beam is rigidly connected to the vibrating frame; the other end is attached to a heavier mass. Because of the induced oscillations over the mass, the material undergoes a longitudinal stress that leads to time-variable magnetization. Both methods share some common needs: a coil wrapped around the magnetostrictive material and a magnetic circuit to convey and close the magnetic flux lines.

In brief, vibration energy harvesting is considered one of the most promising real solutions to provide electrical energy for many low-power electronic devices. Vibration EH devices (from macroscale- to microscale-size) harvest wasted energy from mechanical vibrations and provide the advantage of a robust, reliable, and inexpensive technique. Improvements to the efficiency of vibration EH technologies can lead to efficient nonlinear dynamics, improved material properties, and enhanced conversion efficiency.

1.2.5 Photovoltaic energy harvesting

Ambient light can be also used when harvesting energy to produce electricity using photovoltaic (PV) cells, which transform incident photons into electrical

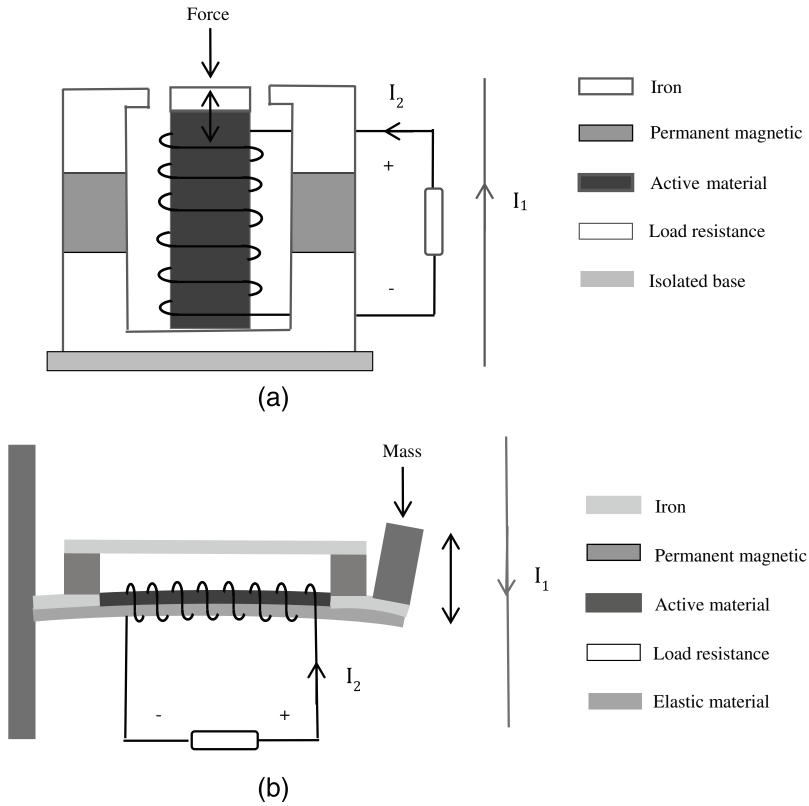


Figure 1.6 Main types of magnetostrictive energy harvesters: (a) force driven and (b) velocity driven.

energy. PV energy harvesting has different advantages compared to other ambient EH methods, such as its status as a self-powered system, outdoor efficiencies that range from 5% to 30% (depending on the material used), an indoor power density of ~10–100 μW/cm^2, and relatively low-cost PV cells.[7,18] Because PV technology is well developed and many reviews have been published (e.g., Ref. 19), it will not be discussed here. In brief, Fig. 1.7 shows types of PV solar cells and their material components, and Fig. 1.8 shows the operating mechanism of a PV solar-cell system.

