Chapter 1

Energy Harvesting

1.1 Introduction

The generation of electrical energy involves an energy-to-energy conversion process such as mechanical-to-electrical (ME), chemical-to-electrical (CE), solar-to-electrical (SE), radio frequency-to-electrical (RFE), and thermal-to-electrical (TE). ME conversion is used in hydroelectric and wind turbines for large-scale generation to meet the demands of cities. CE conversion is used in batteries to provide portable electrical energy. TE conversion is a technology under development. SE conversion uses solar energy to generate electrical energy. Solar farms provide electrical generation on a large industrial scale as well as for individual home owners. RFE converts electromagnetic energy in the millimeter (mm)-to-micron-wavelength range of the electromagnetic spectrum to electrical energy.

Currently, energy harvesting refers to the nonchemical generation of small amounts of electrical energy on a local scale using one of the above energy conversion principles. Among the above energy conversion processes for electrical energy harvesting, even under very low light levels, SE conversion has generally been found to be the best choice and is widely used in consumer goods and many other products. For example, SE conversion is used to power wrist watches, calculators, road signs, and in practically any other application where solar illumination is available and its space and power requirements can be met. The energy output of SE-based energy harvesters is limited by the size of the solar cell. However, in many energy-harvesting applications, a few microwatts of power may suffice and can be obtained. For 24/7 operation, storage devices such as rechargeable batteries and super-capacitors have been used.

It is, however, important to note that in many applications, the use of SE conversion is not practical, such as in enclosed environments where enough light is never available. The use of SE conversion may also be impractical due to the required size of the solar collector and its collection and storage components. Examples of such cases include self-powered and networked sensors used on machinery to monitor vibration and health in industrial plants; sensors for use inside an enclosed space such as in vehicle tires or inside a machine body; or self-powering of encapsulated microelectromechanical systems (MEMS)-type sensors of various types. In many applications, the energy that has been made available for harvesting is in the form of mechanical kinetic and/or potential energy, or even impulsive loading of some form.

As a result, in many applications, energy harvesters based on converting kinetic and/or potential energy to electrical energy become the only viable option. Certain ME-based energy-harvesting devices, such as those employing piezoelectric transducers, also have the unique capability of being used as sensors, for example, for detecting and measuring acceleration or force generated due to a specific emergency event.

Today, energy harvesters may be designed to provide perpetual power for autonomous wireless sensor nodes, or pulse power for short-lived one-time use, as in initiation or emergency systems. Design of energy harvesters is determined by both the local energy source (host system) and by the interfacing mechanism, particularly for motion-based energy-harvesting systems. Available sources of energy for harvesters can be grouped into either ambient or man-made. The former category includes natural sources such as solar radiation, thermal gradients, wind, and ocean waves. Man-made sources may arise as by-products of various activities and processes, for example, background energy from radio-frequency signals generated primarily for use in telecommunication systems, or vibrational energy resulting from vehicles or large industrial systems, such as production machinery.

The choice of a particular energy source is determined by the operational environment, available energy density, and the required energy level to power the intended device. Figure 1.1 shows some of the popular energy sources and the corresponding energy density. It should be noted that, while the solar

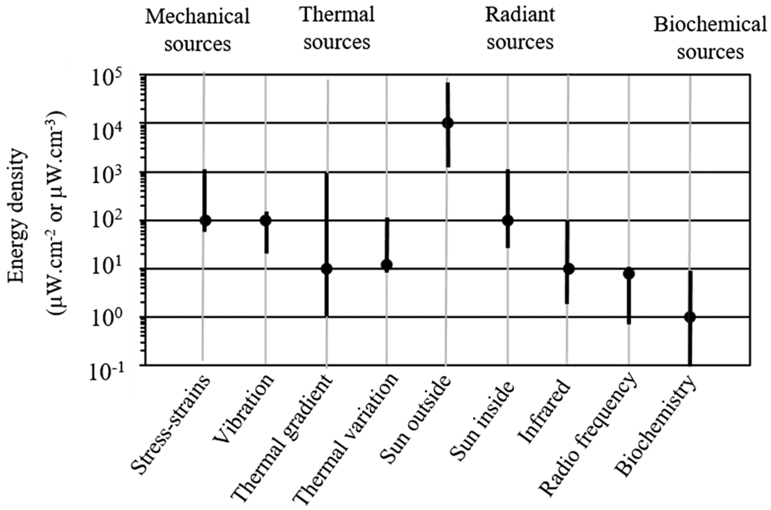

Figure 1.1 Energy densities of typical ambient energy sources.[1]

luminance has the highest available power density, it cannot be changed, and its availability is not always guaranteed.

The primary focus of this book is on harnessing mechanical potential and/or kinetic energy. Other sources of energy are also available, such as thermal gradient and radiated electromagnetic energy. The latter sources of energy are briefly described below. A brief description of the application of energy harvesting for self-powering implantable devices and sensors in the human body is also provided. The reader is referred to available literature for an in-depth treatment of the subject and for other sources of available energy for harvesting.

