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Introduction to Micro Energy Harvesting

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1.1
Introduction to the Topic

We are living in an increasingly intelligent world where countless numbers of autonomous wireless sensing devices continuously monitor, provide information on, and manipulate the environments in which we live. This trend is growing fast and will undoubtedly continue. The vision of this intelligent world has gone by many names including "wireless sensor networks," "ambient intelligence," and, more recently, "the Internet of Things (IoT)." Regardless of the current buzzwords, this vision will continue to take shape. We are now realistically talking about a trillion or more connected sensors populating the world. Almost all of these wireless connected devices are currently powered by batteries that have to be periodically recharged or replaced. This state of affairs is simply not practical if we are to have many hundreds of sensors per person on the planet. Alternative autonomous power supplies are becoming more and more critical. Furthermore, these power sources must be small, inexpensive, and highly reliable. This need has given rise to a new field of research, study, and engineering practice, usually referred to as Energy Harvesting. This book is intended to cover the engineering fundamentals and current state of the art associated with energy harvesting at the small scale, or Micro Energy Harvesting.

The term "Energy Harvesting" usually refers to devices or systems that capture (or harvest) ambient energy in the environment and convert it into a useful form, which is usually electricity. Large-scale renewable power generation such as solar arrays, wind farms, and ocean wave generators can be considered forms of energy harvesting. However, for the purposes of this book, we define the term somewhat more narrowly. We define energy harvesting as technologies, devices, and systems that capture ambient energy to replace or augment the batteries in wireless devices. The title of this book is "*Micro Energy Harvesting*". In the energy harvesting literature, the word "micro" sometimes refers to different aspects of the system. The first is the power level. Micro energy harvesting systems generally produce power best described by microwatts, usually 10 – 100s of microwatts. Sometimes, "micro" refers to the scale of the energy harvesting device, that is,

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micrometers. While the overall dimensions of micro energy harvesters are usually in the millimeter or centimeter range, the key features of the transducers are usually microscale. Finally, "micro" sometimes refers more to the fabrication method, using highly parallel fabrication techniques common to the semiconductor and MEMS industries. While many of the techniques covered in this book can be applied across different size scales, we are generally concerned with energy harvesters that can be mass produced at microscales using microfabrication techniques. In practice, some of the devices will be macroscale devices that are moving toward microscale implementations.

Micro energy harvesting covers a broad range of technologies and relies on quite a broad range of fundamental science. A typical engineer or scientist working in the field will most likely be an expert in only a few areas. However, in order to make good engineering decisions, it is important to be well grounded in the entire breadth of the field. This book is intended, in part, to provide a solid foundation in a broad range of technologies that comprise the field of micro energy harvesting.

An energy harvesting system is comprised of four different components as depicted in Figure 1.1. Some form of environmental energy is available (e.g., thermal, solar, vibration, RF, wind). A device or subsystem captures that energy and presents it to an energy converting transducer (e.g., thermoelectric stack, piezoelectric element, photovoltaic cell). In some systems, such as most PV systems, the capture device and transducer are one element. The transducer outputs an electrical current. This current can be unpredictable and requires conditioning before being stored or used by an electronic load. The role of the power electronics is not only to condition the signal for use but also to optimize the power flow from the transducer.

Let's use a vibration energy harvester as a simple example. The capture mechanism is usually a mechanical oscillator of some sort. This oscillator may be a simple linear oscillator or may have more complex modes and/or nonlinearities. The proof mass of this oscillator transfers the energy from the environmental vibrations to a transducer. If the transducer is a piezoelectric element, it will usually form part of the spring and will create some of the damping that characterizes the behavior of the mechanical oscillator. The output of the piezoelectric device will be a high-impedance AC voltage of unpredictable magnitude. The power electronics must condition this output to a stable DC voltage. However, the power electronics also play a role in influencing the power flow from the transducer, which can affect the apparent level of damping and even the natural oscillation frequency of

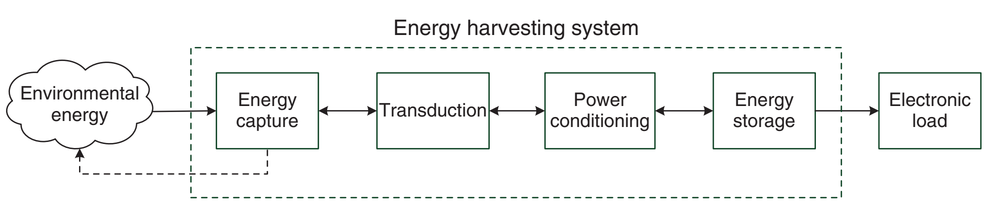

Figure 1.1 General energy harvesting system architecture.

the oscillator. Thus, the arrows shown in Figure 1.1 are bidirectional to indicate that each component of the harvesting system affects the upstream components. While not usually the case, the harvester can even affect the environment in some situations. For example, if the energy harvester is large enough compared to the vibrating body to which it is coupled, it can actually affect the incoming vibrations. A similar breakdown of other types of harvesters could also be made. It is important to recognize that a well-performing harvester needs to be designed with the entire system in mind.