1.2.6 Radio-frequency energy harvesting

Another source of ambient energy is radio-frequency (RF) energy or radio waves that come from radio transmitters around the world, including mobile telephones, handheld radios, mobile base stations, television/radio broadcast stations, and public telecommunication services (e.g., GSM, WLAN frequencies).[7] The ambient RF energy has a low power density, ranging from 0.2 nW/cm^2 to 1 μW/cm^2, compared to other ambient energy sources.[21]

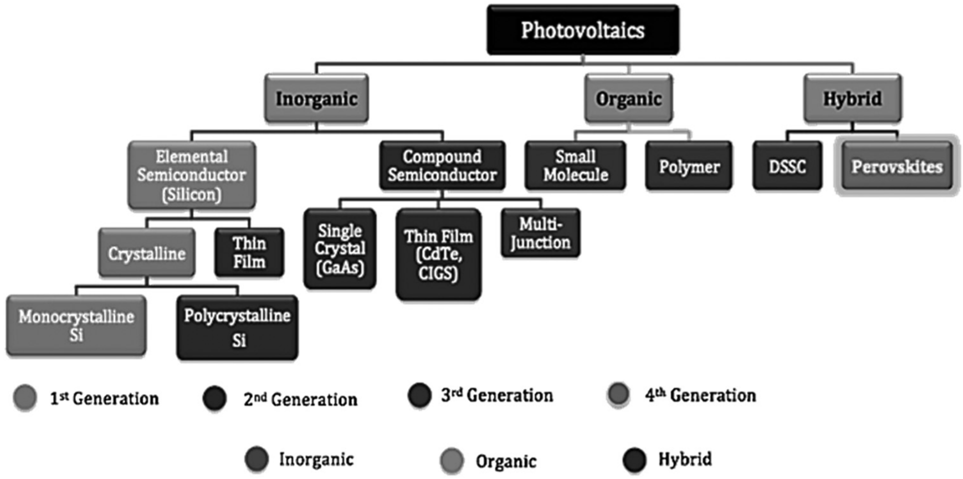


Figure 1.7 Basic classification of photovoltaics.[20]

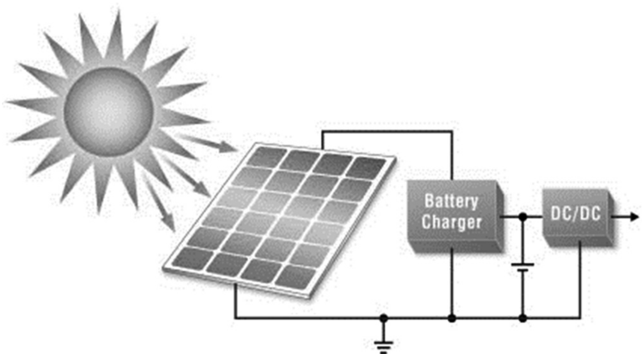


Figure 1.8 Simple operating mechanism of a PV solar cell.

RF energy-harvesting technologies are primarily suitable when charging a battery and a supercapacitor-free wireless sensing node is placed in areas that are difficult to access (e.g., bridges, buildings, chemical plants, and aircraft) with permanent operation.[22] Ambient RF energy-harvesting systems can be easily included with different kinds of antennas along with other harvesting tools, such as solar cells.[23,24] The simple form of converting RF energy into electricity is shown in Fig. 1.9.

1.3 Thermal-to-Electricity Conversion

Thermal-energy harvesting is defined as a process by which the heat energy is collected from an external thermal source and converted to electrical energy by a thermoelectric generator for use in low-power electronic devices. Thermal energy harvesting relies on a basic principle in thermodynamics

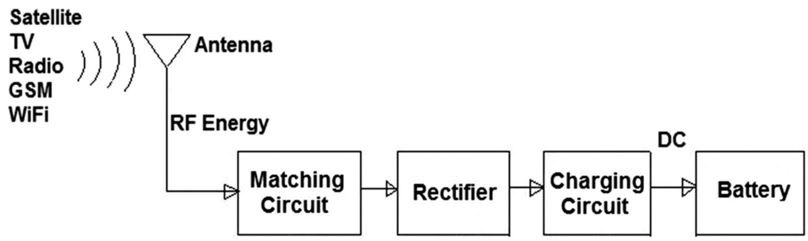


Figure 1.9 Simplified schematic of RF energy-harvesting technology.

