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Environmental Technology & International Affairs

Micropower Energy-Harvesting Devices: Areas of Application and Near-Future Potential

A Master's Thesis submitted for the degree of
"Master of Science"

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Vienna, 16 June 2016

Affidavit

I, **VICTORIA JOYCE HAYKIN**, hereby declare

1. that I am the sole author of the present Master's Thesis, "MICROPOWER ENERGY-HARVESTING DEVICES: AREAS OF APPLICATION AND NEAR-FUTURE POTENTIAL", 71 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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ABSTRACT

Pinpointing secure and reliable methods of renewable-energy generation remains a challenge for policymakers, energy analysts, industry experts and researchers alike. Indeed, it has become increasingly apparent that no “one-size-fits-all” approach to this dilemma exists. This thesis therefore examines a relatively unknown form of small-scale renewable energy generation, namely micropower energy harvesting, which offers a novel and innovative solution to the clean-energy crisis by enhancing energy security, curtailing energy consumption and reducing material and installation costs. Micropower energy-harvesting devices harness the power of energy sources widely available in the ambient, including chiefly mechanical, thermal, solar and magnetic energy, and transform it into useable electricity. As the power output of micropower harvesting modules is in the microwatt to milliwatt range, these technologies can replace or augment the lifetime of batteries in ultra-low power devices, such as wireless sensor networks (WSNs), but have the potential to reclaim waste-heat from the tailpipes of automobiles, to power medical implants and to reduce the conventional power consumption of everyday devices such as mobile phones and laptops, offering numerous benefits to the developed and developing world. Although energy harvesting already constitutes a viable option for WSNs, the results of this thesis reveal that limitations in power output are currently preventing large-scale implementation. Nevertheless, policy-based conclusions and recommendations are offered, and a summary of near-future technological readiness levels and areas of future application, in both industrialized and developing nations, is presented.

Keywords: micropower; energy harvesting; piezoelectric; thermoelectric; electromagnetic; photovoltaic; wireless sensor networks; renewable energy

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LIST OF ABBREVIATIONS

BSN	Body sensor network
CAGR	Compound annual growth rate
DAP	Digital audio player
ETRL	Estimated technological readiness level
FCC	Face-centered cubic (lattice)
FF	Fill factor
GPRS	General packet radio service
HVAC	Heating, ventilating and air conditioning
LDC	Least developed country
MEMS	Microelectromechanical systems
MIC	Middle income country
PDA	Personal digital assistant
PEH	Piezoelectric energy harvester
PV	Photovoltaic
RMS	Root mean square
SSA	Sub-Saharan Africa
TEG	Thermoelectric generator
VEH	Vibration energy harvester
WSN	Wireless sensor network

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si quis amat quod amare iuvat, feliciter ardens
gaudeat, et vento naviget ille suo.

~ Ovid, *Remedia amoris*

1. INTRODUCTION

1.1 RESEARCH QUESTION

As the threat of climate change looms ever closer, viable substitutes for conventional power supplies are becoming increasingly critical. Alternative power sources ought to be renewable, autonomous (requiring very little maintenance), affordable and highly reliable for use in developing nations, where access to energy is unreliable or non-existent, and in industrialized countries actively seeking to decentralize energy generation (Briand et al. 2015). This thesis hypothesizes that an up-and-coming and thus largely uninvestigated avenue of renewable-energy generation, namely micropower energy harvesting, can increase efficient energy usage, provide decentralized solutions for inhabitants of industrialized nations and clean-energy alternatives to the developing world, reduce material consumption associated with infrastructure required for centralized energy distribution and lower installation costs when compared to traditional methods of energy generation. The intention is therefore to determine to what extent the above assumptions hold true under further investigation.

1.2 THESIS OVERVIEW

Energy harvesting has thus far received relatively short shrift outside of certain niche fields of engineering and physics. This thesis therefore fills a gap currently existing in the area of renewable energy technologies. It is intended as a pre-feasibility study and provides a broad overview of potential technologies and techniques, as well as fields of application for further use by policymakers, energy analysts and industry experts alike. To this end, the physical principles and mathematics underlying each device are explained in as accessible a manner as possible, and greater attention is paid to current and technological potential from a policy standpoint, namely ways in which these technologies may in future reduce electricity consumption and provide simple yet cost-effective energy solutions for countries still without widespread access to electricity.

The thesis opens with an introduction to the concept of energy harvesting, in general, and micropower energy harvesting, in particular. It then outlines the various advantages associated with energy harvesting, as well as its disadvantages. The importance of decentralized energy generation for developed and developing countries is likewise considered. The chapter concludes with a brief market analysis, analyzing recent trends and projecting near-future growth to determine the likelihood of continued investment in and production of energy-harvesting devices.

In the following chapters, a state-of-the-art device review of the various most promising energy-harvesting technologies is presented. This includes elaboration of both their technical and physical principles and device parameters to be optimized, in addition to materials, manufacturing trends and potential for power generation. Then, energy-harvesting applications, first in industrialized nations, are considered in order to assess the extent to which commercially viable energy-harvesting technologies are already available, in which sectors they can be applied and their potential for delivering cost-effective and efficient low-power solutions. Fields of application in developing nations are likewise considered. Due to the relative novelty of energy harvesting, little to no literature is available in this area. Analysis of application potential is therefore based upon those energy-harvesting solutions already or soon to be available in the developed world.

1.3 METHODOLOGY

This thesis compiles all relevant technological literature related to the theory and operation of energy-harvesting devices. An economic analysis of market presence is assembled and briefly discussed, and projections for future growth are considered. Data regarding power output, voltage output, efficiencies and other important operating parameters are collated, presented and analyzed. Finally, an overview of major energy-harvesting companies is considered, the performance values of their devices and potential for widespread application are examined.

2. THE BASICS OF MICROPOWER ENERGY HARVESTING

2.1 THE SIGNIFICANCE OF ENERGY HARVESTING

This section presents an overview of energy harvesting and its significance. In addition, the generic advantages and disadvantages of energy harvesting are explored, as well as the important role that energy-harvesting devices can play in reducing society's reliance upon centralized, grid-based power distribution networks.

2.1.1 DEFINING (MICROPOWER) ENERGY HARVESTING

Energy harvesting is a process whereby some amount of energy (small or large) is captured from naturally occurring energy sources in the environment and stored for later use. In contradistinction to "energy scavenging", which implies the existence of unknown or irregular energy sources, "energy harvesting" implies the relative uniformity of energy available in the ambient (Steingart 2009). Energy sources may be thermal, vibrational or photonic in nature (Dervojeda et al. 2015).[1]

Energy-harvesting technologies have been in existence for decades, powering everything from bicycle dynamos and watches to standard pocket calculators (Snyder 2008). Due to the expense of fabrication and low device efficiencies, however, many energy-harvesting techniques have traditionally been employed in extremely niche applications, including space-based technologies and medical devices.[2] Nevertheless, energy-harvesting devices have, in recent years, become increasingly attractive for application in wireless sensors (Dervojeda et al. 2015).[3]

Although large-scale solar power stations and wind farms could be considered forms of "energy harvesting" in the traditional sense of the term, this thesis is concerned chiefly with micropower applications. At the micro-level, energy harvesting usually refers to devices, systems or technologies that capture well-characterized ambient energy at the small-scale and transfer it into useable energy, usually electrical energy (Briand et al. 2015). Micropower energy-harvesting devices are primarily intended to augment the lifetime of a battery or to replace it entirely (Briand et al. 2015).

[1] This list is by no means exhaustive. See Chapter 3, Section 3.1 for a more comprehensive overview of ambient energy sources.

[2] For example, thermoelectric generators (TEGs) were used to moderate the power supply during the Apollo mission and radioisotope thermoelectric generators (RTEGs) have been used to power missions beyond Mars (Jarman et al. 2013). In addition, bio-thermoelectric pacemakers can be powered by temperature differences within the human body or between the body (37 °C) and ambient air (20 °C) (Jarman et al. 2013).

[3] Energy-harvesting applications are discussed in greater detail in Chapters 4 and 5.

In energy-harvesting literature, the prefatory modifier “micropower” may refer to one (or more) of the following aspects of an energy-harvesting system (Briand et al. 2015):

1) Power Level: As the term “micropower” implies, micropower devices typically produce power in the microwatt range (10–100 μW).
2) Device Size: Often “micro” is used to refer to the size of the device. Key features of the transducer (i.e. the device that converts ambient energy into electricity) are usually on the scale of micrometres, although the overall dimensions of the device may span several millimetres or centimetres.
3) Fabrication Method: “Micro” may also refer to the fabrication method of the device. Micropower harvesting devices are sometimes manufactured using highly parallel fabrication techniques similar to those used in the semiconductor and microelectromechanical systems (MEMS) industries.