1.2 Thermal-to-Electrical-based Energy Harvesting

The thermoelectric effect[2] is used to convert temperature difference into voltage. An implementation of the effect in a loop constructed of two dissimilar conductors generates an electromotive force V_{emf} when a constant temperature gradient exists between the two common points. The generated voltage is given by

$$V_{emf} = (\alpha_1 - \alpha_2)\Delta T, \tag{1.1}$$

where α_1 and α_2 are the Seebeck coefficients for the two dissimilar conductors. The value of α may range from –100 μV/K to 1000 μV/K for common conductors.[3] Very large temperature differences are needed to produce useful operating voltages compatible with electronic integrated circuits. In order to make a useful generator, conductors are typically replaced by n- and p-type semiconductors, as illustrated in Fig. 1.2. This configuration allows heat transfer in the same direction, while the voltage difference across the n- and p-type materials is additive.

The power output of an n-p-based thermoelectric generator is proportional to the square of the temperature difference between the hot and cold surfaces and is proportional to the physical cross-sectional area of the n-p legs. For example, the generated power density at a temperature difference of 200 °C is on the order of 100 mW/cm^2.[5]

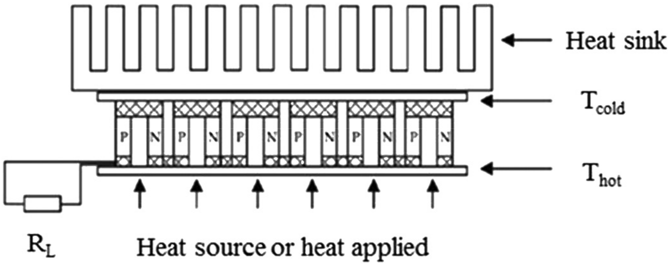

Figure 1.2 Thermoelectric-generating cell n- and p-type semiconductors.[4]

1.3 Solar-to-Electrical-based Energy Harvesting

The most dominant source of radiated electromagnetic energy is solar energy, which illuminates the surface of the earth at a nominal value of 1 $\mathrm{kW \cdot m^{-2}}$. Solar energy may be harvested indoors and outdoors using photovoltaic devices. This makes solar energy the first choice for harvesting, as long as it satisfies the constraints of the devices or systems to be powered. For example, the device to be powered may not have direct solar radiation or may require uninterrupted power during daytime as well as during the night without the use of a storage device due to size or weight limitations.

Photovoltaics technology primarily targets the visible-to-near infrared part of the electromagnetic spectrum. The transducers, commonly referred to as photovoltaics or photocells, are quantum devices that directly generate electron–hole pairs from the absorption of incident photons within the depletion region of a p-n junction device. These devices are generally modeled as a current source shunted by an ideal p-n junction diode. For indoor applications, electrical energy generated will also depend on the spatial characteristics of the light source as well as the distance of the transducer from the source. For example, a 100-W incandescent bulb is expected to generate a few microwatts at the output of a 2-mm diameter photovoltaic cell placed at a distance of 2 m.

1.4 Radio-Frequency-to-Electrical-based Energy Harvesting

RFE technology harvests electromagnetic energy in the radio-frequency band from megahertz to microwave. RFE devices typically have a tuned receiving antenna for converting the received RF energy into electrical energy. The power generated by RFE harvesters is extremely low unless the receiver is in close proximity to the source and/or the receiver is very large. Some of these energy-harvesting devices use the ambient electromagnetic energy emitted by nearby sources and are finding use in autonomous sensor nodes. However, these types of harvesters cannot be placed inside conductive enclosures.

Directed radiofrequency emissions have also been used for collection by matched receiving antennas (the so-called rectenna).[6] For example, active and passive radio-frequency identification (RFID) systems use such technologies.[7]

1.5 Sources of Energy from Human Activity

Due to the recent proliferation of wearable health monitoring devices and portable electronics, considerable effort is being devoted to harnessing power from voluntary and involuntary human activities, for example, from the pulsating motion of the heart.[8,9] Table 1.1[10] compares nominal values of power available from human activity and the corresponding power needs of some typical applications. In addition to harnessing energy from human locomotion,

Table 1.1 Energy output from human locomotion[10]

Human Activity	Power (W)	Application	Power (W)	Possible human activity
Pushing a button	0.3	TV remote	0.1	Finger movement
Shaking	0.4	Portable radio	0.72	Finger movement/Hand crank
Squeezing a handle	3.6	Mp3 player	0.16	Hand crank
Twisting	12.6	Cell phone	2	Hand crank
Bending	20	Laptop	2	Hand crank
Pushing	20	Flash light	4	Hand crank
Turning a handle	21	Video & camcorder	6	Hand crank
Pulling	23	Notebook	10	Hand crank
Swinging	25	Television	75	Pedaling

devices to convert body heat to electrical energy through thermoelectric conversion and flexible piezoelectric materials embedded into fabrics may soon be coming to the market.