called the thermoelectric or Seebeck effect, discovered by Thomas Johann Seebeck in 1821. It states that the gradient temperature between two junctions of dissimilar metals generates an electric potential. In contrast, the application of an electric current through two junctions of dissimilar metals generates a temperature difference between junction points, a property called the Peltier effect. However, the produced energy that comes from thermal energy is generally low, but it has many applications, especially in industry and military, e.g., microelectromechanical systems and infrared detectors. A simple version of a thermoelectric system that converts thermal energy into electrical energy is shown in Fig. 1.10. There are two major implementations that use the thermoelectric effect: a Seebeck-effect thermoelectric generator and Peltier-effect thermoelectric cooling.

1.3.1 Seebeck-effect thermoelectric generator

A thermoelectric generator (TEG) is a solid device that converts heat (temperature difference) into electrical energy; spacecraft represent one example of an application of this property. Unlike solar PV cells, which use large surfaces to generate power, TEG modules are designed for very high power densities, on the order of 50 times greater than a solar PV. A simple TEG includes two metal-semiconductor junctions, where one side is hot and the other is cold. The hot side of the metal has a higher concentration of

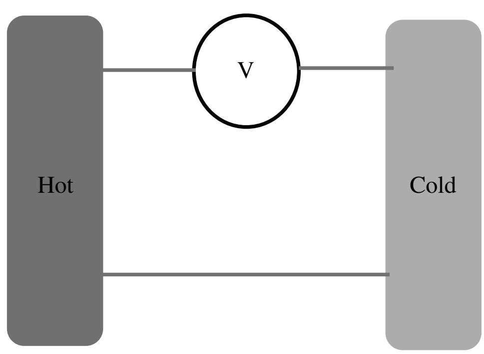


Figure 1.10 Schematic of a simple thermoelectric generator.

electrons and higher energy. The electrons start moving towards a cold side that has lower energy, the gradient in concentration drives diffusion of electrons and holes from hot to cold (p-n in Fig. 1.11), and a current is generated as a result of this motion.[25]

1.3.2 Peltier-effect thermoelectric cooling

Thermoelectric cooling (TEC) converts electrical energy or power into heat flux between the junctions of two types of materials. A device using TEC has several names, such as Peltier heat pump, solid state refrigerator, and thermoelectric cooler. The Peltier device is a heat pump, i.e., when direct current runs through it, heat is moved from one side to the other. Therefore, it can be used for either heating or cooling (refrigeration), although in practice the latter is more common. Practically, the net amount of heat absorbed at the cold end due to the Peltier effect is decreased by two sources: conducted heat and Joule heat.[26] As shown in Fig. 1.11(b), when current is passed through two different semiconductor materials, connected electrically in series, one surface becomes cold, and the opposing surface is hotter. The efficiency of this process depends on the Peltier coefficient and the thermal conductivity of the materials. The main advantages of TEC are as follows: infrequent maintenance is required, no toxic gases (e.g., chlorofluorocarbons), very small physical sizes or low cooling capacities are possible, and unusual shapes can be accommodated. However, the semiconductor materials can be brittle and require a large amount of power; therefore, thermoelectric modules exhibit a relatively low efficiency. Thermoelectricity still requires fans and conventionally finned heat exchangers to dissipate heat to air.

1.3.3 Thermoelectric materials

Thermoelectric materials produce electrical power directly from heat by conversion of temperature gradient into electric voltage. Good thermoelectric materials have high electrical conductivity, low thermal conductivity, and a

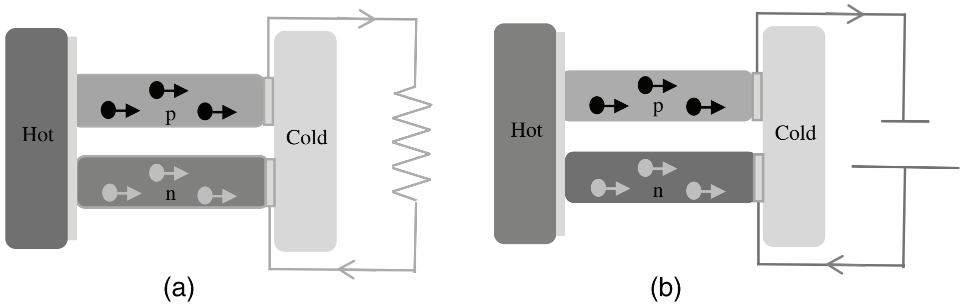


Figure 1.11 A thermoelectric circuit composed of (a) a Seebeck thermoelectric generator and (b) Peltier thermoelectric cooling.