A micropower energy-harvesting system generally consists of four basic constituents (Briand et al. 2015):

1) Environmental Energy: One of the abovementioned forms of ambient energy is available.
2) Energy Capture and Transformation: A device or system captures the available energy and relays it to a transducer (the “capturing” device and transducer may be combined as in photovoltaic systems).
3) Power Conditioning: Following the conversion process, the transducer outputs an electrical current.
4) Power Storage or Use: As the current may be unpredictable, “conditioning” is required prior to further use or storage.

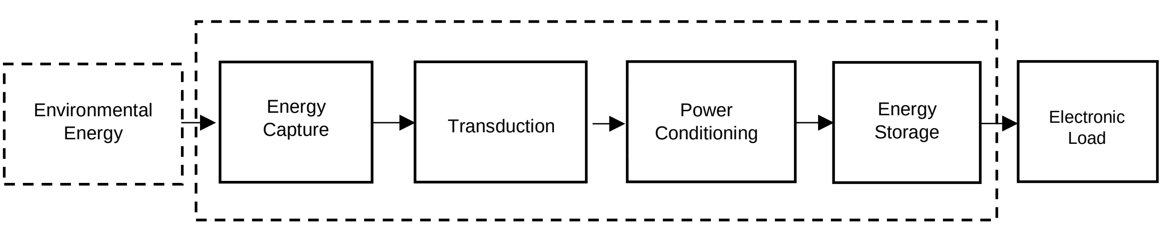


Figure 2-1: General Architecture of an Energy-Harvesting System (after Briand et al. 2015)

2.1.2 GENERIC ADVANTAGES AND DISADVANTAGES OF ENERGY HARVESTING

Energy-harvesting devices have many advantages over more traditional forms of energy generation. By powering sensors or devices wirelessly, the high costs associated with the installation of non-wireless alternatives are removed (Dervojeda et al. 2015). These include chiefly material costs necessitated by the laying of lines and copper cables to accommodate devices connected to the grid. Maintenance costs are likewise reduced as infrastructural upkeep is non-existent and some energy-harvesting devices can operate independently for up to 100,000 hours. Finally, energy harvesters increase efficiency and curtail the consumption or traditional energy sources and their accompanying carbon footprint (Dervojeda et al. 2015).

The disadvantages of energy harvesting are few in number. Energy-harvesting devices are, however, very much application-driven. There is no “one-size-fits-all” solution. Each device must be outfitted to the specifications of the desired application. This naturally places a limit on the energy budget for each existing application (Steingart 2009). In order to ensure fruitful results, therefore, the boundary conditions and gradients of available ambient energy in any given region must be thoroughly considered.

2.1.3 THE IMPORTANCE OF ENERGY DECENTRALIZATION

In addition to the definition of micropower energy harvesting provided above, an understanding of the concept of “energy decentralization” is integral to this thesis. Conventionally, power plants have acted as large centralized units from which generated electricity is distributed to a wide variety of consumers. In future, however, as the share of renewable energy sources continues to rise, base-load fossil-fuelled power stations must offer flexible alternatives, covering energy demand only in periods of limited access to renewable sources (Brauner et al. 2012; Brauner 2013).

As the storage and long-range transfer of renewable energy sources remains an issue, one possible near-future solution involves the adoption of distributed energy systems. Distributed, or decentralized, energy networks not only offer a sustainable, efficient and reliable alternative to centralized power stations, they also bypass many of the complications associated with the large-scale distribution of renewable energies (Alanne and Saari 2006). In a decentralized system, energy distribution units are located in close proximity to consumers, organized and operated in such a way as to ensure the proper amount of electricity is generated to fulfill each individual consumer’s needs.

In industrialized nations, therefore, emerging energy-harvesting techniques can play a significant role during the process of transition from centralized to distributed energy systems. They offer wireless, long-lasting and virtually maintenance-free solutions to more traditional forms of energy generation. Furthermore, decentralized distribution methods may prove the best solution to the energy crisis currently facing many developing nations. In areas where access to the grid is simply not feasible, for climate-related or infrastructural reasons, distributed energy networks tailored to suit the energy demands of each city or village will be required.

2.2 Market Outlook and Prognosis

With an estimated market potential of EUR 3 billion by 2020 and many opportunities for job creation, the market outlook for energy-harvesting devices is largely positive (Curtiss and Eustis 2013). In the following two sections, recent and near-future market trends, including employment opportunities and applications in developing markets, are discussed and analyzed in greater detail.

2.2.1 Recent Market Trends

In 2009, the market for energy-harvesting devices already amounted to EUR 463 million, and by 2011 this number had grown to EUR 530 million with EUR 11 million spent on 1.6 million energy-harvesting devices for application in wireless sensors (Harrop and Das 2011). In 2011, the majority of the energy harvesters in the market segments identified below were solar cells and electro dynamos, both well-established energy-harvesting technologies:

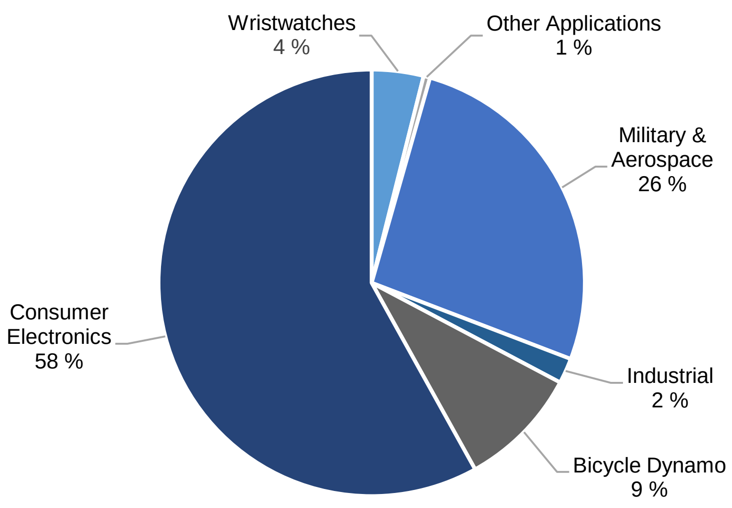


Figure 2-2: Division of Energy-Harvesting Applications in 2011 (Data: Dervojeda et al. 2015)

The global market for energy-harvesting devices topped EUR 750 million in 2014, reaching nearly EUR 1 billion in 2015 with a compound annual growth rate (CAGR) of 23.9 % (Shalini 2015). Currently, energy harvesting is a largely North American and to a lesser extent, European preoccupation. The North American market for energy-harvesting technologies accounted for nearly EUR 500 million in 2014 with a CAGR of 22.7 % through 2020 (Shalini 2015). In future, however, the East Asian market is predicted to gain traction. The Asia-Pacific market approximated around EUR 200 million in 2015 but is estimated to reach nearly EUR 1 billion by 2019, exhibiting a CAGR of 25.6 % (Shalini 2015).

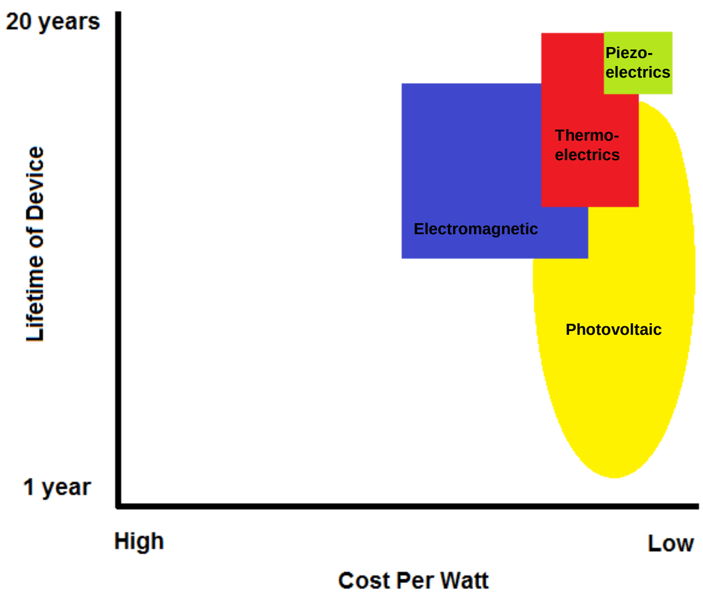


Figure 2-3: Cost-Effectiveness of Energy-Harvesting Devices

As illustrated in Figure 2-3, different energy-harvesting devices (discussed in greater detail below) exhibit different costs per watt (when powering small sensors) over the course of their lifetimes.[4] In general, however, photovoltaic, thermoelectric and piezoelectric devices are all currently quite cost-effective and enjoy long lifetimes. Electromagnetic energy harvesting is an outlier with a higher cost per watt and slightly shorter lifetime than thermoelectric and piezoelectric devices. PV spans a wider range due to the spectrum of available technologies, some of which have short lifetimes.