In addition to harnessing energy from human activity, there is considerable interest in attaching self-powered health-monitoring sensors directly to organs, such as the heart. The sensors may also assist the organ's function by providing electrical stimulus, as is the case with heart pacemakers. Figure 1.3 shows an example of an autonomous device mounted on a bovine heart. This heart-assist device uses a flexible piezoelectric energy harvester.[11,12]

On another note, the hidden cost of attaching an energy-harvesting device to a system such as the heart, which is optimized for a particular function, should not be underestimated or overlooked. For instance, the heart, which is a pulsating oscillator with a life cycle of over 5 billion beats has taken nature over 65 million years to perfect. It pumps blood through a circulatory system

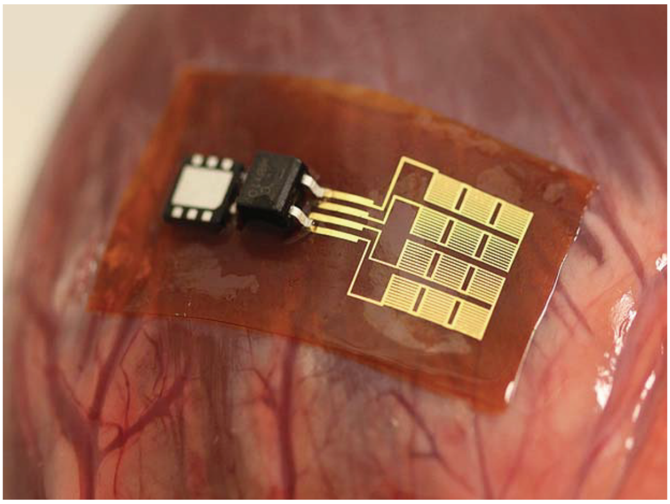

Figure 1.3 A piezoelectric energy harvester, with rectifier and microbattery, mounted on a bovine heart. (Reprinted with permission from Ref. 12.)

of vessels to deliver oxygen and nutrients to individual cells and removes metabolic waste.[13] Attaching an external device, no matter how small, may produce a reactive chain of events from the cardiovascular system. The long-term effects of loading the cardiovascular system are difficult to predict and will require the accumulation of clinical data over many years.

1.6 Mechanical-to-Electrical-based Energy Harvesting

This book focuses on the design of energy harvesters intended for converting mechanical kinetic and/or potential energy from a host system to electrical energy for direct consumption or storage for later use. The process of converting mechanical energy to electrical energy may be described in three distinct phases, as shown in Fig. 1.4. In the first phase, an interfacing mechanism properly transfers the mechanical energy to the transducer. In the second phase, the transducer generates electrical energy. In the third phase, the generated electrical energy is collected and conditioned to be either stored in an energy storage device such as a rechargeable battery or a capacitor or to be delivered directly to the intended electrical energy consuming device (load).

The remainder of this book is divided into four chapters. Chapter 2 describes the three primary types of transducers typically used for converting mechanical energy to electrical energy, that is, piezoelectric, electromagnetic, and electrostatic transducers. Magnetostrictive-based transducers are also briefly introduced. Chapter 3 presents an in-depth analysis of the interfacing mechanisms used for coupling mechanical kinetic and/or potential energy to the transducer for effective energy transfer. Chapter 4 addresses coupling and conditioning circuits needed to extract the generated electrical energy for delivery to the load. The theme of these chapters shows the connection between the three components of an energy-harvesting system, namely, the

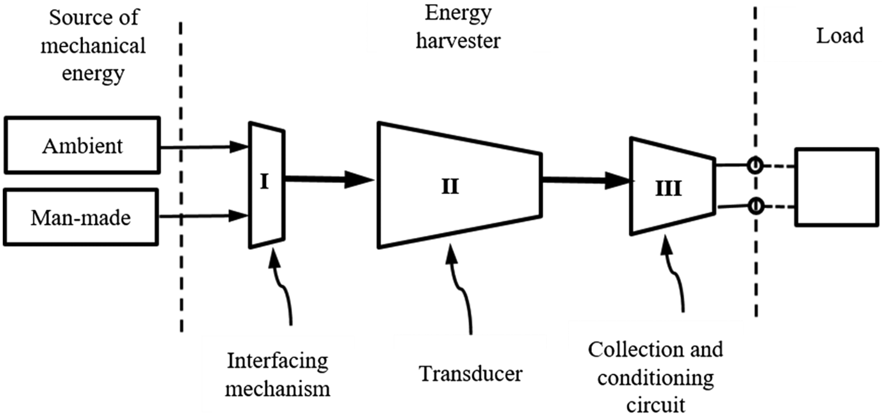

Figure 1.4 The process of harvesting electrical energy from a host system.

interfacing mechanism, the transducer, and the collection and conditioning circuit. Chapter 5 presents case studies of some available energy harvesting system solutions.

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