high Seebeck-coefficient value; the efficiency of thermoelectric materials is given by their figure of merit. Various thermoelectric materials have been synthesized and developed in recent years. Thermoelectric materials are little known, very expensive, and commercially available. The most common thermoelectric materials are bismuth telluride (Bi_2Te_3) and lead telluride (PbTe). The crystal structure of PbTe is shown in Fig. 1.12.

1.4 Commercial Energy-Harvesting Devices

Typically, each energy harvester is designed to harvest a single form of ambient energy, but a few companies have reported new chips that can harvest energy from multiple sources, such as RF, thermal, and solar energy. The most common commercial EH devices that are available in markets are listed in Table 1.4. In general, EH devices are designed based on different criteria, such as the frequency of operation, the power generated, and the power transferred to the management circuit.[27] There are a limited number of companies that specialize in manufacturing energy harvesters from one or a small number of energy sources, such as Linear Technology's (Milpitas, CA, USA) LTC3107, which is designed to collect power only through the use of thermoelectric devices. Powercast's (Pittsburgh, PA, USA) PCC110 also has a high peak-conversion efficiency of 75%, as well as a good sensitivity of 17 dBm, because it is optimized to harvest only from RF energy sources within the broadband range of 100 MHz to 6 GHz. Powercast offers transmitter (WPT series) and receiver (WPR series) devices that can respectively beam and harvest RF energy. The maximal transmitted power is limited to 1 W for compliance with RF safety standards. The receiver has a conversion efficiency of up to 70%. Voltage outputs from 1.2 V to 6 V are available.[21,28] However, other devices (bq25505, SPV1050, and MAX17710)

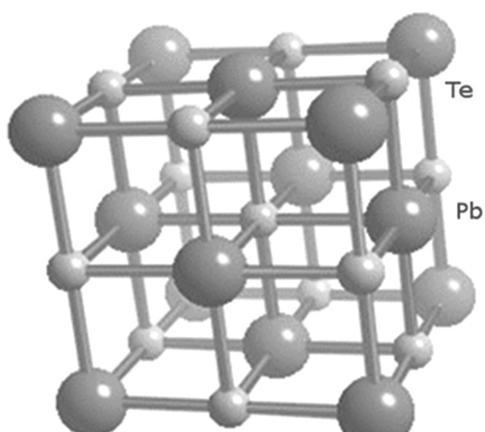


Figure 1.12 Crystal structure of a thermoelectric material, lead telluride (PbTe).

Table 1.4 Commercial EH devices and their characteristics.[21,27]