2.2.2 NEAR-FUTURE MARKET POTENTIAL

Estimates of near-future market potential vary slightly. Market analysts at Yole Développement predict a modest increase to approximately EUR 190 million annually by 2017 (Bonnabel and de Charentenay 2012). They expect the fastest growing market segment to be thin-film thermal technologies for use in wireless sensor networks in the construction and industrial sectors. Figure 2-4 presents a breakdown of the

[4] Note that in general cost per watt figures are poorly defined as a great deal of contention surrounds exact numbers. In addition, the cost-effectiveness of application refers to energy harvesters used primarily to power ultra-low power sensors nodes (see Chapter 4 for context).

development of three primary energy-harvesting sources by industry projected for 2017:

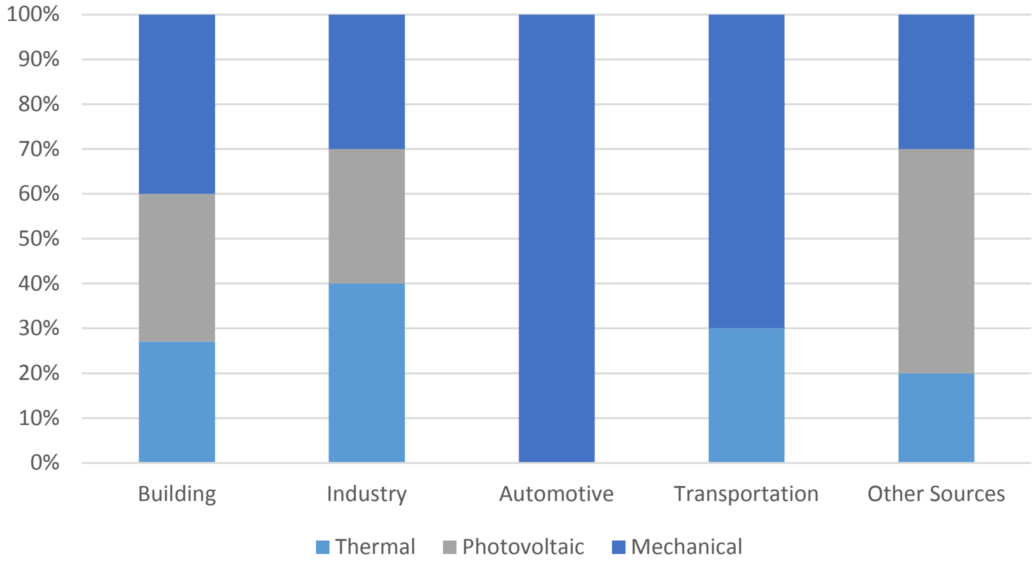


Figure 2-4: Energy-Harvesting Sources by Application in 2017 (Data: Bonnabel and de Charentenay 2012)

The *Energy Harvesting Journal* predicts a projected growth of EUR 3 billion annually by 2019 driven by increased use in consumer products (Harrop and Das 2011). Similar numbers are confirmed by another report, which forecasts that the market for energy-harvesting technologies will reach EUR 3 billion by the year 2020 (Curtiss and Eustis 2013). Technological development and market demand will be largely centred on micropower energy applications requiring microwatts to milliwatts of power (Dervojeda et al. 2015).

2.2.3 ENERGY-HARVESTING DEVICES AND THE JOB MARKET

Although energy-harvesting technologies may render obsolete certain traditional forms of employment (e.g. manufacture or maintenance of non-wireless applications), the positive market outlook promises job opportunities in new application domains. In Europe, leading energy-harvesting companies currently retain very few staff members.[5] As the market for energy-harvesting devices continues to grow, however, analysts predict that the employment outlook will significantly improve (Dervojeda et al. 2015).

[5] EnOcean, the world's largest supplier of energy-harvesting technologies, employed only 60 people in 2010 (Das 2010).

2.2.4 VOLATILE MARKETS AND SCARCITY OF RESOURCES

Technologies competing for market prominence alongside energy-harvesting devices are their non-wireless and battery-powered alternatives. As the material costs for installation (i.e. copper) and battery replacements (i.e lithium) continue to rise, the economical attractiveness and feasibility of wireless alternatives will increase (Dervojeda et al. 2015). In terms of energy consumption, energy harvesters are much more efficient than their wired or battery-powered counterparts. As a result, rising energy prices are also predicted to add value to wireless energy-harvesting solutions (Dervojeda et al. 2015).

2.2.5 MARKET POTENTIAL IN DEVELOPING NATIONS

In developing nations, where energy-harvesting technologies promise to provide wireless, sustainable alternatives to traditional energy sources, the market also shows great promise. Many prominent energy-harvesting companies are looking to expand into emerging economies in the near future.[6] In countries where rotational load shedding is common, energy-harvesting solutions hold the key to electrifying vital systems and infrastructure during blackouts (Dervojeda et al. 2015). Energy harvesters can likewise provide power for critical systems in remote regions and rural areas.

[6] For example, Pavegen Systems' CEO, Laurence Kemball-Cook, aims to bring his company's pioneering floor tiles, which translate pedestrian footsteps into useable energy, into developing markets in the near future (Dervojeda et al. 2015).

3. MICROPOWER ENERGY-HARVESTING DEVICES

3.1 AMBIENT ENERGY SOURCES AND HARVESTING TECHNIQUES

Energy for use by micropower devices can be harvested from a wide variety of energy sources, including vibrational, electromagnetic, acoustic, airflow, thermal and solar. In accordance with Thomas et al.'s early categorization of harvestable energy sources for small-scale systems, the following section explores ambient energy sources that fall within the following classifications (Thomas et al. 2006):[1]

1) Optical Energy:[2] Solar energy provides near limitless potential. Both indoor and solar illumination can be captured using photo sensors, photo diodes and photovoltaic (PV) panels.
2) Thermal Energy: Waste heat from mobile and stationary sources, such as automobiles and machinery, can be reclaimed. Thermal gradients in the human body can be exploited.
3) Magnetic Energy: Depending on application requirements, current-carrying conductors and rotating machinery can be considered sources of ambient energy, assuming they were not constructed solely for the purpose of energy harvesting.
4) Mechanical Energy: Vibrations from manufacturing machines and motors, as well as mechanical stress and strain can be harvested for use as energy sources. Mechanical energy can also be generated from the movement of the human (or animal) body.

3.1.1 OPTICAL ENERGY SOURCES AND HARVESTING TECHNIQUES

Optical energy, in the context of this thesis, spans the infrared to ultraviolet portion of the electromagnetic spectrum. Generally speaking, ambient optical illumination is provided by the sun. Due to the scattering and absorption of light as it enters the Earth's atmosphere, the intensity of solar irradiance per unit area fluctuates. Available power density is dependent upon several factors, including latitude, weather patterns, time of year and hour of the day (Penella-López and Gasulla-Forner 2011). On a sunny day at noon, for example, the incident light on the Earth's surface has a power density

[1] Chemical/biological sources could be included, but are not discussed in what follows. (Biochemical energy can be extracted using fuel cells from enzymes, microbes, glucose or marine sediment.)

[2] Note that optical energy actually falls under the umbrella of "radiant" energy sources, which also includes radioactive energy and radiofrequency (RF) signals. Although radioactive energy sources have extremely high energy densities, they are not explicitly considered here as viable sources of well-characterized ambient energy due to the oftentimes volatile nature of radioactive substances. RF signals are deliberately broadcasted and cannot, therefore, be considered naturally-occurring. For this reason, they have also been excluded from this study.

of approximately 100 mW/cm^2 or 1000 W/m^2 (Penella-López and Gasulla-Forner 2011).

Indoors, optical energy is derived from artificial illumination (e.g. filament and fluorescent bulbs) and solar energy transmitted through windows. Power density in a room is dependent upon distance to the source(s), size, shape and spectral density of the source(s) and the spatial distribution of light (Randall 2005). Power density, when lights are switched on, ranges from 100 µW/cm^2 to 1000 µW/cm^2 (Penella-López and Gasulla-Forner 2011). Photonic energy, both in indoor and outdoor environments, can be converted directly to electricity using PV cells.

3.1.2 THERMAL ENERGY SOURCES AND HARVESTING TECHNIQUES

In the presence of a temperature differential, or gradient, between thermal reservoirs of different temperatures, a harvestable flow of heat occurs. Low-grade (i.e. small) heat differentials, defined generally as temperature differences less than 230 ºC, are widely available between various objects in the environment (Thomas et al. 2006; Johnson et al. 2008). Heat produced as a by-product of industrial processes is a prime example of readily available thermal energy that would otherwise go unrecovered (Johansson and Söderström 2013). Thermal energy is most commonly converted using thermoelectric or pyroelectric transducers (Penella-López and Gasulla-Forner 2011).[3]

3.1.3 MAGNETIC ENERGY SOURCES AND HARVESTING TECHNIQUES

Electromagnetic energy harvesting can be achieved by using a time-varying magnetic field to convert mechanical energy into electricity (Amirtharajah and Chandrakasan 1998). Current-carrying conductors (e.g. power grids) and electric rotating machinery, as well as inductors, coils and transformers can all act as sources of magnetic energy (Penella-López and Gasulla-Forner 2011; Yildiz 2009). Electromagnetic induction in a transducer, in which rotation is induced not by physical movement but rather an alternating current, is the most commonly exploited conversion principle (Penella-López and Gasulla-Forner 2011).