The block diagram of Figure 1.1 is similar to that of a sensor or detector, and, indeed, energy harvesters share many characteristics with these, including the transduction methods employed. However, there are also important differences. In sensor and detector systems, additional power is typically added to the signal at the first stage of conditioning (e.g., in amplification) in order to reduce degradation of the signal fidelity (e.g., by additive noise) in subsequent stages, and this power level is often much larger than that of the received signal. In an energy harvester, of course, any added power for signal conditioning and control functions must be minimized and constitutes a penalty against the power harvested. On the other hand, there is no need to preserve the received waveform characteristics. Within these different constraints, both harvesting and detection/sensing systems generally aim at maximizing the power extracted from the source.

1.2 Current Status and Trends

Of the main types of energy harvesting for small-scale applications, solar (or photovoltaic (PV)) cells are the most mature and long established, with devices such as PV-powered pocket calculators having been available for over 30 years. Further PV development in the last few decades has focused on conversion efficiency and cost, the latter being particularly critical in large-scale applications. Major advances have been made in these metrics. Another area of PV research is the development of devices based on organic materials, which are enabling new integration possibilities such as flexible substrates. Thermoelectric devices for power generation are also long established, but less extensively commercialized than PV systems, although this is beginning to change. In recent years, major research efforts have been witnessed in this field, using a wide range of materials systems, with a strong emphasis on increasing conversion efficiency, but with developments in size, weight and cost reduction, and use of more sustainable materials as well. Nanostructured materials have shown particular promise in recent years for increasing efficiency.

Motion-based energy harvesting has seen major international research efforts for the past 10–15 years, with particular emphasis on inertial devices, that is, devices that extract power from the relative motion of an internal proof mass. The fundamental theory is now well established, and recent developments have concentrated on improved conversion circuits, broadband operation, and application-specific implementations. Some commercial devices have been launched, and this looks set to be a growing business opportunity. Devices based on fluid flow, such as microturbines, have also made impressive advances. A further harvesting method that is attracting attention is the extraction of power from human-made radiation, that is, radio signals from various systems such as cellular communications, WiFi, and others. With the increasing use of wireless communications, opportunities for radio frequency harvesting are growing. One key challenge, as also found in some motion harvesting methods, is to produce DC power from AC sources with voltages below those required for conventional rectification. Promising advances are being made in tackling this problem. Among other harvesting methods, fuel cells using biological sources are also attracting interest.

As discussed above, a key driver for small-scale energy harvesting is the proliferation of electronic devices, particularly sensors, which are not connected to mains power. This includes mobile devices, but also fixed devices where mains connection would be impractical or involve excessive installation costs. Because in most such applications, harvesters will be considered an alternative to batteries, for large-scale adoption they will need to be an attractive alternative. This means they must provide their theoretical promise of perpetual, maintenance-free power by having long lifetimes and high reliability. They must also be competitive on size and cost. An important challenge to achieving low cost is that harvesters tend to need to be designed with specific applications in mind, and so they do not achieve the economies of scale in production that batteries do. Thus, identifying high-volume applications, or harvesters suitable for wide ranges of application without customization, will be critical aims in coming years. On the other hand, the power requirements of key electronic functions, including computation and wireless communication, continue to drop, so the further growth of both the number of wireless devices and the opportunities for micro energy harvesters can be predicted with confidence.

1.3
Book Content and Structure

Micro energy harvesting covers a broad range of technologies and relies on quite a broad range of fundamental science. A typical engineer or scientist working in the field will most likely be an expert in only a few areas. However, in order to make good engineering decisions, it is important to be well grounded in the entire breadth of the field. This book is intended, in part, to provide a solid foundation in the broad range of technologies that comprise the field of micro energy harvesting, and in another part, to cover the state of the art and trends in the field. We consider the book to be valuable for engineers who would like to get an introduction to the topic. Moreover, its structure and large coverage of the topic are intended to support graduate courses and lectures. The book would also be an excellent reference to early stage researchers who consider to research in this field or to apply part of the knowledge and technology available to their research. The topic of energy harvesting is broad. So, hopefully there is something valuable to learn here for readers from diverse backgrounds. We believe that the content of this book is sufficiently broad, yet detailed and deep enough that even those readers who are familiar with the topic will profit from reading and studying its contents.

This book covers fundamentals and devices for harvesting energy from vibrations, fluid flow, acoustics, heat, light, RF radiation, and chemicals. An emphasis is especially given on the topics of kinetic and thermal energy harvesting for which microscale technologies have been readily developed. In addition, it covers topics applicable to any energy source, such as power electronics, and micro energy storage devices, and it gives some insights into few selected applications and the trends in the field. These topics are divided into three specific sections: Fundamentals and Theory, Materials and Devices, and Systems and Applications. The section on Fundamentals addresses all the aspects related to the basics and theory of power electronics as well as micro harvesting from thermal and mechanical energy, such as heat transfer, thermophotovoltaics, mechanics and dynamics, and transduction principles. In the section on Materials and Devices, thermoelectric and piezoelectric materials and harvesting devices are thoroughly reviewed in a set of chapters. The topic of vibration energy harvesting also includes chapters on electrostatic, electromagnetic, and wideband energy harvesters. These are also complemented by contributions on fluid flow and acoustics energy harvesting. This section is finally completed with chapters on harvesting energy from RF radiation, light and chemical energy sources, addressing rectennas, solar cells and microbial fuel cells, respectively. In the last section on Systems and Applications, electronics for energy conversion and power management as well as energy storage devices are addressed. Applicative chapters focusing on kinetic and heat energy harvesting are concluding the book.

Finally, we would like to take the opportunity to warmly thank all the authors who contributed with an outstanding chapter in their field of expertise, which, by their quality, will hopefully make this book become a standard reference in the field.