Device Name	Company	Output Voltage	Output Current or Output Power	Type of EH	Energy Source
WPT + WPR series	Powercast	1.2–6.0	160 μA @ 905.8 MHz; 23 μA @ 2.4 GHz	EM	RF
MAX17710	Maxim Integrated	1.8, 2.3, or 3.3	625 nA	EM, optical, thermal	RF, solar, and thermal
PCC210	Powercast	5.5	50 mA	EM	RF
LTC3107	Linear Technology	4.3	80 nA (energy harvesting); 6 μA (no energy harvesting)	Thermal	Solar and thermal
bq25505	Texas Instruments	5.0	325 nA	Thermal	Solar and thermal
SPV1050	STMicroelectronics	3.6	70 mA	Thermal	Solar and thermal
STM 330/331/332U/333U	EnOcean	3–5	22 μA to 5 mA @ 1000 lx	Optical or thermal	Solar
Solio® Solar Charger	Solio	4–12	165 mA @ 1000 W/m^2	Optical or thermal	Solar
HZ-2	HiZ Technology	3.3	300 mW @ $\Delta\theta$ = (100°C – 20°C) load matched	Thermal	Thermal
TGM-127-1.0-1.3	Kryotherm	2.6	485 mW @ $\Delta\theta$ = (100°C – 20°C) load matched	Thermal	Thermal
CZ1-1.0-127-1.27HT	Tellurex	3.5	500 mW @ $\Delta\theta$ = (100°C – 20°C) load matched	Thermal	Thermal
PMG7-50/60	Perpetuum	3.3	0.1–0.4 mW @ 25 mg; 2–5 mW @ 100 mg	Piezoelectric	Mechanical
FS energy harvesters	FerroSolutions	3.3	0.4 mW@ 20 mg; 9.3 mW @ 100 mg	Piezoelectric	Mechanical
APA400M-MD	Cedrat	N/A	40 mW @ 35 μm, 110 Hz	Piezoelectric	Mechanical
Volture	MIDE	N/A	43 μW @ 240 mg, 120 Hz	Piezoelectric	Mechanical
MFC	Smart Material		120–390 mJ @ 1 G, 10 Hz	Piezoelectric	Mechanical

can harvest power from multiple energy sources, including solar, RF, and thermal energy, to produce more power. For the purpose of design and development, a universal energy-harvesting evaluation kit—the EnerChip energy processor (CBC-EVAL-12)—was developed by Cymbet Corporation (Elk River, MN, USA).[29] This kit can harvest multiple ambient energy sources, such as RF/EM, solar, thermal, and mechanical energy, while having two internal 50-Ah solid state batteries in parallel as an energy-storage device.

The STM 33x series (EnOcean) is an autonomous system that accepts signals from output voltage sensors. STM 33x is optimized to realize wireless and maintenance-free temperature sensors, or room operating panels, including a set-point dial and occupancy button. It requires only a minimal number of external components and provides an integrated and calibrated temperature sensor. The solar cell is divided into two sections: 70% of the area is used to charge a 0.1-F supercapacitor (main energy storage), and the remaining 30% area is used to enable a fast start when the supercapacitor is depleted.

The Solio® Universal Hybrid Solar Charger has been designed to charge iPods® or cell phones at outdoor irradiances. An internal rechargeable battery (3.6 V and 1600 mAh) is provided for extra energy storage. It can also be charged from a wall adapter. Some kind of power management is also implemented to provide voltage outputs between 4 V and 12 V; with an outdoor irradiance of 1000 W/m^2, the current generated is 165 mA.

The PMG7 (Perpetuum) is designed essentially from a magnet and coil arrangement that converts the kinetic energy of vibration into a low-power electrical signal (Faraday's law). It is designed to resonate at the main frequency (50 Hz or 60 Hz). A 3.3-V regulated output is provided, but otherwise there is no energy storage. The FS energy harvester (Ferro Solutions) also relies on Faraday's law. Its natural frequency is 21 Hz. A 3.3-V regulated output (by default) is provided; a supercapacitor is used to store energy, but no data about its value is available. An APA400M-MD (Cedrat) is a piezoelectric harvester based on a proof mass configuration. Its natural frequency is 110 Hz. This harvester includes an AC–DC rectification stage and a fly-back DC–DC converter.

Volture (MIDE) uses the piezoelectric principle. Natural frequencies from 50 Hz to 150 Hz are available. Kinetron provides only energy transducers that transfer mechanical energy to an AC voltage. ECO 100 (EnOcean) harvests energy from linear motion to power its own transceiver, but it cannot power the Ember transceiver. The harvester provides a burst of power each time it is externally actuated. Model 101 (Etesian Technologies) powers an internal wind meter with the same wind source.

Manufacturers of commercial thermal transducers based on the thermoelectric (Seebeck) effect include Thermo Life, Micropelt, TECA Corp., Peltron GmbH, TE Technology Inc., HiZ Technology, Kryotherm, and

Tellurex. Devices from the last three manufacturers can accept continuous operation of the Ember transceiver if there is a temperature difference of 80ºC.

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