3.1.4 MECHANICAL ENERGY SOURCES AND HARVESTING TECHNIQUES

Mechanical energy is derived from kinetic energy sources, including liquid and gas flow, vibrations, human activity and pressure variations (Roundy et al. 2004). Power

[3] Pyroelectric converters are not discussed in what follows as reported Carnot efficiencies are extremely low (0.02 % and 0.05 % at ambient temperature) (Guyomar et al. 2009). Pyroelectricity is the ability of certain materials to generate voltage when they are heated or cooled. They function very much like piezoelectric generators and can be modelled as a source of AC current in parallel with a capacitor (Penella-López and Gasulla-Forner 2011).

available in the energy of the flow of liquid or gaseous sources increases like the volumetric flow speed cubed (Penella-López and Gasulla-Forner 2011). Ambient vibrations from machinery and vehicles commonly produce frequencies between 50 Hz and 200 Hz and acceleration amplitudes between 1 m/s^2 and 10 m/s^2 (Penella-López and Gasulla-Forner 2011). Mechanical energy can primarily be harnessed using one of three principles: piezoelectric, electrostatic or electromagnetic (mechanical) conversion (Beeby et al. 2006).

In the case of human activity, kinetic energy can be generated either actively or passively. Active generation requires deliberate movement or motion (e.g. hand generators), whereas passive generation exploits the power of everyday activities (e.g. heel strikes). The average human body burns 10.5 MJ daily, the equivalent of 121 W of power dissipation (Yildiz 2009). As sources of power dissipation in the human body are both active and passive, body movement is therefore quite an attractive source of ambient energy.

3.1.5 OVERVIEW OF ENERGY SYSTEMS

By way of summary, Figure 3-1 depicts ambient energy sources available for harvesting (row 1), followed by methods and techniques for implementation (row 2), as outlined in greater detail above:

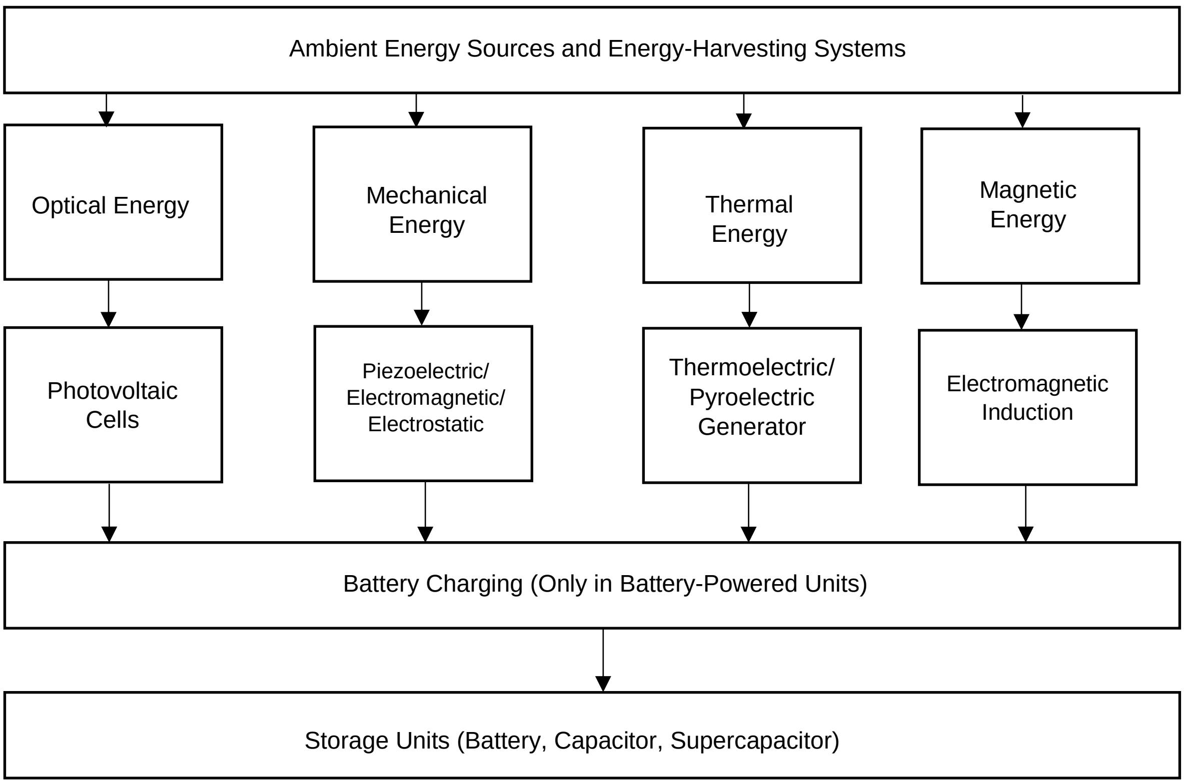


Figure 3-1: Overview of Ambient Energy Systems

As indicated in Chapter 2, no single ambient energy source is sufficient for every conceivable application. The source and its system must therefore be selected in accordance with the characteristics of the desired application as the power density of the various sources varies widely (see Table 3-1).

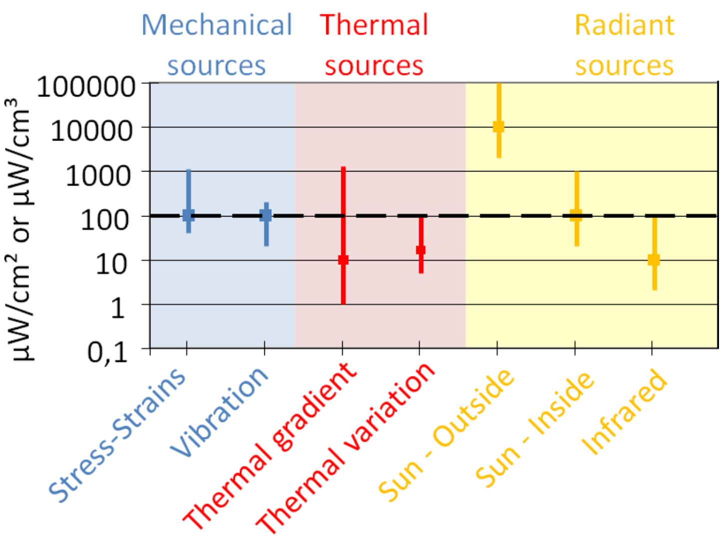


Figure 3-2: Power Densities of Ambient Energy Sources Prior to Harvesting (Source: Boisseau et al. 2012)[4]

Of particular interest is that fact that, under ideal conditions, magnetic energy harvesting offers similar potential to that of ambient indoor illumination.

Table 3-1: Comparison of Power Densities of Primary Ambient Energy Sources

ENERGY SOURCE	POWER DENSITY	REFERENCE
Optical Energy		
Ambient Light (Outdoor)	100 mW/cm^2	Penella-López and Gasulla-Forner 2011
Ambient Light (Indoor)	100 µW/cm^2	Penella-López and Gasulla-Forner 2011
Mechanical Energy		
Ambient Vibrations	0.01–0.1 mW/cm^3	Rabaey et al. 2000
Vibrations (Passive Human Power)	1.8 mW/cm^3 (shoe inserts)	Rabaey et al. 2000
Thermal Energy		
Temperature Variation	10 µW/cm^3	Rabaey et al. 2000
Magnetic Energy		
Magnetic Energy (AC Power Lines)	130 µW/cm^3 (if magnetic flux density is 200 µT at 60 Hz)	Tashiro et al. 2011

[4] Excluding magnetic energy sources.

A state-of-the-art device review follows. For the sake of concision, only a selection of the most promising energy-harvesting devices is considered.

3.2 SOLAR ENERGY HARVESTING

In many environments, solar illumination is the most copious source of ambient energy and can be harvested using a photovoltaic (PV) cell fashioned from semiconductor materials. Optical energy harvesting for micropower applications exploits the same technology used for large-scale solar installations. Indeed, most advances in the area of low-power solar energy harvesting have emerged from research for high-power applications (Penella-López and Gasulla-Forner 2011).

A typical solar cell contains a semiconductor diode with a large p-type and n-type junction located near the surface of the cell (Thomas et al. 2006). When the junction is exposed to photon radiation, electrons (*e*-) are knocked loose in the n-type semiconductor material. Electrons then settle into the (*h*+) holes in the p-type material, and an electric potential develops between the p-type and n-type materials (Thomas et al. 2006).

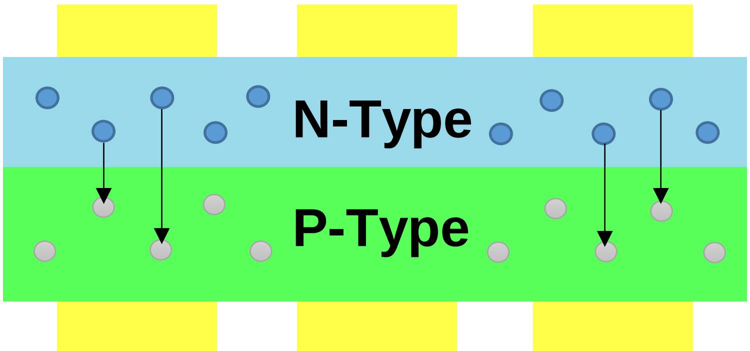


Figure 3-3: Schematic Overview of a Photovoltaic (Solar) Cell

Typically, a PV cell can produce voltages of up to 0.5 V (Thomas et al. 2006). At lower voltages, current is largely independent of voltage but varies with the intensity of the solar radiation (Thomas et al. 2006). The short-circuit current (I_{SC}), the current through the solar cell when the voltage is zero, and the open-circuit voltage (V_{oc}) are the two defining characteristics of a PV cell. Together with a third term, the maximum power output of the cell (P_{MAX}), they form the so-called fill factor (FF):

$$FF = \frac{P_{MAX}}{I_{SC} * V_{OC}}. \tag{3.1}$$

The fill factor is a measure of the quality of PV cell, ranging from 0 % (very poor) to 100 % (excellent) (Thomas et al. 2006). FFs of commercially available PV cells range from 70 % to 80 %.

The efficiency of PV cells is measured by the proportion of electrical power out (P_{OUT}) compared with the radiation power received (P_{IN}):

$$\eta = \frac{P_{OUT}}{P_{IN}} \rightarrow \eta = \frac{P_{MAX}}{P_{IN}}. \tag{3.2}$$

The efficiency of conversion from photonic to electrical energy ranges from around 8 % to state-of-the-art values of 30 %, with efficiencies of up to 35 % achievable in experimental settings (Green et al. 2005). Common PV materials, such as crystalline silicon (c-Si), can achieve efficiencies of 10 % to 23 % in state-of-the-art cells (Thomas et al. 2006). Amorphous silicon (a-Si) is especially suited to low-power applications due to its low efficiency of around 11 % (Steingart 2009). Organic solar systems, such as copper indium gallium selenide (CIGS), are both flexible and durable, but conversion efficiencies remain on par with those of a-Si cells (Steingart 2009).

Important design factors for solar energy-harvesting systems include the radiation intensity and ambient temperature at the installation site, the incident angle of radiation, and load-matching. Load-matching is required for maximum power output and energy collection capability (Thomas et al. 2006). It involves properly matching the current and voltage characteristics with the system load (Thomas et al. 2006). The maximum power output point (P_{MPP}) is dependent on the number of cells connected in series and their temperature (Thomas et al. 2006). Lower temperatures shift the *I-V* curve to lower short-circuit currents (I_{SC}) and higher open-circuit voltage (V_{OC}) values, thereby increasing output power:

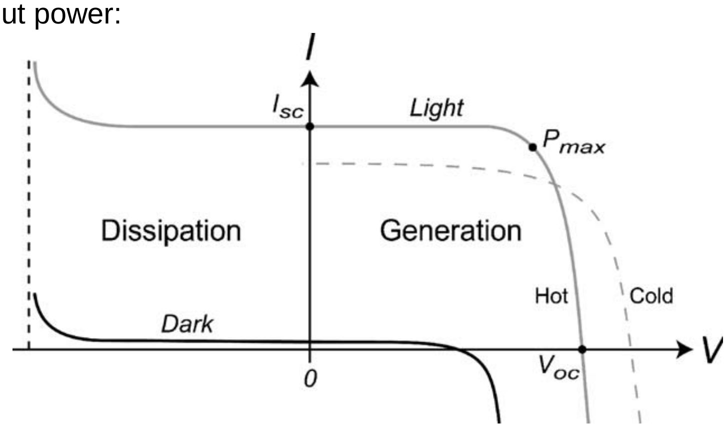


Figure 3-4: I-V Behaviour of Silicon PV Cells (Source: Thomas et al. 2006)

Radiation intensity and incident angle affect output current. The intensity of radiation depends significantly on weather patterns. Weather fluctuations over time therefore need to be considered in order to accurately predict power output at any given location over a period of time (Thomas et al. 2006). Depending on the region and ambient conditions, a DC–DC converter may also be necessary (Steingart 2009). Table 3-2 summarizes power available per cm^2 under various conditions of illumination:

Table 3-2: Power Available for Different Lighting Conditions (after Roundy et al. 2003)

CONDITIONS	POWER AVAILABLE (mW/cm^2)
Mid-day (no clouds)	100
Overcast conditions	5
10 ft. from an incandescent bulb	10
10 ft. from a compact fluorescent light	1

3.3 THERMOELECTRIC ENERGY HARVESTING

In 1822, Thomas Seebeck discovered that when a temperature gradient was applied across certain materials an electrical voltage would result (Seebeck 1825). Via the Seebeck effect, the resultant voltage difference can be used to drive an electrical current and power a circuit. The Seebeck effect arises due to the ability of charge carriers in metals and semiconductors to move freely carrying with them charge as well as heat (Snyder and Toberer 2008). When a temperature gradient is applied to a thermoelectric material, these mobile charge carries diffuse preferentially from the hot to the cold end of the gradient (Snyder 2009).

Thermoelectric devices contain many p-type (containing free holes) and n-type (containing free electrons) thermoelectric couples arranged thermally in parallel and connected electrically in series (Penella-López and Gasulla-Forner 2011):

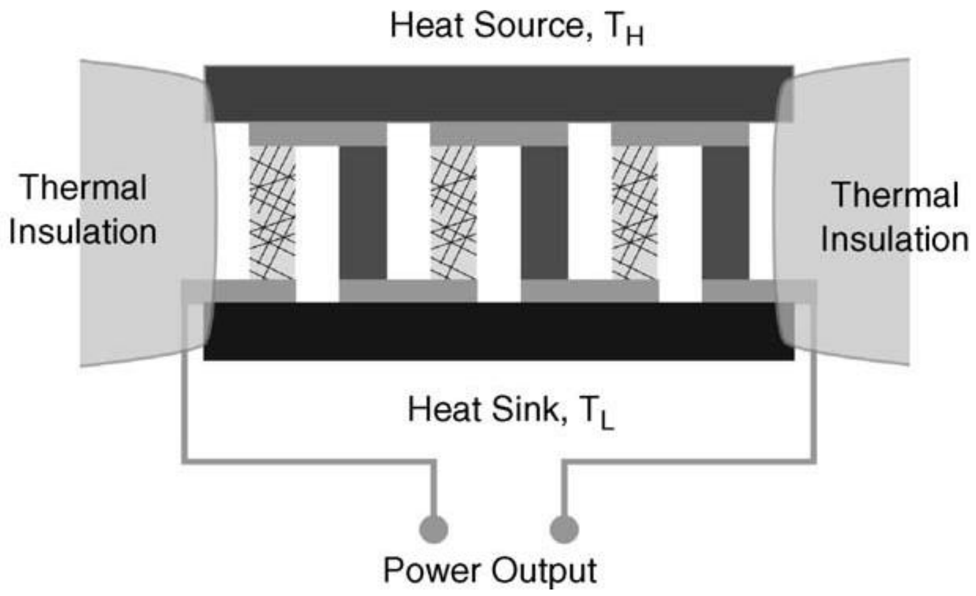


Figure 3-5: Thermocouples Arranged in Electrically Series and Thermally in Parallel (Source: Thomas et al. 2006)

The build-up of mobile charge carriers elaborated above therefore generates a net charge (negative for electrons, *e*-, and positive for the holes, *h*+) (Snyder 2009). As thermoelectric devices are solid-state (i.e. they contain no moving parts and require no maintenance), reliable, scalable and silent, they are perfect for decentralized energy generation and energy-harvesting applications (Rowe 1999; Snyder 2009).

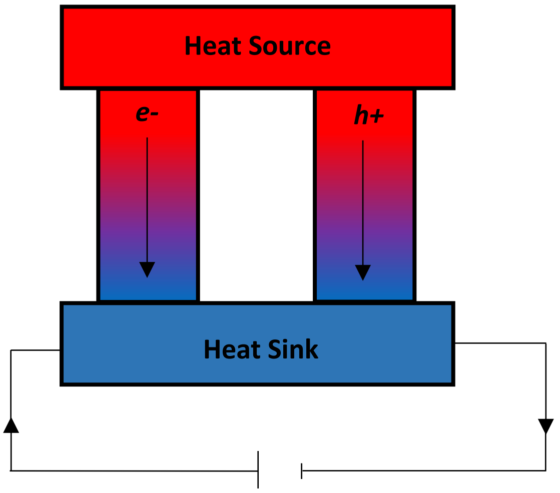


Figure 3-6: Schematic Representation of a Single Thermoelectric Couple

Thermoelectric generators (TEGs) can be modelled as a DC voltage source in series (Penella-López and Gasulla-Forner 2011). The open circuit voltage (V_{OC}) of a TEG is dependent on the change in temperature (ΔT) between the hot and cold sides of the device and on the Seebeck coefficient (α), an inherently material property:

$$V_{OC} = \alpha_1 \Delta T - a_2 \Delta T. \tag{3.3}$$

The maximum efficiency of a TEG is determined by two terms. First, when harvesting thermal energy, the maximum efficiency any heat engine, including TEGs, can obtain is dictated by the Carnot efficiency:

$$\eta = \frac{(T_H - T_C)}{T_H}, \tag{3.4}$$

where efficiency (η) is defined by the temperature of the hot side (T_H) subtracted from the temperature of the cold side (T_C) measured in Kelvin, divided by the temperature of the hot side (T_H). If, for instance, the temperature difference between the hot and cold side of a TEG is 10 K at ambient temperature, 293 K (T_C), the Carnot efficiency (η) would be 3.3 %. For TEGs, Carnot efficiencies of up to 17 % are theoretically possible at body-temperature gradients (Sebald et al. 2008).

Second, maximum TEG efficiencies depend on three material properties: the Seebeck coefficient (α), electrical resistivity (ρ) and thermal conductivity (κ). When multiplied by temperature (T), these properties can be combined to form the dimensionless figure of merit, or *ZT*, of a thermoelectric material:

$$ZT = \frac{\alpha^2 T}{\rho\kappa}. \tag{3.5}$$

Even though a *ZT* of inifinity corresponds to a TEG operating at the Carnot limit, the maximum energy efficiency for any process allowed by the law of thermodynamics, *ZT*s of around 1 are, at present, typical for commercially available thermoelectric devices (Altenkirch 1911; Tritt 2011). In a laboratory setting, *ZT*s of between 1.3 and 1.5 have been achieved in bulk (i.e. macroscopically large) materials (Heremans et al. 2012). A landmark paper by Hicks and Dresselhaus, suggested promising new avenues for *ZT* gains through the use of nanostructured devices, either of macroscopic or nanometer size (Hicks and Dresselhaus 1993). With these, *ZT*s as high as ~3.5 have been achieved in research labs (Vining 2009). As of yet, however, these devices are not yet scalable for widespread production or use and progress remains insufficient for application in energy-harvesting devices (Berger et al. 2011).

Combined, the Carnot efficiency and figure of merit define the maximum efficiency (η_{max}) of a thermoelectric device:

$$\eta_{max} = \frac{\Delta T}{T_H} \cdot \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+1}. \tag{3.6}$$

The energy conversion efficiency of thermoelectrics is in the range of ~5 %–10 %, substantially less than that of conventional heat engines, which exhibit conversion efficiencies of ~20 %–25 % (Liu 2014; Hansen 1985).

In terms of device fabrication, the best thermoelectric materials are heavily doped semiconductors (Snyder 2009). Three semiconductor materials are commonly used in thermoelectric devices: bismuth telluride alloys (Bi_2Te_3), lead telluride (PbTe) and polycrystalline silicon germanium (Poly-SiGe) (Penella-López and Gasulla-Forner 2011). Each material exhibits a different *ZT* achievable up to a given maximum temperature (*T*), as summarized in Table 3-3:

Table 3-3: Comparison of Three Popular Thermoelectric Materials (after Thomas et al. 2006)

	Bi_2Te_3	**PbTe**	**Poly-SiGe**
FIGURE OF MERIT	Highest	Second highest	Lowest
MAXIMUM TEMPERATURE	$T < 250$ ºC	$T < 500$ ºC	T up to 1000 ºC

In order to optimize extracted power, additional elements, including a radiator used to dissipate heat into the environment, as well as thermal shunts, which direct heat between the hot and cold side into the thermocouple's legs, are required (Vullers et al. 2009). Even while operating under steady-state conditions, the output voltage of thermoelectric generators is quite low (typically 0.2 mV/K) (Snyder 2009). Nevertheless, a DC–DC converter can condition the power output and achieve the voltage necessary for low-power applications (Snyder 2009). Alterations in the thermal gradient being harvested can however adversely affect device performance. As devices are generally designed under the assumption that the thermal supply will remain constant, power and voltage output will decrease if heat and temperatures drop significantly (Snyder 2009). A dramatic increase in temperature may also harm the components of the device itself (Snyder 2009).

3.4. MAGNETIC ENERGY HARVESTING

Magnetic energy harvesting involves tapping into magnetic fields produced by pre-existing AC current-carrying wires and equipment using a coil as a transducer. The transducer outputs AC voltage with inductive impedance, which considers resistance in the wire itself and load resistance, modelled in series (Penella-López and Gasulla-Forner 2011). Although live and neutral wires are often placed close together, which would cancel out the magnetic field, in a typical home and office building there exists electromagnetic energy due to the distance between the wires or imbalances in the ground line (Olsen et al. 1988). In industry even, it has been observed that between wires only a few centimetres apart the cancellation factor is negligible enough to afford ample opportunity for magnetic energy harvesting (Gupta et al. 2010).

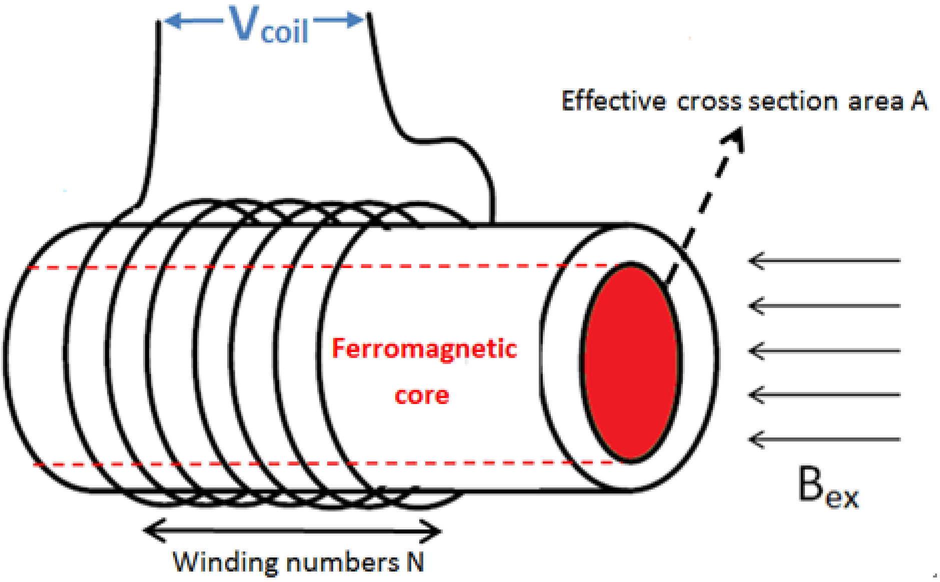


Figure 3-7: Operating Principle of a Magnetic Energy Harvester (Source: Yuan et al. 2015)

Magnetic fields are physical phenomena that have both a magnitude and direction at all points in space, otherwise known mathematically as a vector field. They are often visualized as directed lines that permeate space with the density of lines representing the strength of the field and the arrows of the lines indicating direction at that location. From this conceptualization, it is easy to understand the concept of a magnetic flux. The number of lines of the magnetic field that pass through a given hypothetical surface area is the magnetic flux through that surface, see for example Figure 3-8.

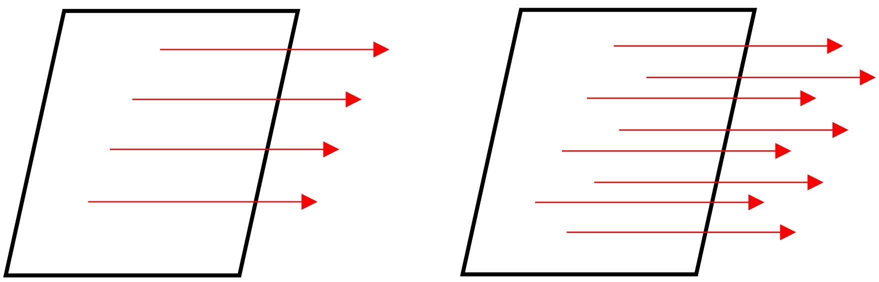


Figure 3-8: Schematic Representation of Flux Densities

According to Ampère's law, as it applies to energy-harvesting devices, a metal wire carrying a constant (i.e. DC) current will produce a circulating constant magnetic field (see Fig. 3-9). An object placed some distance from a wire will therefore be pierced by a constant magnetic flux.

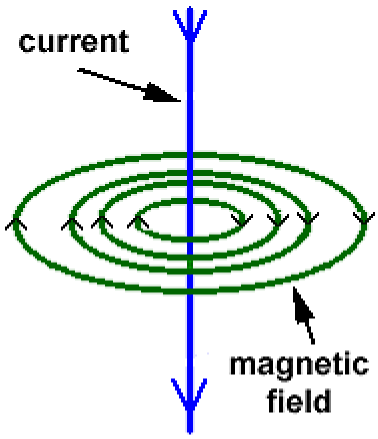


Figure 3-9: Magnetic Field Rotating Around a Wire

According to Faraday's law of induction, as it applies to energy-harvesting devices, a magnetic flux which is changing in time or oscillating in direction or strength will induce a potential difference or voltage. In the case of a wire carrying a constant DC current, therefore, there will be no change in the magnetic flux in time and thus no induced voltage. If the wire is instead carrying an AC current, which is a current that oscillates from positive to negative many times a second, in the same wire, the magnetic field it produces will be constantly oscillating between positive and negative extremes. If an object is placed in the vicinity of such an AC wire, it will then be pierced by a magnetic flux which is changing in time. According to Faraday's law, therefore, a potential difference will be induced across the object.

The goal of electromagnetic energy harvesting is to optimally design a device such that it results in the largest induced potential difference possible for a given time-varying magnetic field. The subsequent potential difference can then be used to drive a circuit. Electromagnetic devices consist of a magnetic coil comprised of a ferromagnetic core material (usually iron) surrounded by a great number of tightly wrapped loops of wire. If the magnetic flux piercing through the core is changing in time, then a voltage will be induced across both ends of the wire. In the case of a time-varying magnetic field resulting from a sinusoidal varying AC current, the voltage ultimately produced likewise varies in time. For this reason, electromagnetic harvesting devices output AC voltage.

It is possible to relate the root mean square (RMS) power (i.e. power averaged over oscillations in time) produced to the design of the coil by the equation:

$$P_{RMS} = \frac{N^2\, \mu_{core}^2\, f^2\, I_{RMS}^2}{Z\, r^2}\, A_{core}^2, \tag{3.7}$$

where the power output of the magnetic harvesters is controlled by the design variables (i.e. the number of coil turns [*N*], the permeability of the coil core [μ_{core}] and surface of the coil [A_{core}]), system impedance (Z), the distance (r) from the AC current source and magnetic field characteristics of the source (i.e. the frequency [f] and amplitude [I_{RMS}]) (Thomas et al. 2006; Penella-López and Gasulla-Forner 2011).

Thomas et al. report calculated output values for electromagnetic harvesting devices based on the following notional device designs: A_{core} = 1 cm^2, Z = 1Ω and f = 60 Hz (Thomas et al. 2006). The results of their calculations reveal that the power output of electromagnetic magnetic energy harvesters spans a wide but largely promising range.

Table 3-4: Power Outputs Based on Notional Device Design (after Thomas et al. 2006)

N	μ_{core} (W At−1 m−1)	r (m)	I (A)	P_{RMS} (W)
1	$4\pi \times 10^{-7}$ (air core)	1	1	5.68×10^{-17}
1	$1000 \times (4\pi \times 10^{-7})$	1	1	5.68×10^{-11}
100	$1000 \times (4\pi \times 10^{-7})$	0.01	100	56.8
100	$1000 \times (4\pi \times 10^{-7})$	0.1	100	0.568
100	$1000 \times (1\pi \times 10^{-7})$	1	10	0.00568

Several challenges to implementation have been encountered, however. These include transducer design geometries and materials for optimal energy collection (Thomas et al. 2006). Furthermore, the strength of the magnetic field is sufficient for harvesting only in close proximity to current-carrying wires (Gupta et al. 2010). This means freedom of placement is limited. Nevertheless, harvesting can still occur even if wires are located a few centimetres inside the wall, assuming they are not encased in metal (Gupta et al. 2010). Recent studies have also demonstrated that employing certain novel coil configurations (e.g. bow-tie-shaped transducers) greatly lowers the demagnetization factor, thereby generating more power than the standard solenoid shape (refer to Figure 3-7) (Yuan et al. 2015). In contrast to iron, manganese-zinc ferrite (MnZn) reduces eddy current losses and has a high permeability (Yuan et al. 2015).

3.5 MECHANICAL ENERGY HARVESTING

Mechanical energy harvesting requires a mechanism of transduction to convert kinetic energy available in the ambient into electrical energy. This entails the use of a mechanical system that couples environmental displacements to the transducer. The harvesting system ought to be designed such that the coupling between the ambient mechanical energy sources and the transduction mechanism is maximized (Beeby et al. 2006). Maximizing this design parameter however is directly dependent on the form of mechanical energy available (Beeby et al. 2006). As aforementioned in 3.1.4, ambient sources of mechanical energy can be harvested by one of three conversion principles: piezoelectric, electromagnetic and electrostatic.

Although piezoelectricity was first demonstrated in 1880, it did not become a popular avenue of scientific inquiry until the 1990s. Since that time, it has emerged as an extremely promising method of harvesting kinetic energy due to a number of advantages, laid out in what follows (Toprak and Tigli 2014; Caliò et al. 2014). The technical principle behind electromagnetic energy harvesting, predicated upon Faraday's law of induction, is well-established and therefore merits additional discussion. Electrostatic energy harvesting, on the other hand, has received far less scholarly attention and boasts none of the material advantages of piezoelectric harvesting.[5]

As illustrated in Figure 3-10, the paucity of papers addressing electrostatic energy harvesting is marked. Consequently, electrostatic harvesting is not addressed in the following section. Electromagnetic harvesting techniques have likewise received comparatively limited treatment. This is likely due to the fact that the underlying technical principle of electromagnetic harvesters is already well documented and not necessarily indicative of limited potential. Where piezoelectric harvesting is concerned, a significant positive trend is observable. Little in the way of justification for its inclusion in this thesis is therefore required.

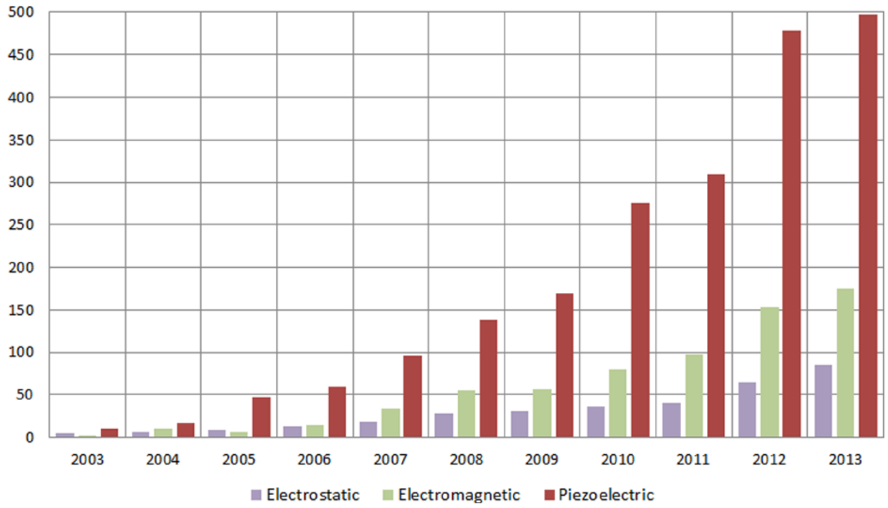


Figure 3-10: Number of Publications in "Web of Science" on Mechanical Energy-Harvesting Techniques (2003–2013) (Source: Toprak and Tigli)

[5] Electrostatic energy harvesters use a variable capacitor structure to generate charge from relative motion between two planes (Boisseau et al. 2012).

3.2.1 PIEZOELECTRIC ENERGY HARVESTING

The piezoelectric effect was discovered by Jacques and Pierre Currie in 1880. They found that when certain crystals are subjected to mechanical strain, they become electrically polarized (Mason 1981). Moreover, the degree of polarization was proportional to the strain (Mason 1981). The direct piezoelectric effect describes the ability of certain (piezoelectric) materials to convert mechanical strain into electrical voltage. It is a bidirectional process, meaning that the piezoelectric effect can be reversed due to mechanical strain in response to electric potential, resulting in the indirect piezoelectric effect (Toprak and Tigli 2014).

If a positive or negative charge becomes isolated, it will produce an electric field and therefore a force on any other charges in its vicinity due to Coulomb's law. Electric fields can ultimately be used to drive charge towards accomplishing some task, as in an electric circuit. If one has a positive charge, like a proton, however, and an additional negative charge, such as an electron, both of which are equal in charge magnitude and located in the same spot, they act to cancel one another out and no net electric field exists. At the most fundamental conceptual level, the source of the power generated by a piezolectric material comes from the fact that although opposite charges at the same spot cancel one another out, when a positive and negative charge of the same magnitude are slightly separated in space from one another, a weak net electric field, called an electric dipole, will result.

Metals, insulators and semiconductors are materials composed of atoms in an orderly, repeating arrangement called a crystal lattice. This is in contrast, for instance, to a polymer in which solidity is due to the extensive knotting and entanglement of long, separate molecules comprised of strings of atoms. In a crystalline material, such as lead, silicon or quartz, the atomic lattice can be conceptualized as a certain base unit cell, such as the face-centred cubic (FCC) lattice displayed in Figure 3-11, repeated ad infinitum in all directions.

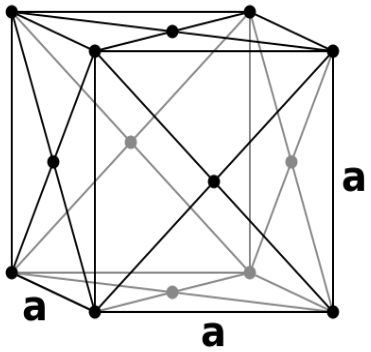


Figure 3-11: Illustration of an FCC Lattice

Within each unit cell, there are a certain number of atoms. As shown in the FCC lattice above, there are four whole atoms (sixth halves of an atom and eight eighths of an atom). Each atom, on the whole, is electrically neutral and therefore so is the unit cell. In a single atom by itself, however, there is a positively charged atomic nucleus surrounded by negatively charged electrons in an orbital configuration some distance radially from the centre. As atoms come together and bond chemically with one another to form a crystal lattice, the positive charge of the nuclei may be separated spatially from the average positions of the negatively charged electrons. The extent to which this occurs is strongly dictated by the set of symmetries the crystal unit cell possesses.

The enumeration and classification of crystal symmetries is a very involved application of the mathematics of symmetry. The key result however is that there are ultimately thirty-two, symmetrically distinct, possible unit-cell arrangements. Of these, twenty are classified as piezoelectric, ten of which are polar and ten of which are non-polar. In a polar unit cell, the total amount of charge is zero (i.e. there are equal amounts of positive and negative charge). The spatial distribution of that charge is such that even in the natural equilibrium state, there is a net dipole in each cell.

In a non-polar cell, however, this is not the case in equilibrium. If the cell is squished (i.e. distorted along some directional axis), this distortion will separate the charges and produce a net dipole. This is the central mechanism of piezoelectricity. A straining or distortion of the basic atomic unit cell results in the formation of a net electrical field across the material. This resulting electric field can be used to drive an electric circuit. The greater the electric field that results for any given strain, the better the piezoelectric material.

In general, the subtleties of the piezoelectric effect are complex as the electric field that results from any given strain is not solely dependent on the amount of strain, but also on the axis (x, y or z) of the unit cell in which it is applied. In fact, it is quite common for the direction of the electric field to be different than the direction of the strain that produced it. This relationship between strain and the electric field is therefore called a "tensor" quantity, meaning that action along one axis produces effects, in principle, not only along the same direction but in all others as well and that different axes are consequently interrelated. It is the symmetry of the crystal unit cell that ultimately dictates this relationship. When discussing piezoelectric power generation, however, generally only two scenarios require further elaboration.

In the first scenario, the piezoelectric material is such that strain along a given direction produces an electric field <u>parallel</u> to the strain. A device designed around such a piezoelectric element is said to be operating in d_{33} mode (Penella-López and Gasulla-Forner 2011). In the second situation, the piezoelectric material is such that the strain along a given direction produces an electric field perpendicular to the applied strain (Penella-López and Gasulla-Forner 2011). This is called d_{31} mode, where *d* (in the case of both modes) represents the piezoelectric strain constant. The strain constant (*d*) is defined as:

$$d = \frac{strain\ developed}{strain\ applied}\ m/V. \tag{3.8}$$

In general, any given piezoelectric material will exhibit a different amount of piezoelectricity depending on which mode it is in. When considering what material to use for a given device, one must therefore consider how the strain will ultimately be applied and in what way the resulting electric field is to be harnessed.

Piezoelectric materials are available in many forms, although lead zirconate titanate (PZT), a piezoceramic, is a popular choice and displays the highest power density of any piezoelectric material. PZT is however not particularly well-suited to all applications. Under conditions of gravitational acceleration or in the presence of larger vibration amplitudes, it is prone to fracture (Shen et al. 2007). The composition of piezoelectric PZT ceramics can also be hard (PZT-5A) or soft (PZT-5H). PZT-5H is naturally more susceptible to stress-induced changes than its less flexible counterpart (Beeby et al. 2006). Other popular piezoelectric materials include single crystals (e.g. quartz), barium titanante (BaTiO3), zinc-oxide (ZnO), which is particularly suited to nano-scale applications, and polymeric PVDF (polyvinylidene fluoride) and micro-fibre composites (MFCs) (Toprak and Tigli 2014; Koka et al. 2014; Caliò et al. 2014; Anton and Sodano 2007; Shen et al. 2007; Kranz et al. 2013). Every piezoelectric material exhibits a different mode-dependent coefficient, as seen in Table 3-5.

Table 3-5: Coefficients of Common Piezoelectric Materials (after Beeby et al. 2006)

MODE	PZT-5H	PZT-5A	$BaTiO_3$	PVDF
d_{33} (10^{-12} C N^{-1})	593	374	149	-33
d_{31}(10^{-12} C N^{-1})	-274	-171	78	23

Each mode is likewise better suited to a different application. PEHs in mode d_{33}, for example, extract mechanical energy from impact pressure and human motion (Penella-López and Gasulla-Forner 2011). The power output in mode d_{33} can be improved by increasing the thickness of the thermoelectric element or by stacking piezoelectric elements in a multi-layer formation (Beeby et al. 2006). Mode d_{31}, on the other hand, is better suited to cantilever structures with a proof mass at the free end (Penella-López and Gasulla-Forner 2011). Cantilevers are typically bimorphic structures, meaning that they contain two active layers of piezoelectric material bound together and separated by a shim (Penella-López and Gasulla-Forner 2011). As the charge generated in a piezoelectric material is proportional to the stress applied, PEHs are designed to maximize the stress under any given load (Toprak and Tigli 2014).

Of all available state-of-the-art designs for PEH devices, the cantilever structure, operating in mode d_{31}, is the most commonly used as it best maximizes the strain for any given input force (Toprak and Tigli 2014). Figure 3-12 depicts a cantilever PEH device where the three coordinate axes defining the operation mode are clearly visible, the proof mass at the free end is labelled **M** and the **z** term illustrates the strain-induced displacement (i.e. amplitude) resulting in the output of an electrical voltage (**V**). Via the base of the cantilever, ambient vibrations are coupled to the cantilever causing the structure to oscillate (Toprak and Tigli 2014). The alternate bending is then transferred into an AC voltage by the piezoelectric material (Toprak and Tigli 2014).

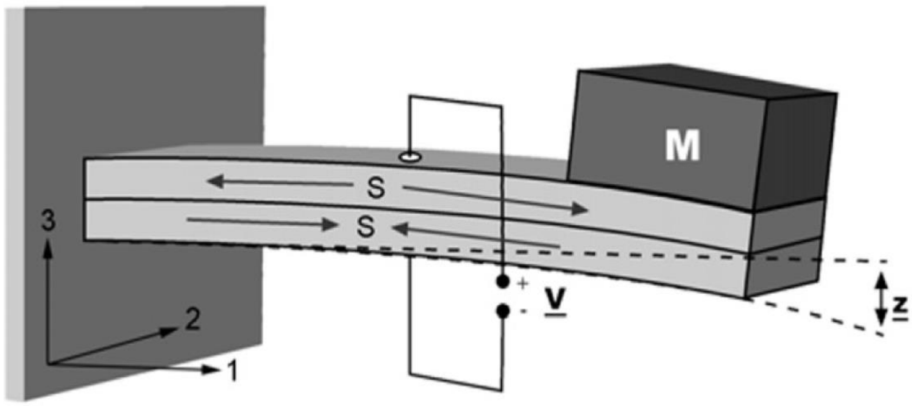


Figure 3-12: Schematic View of a PEH Cantilever Device (Source: Roundy and Wright 2004)

In cantilever PEHs, frequency matching is of the utmost importance. The PEH must be designed such that its own oscillating frequency is synced with that of the ambient vibrational frequency it wishes to harvest (Toprak and Tigli 2014). Most ambient vibrations are at low frequencies, which necessitates the addition of supplementary proof masses to reduce the device's natural resonance frequency (Toprak and Tigli 2014). Moreover, proof masses increase the overall mechanical energy stored in the system and correspondingly, the amount of harvestable energy (Toprak and Tigli 2014).

Pressure-motivated PEHs in operation mode d_{33} are frequently achieved using the multi-layer stack architecture. Poling axes in the multi-layer architecture of such devices are aligned along the same axis as the applied pressure (Toprak and Tigli 2014). In Figure 3-13, a four-layer simplification is depicted, with the arrows indicating poling direction along the same the axes as the pressure applied above the device. The mechanical energy harvested from the applied pressure is usually low due to the inherent stiffness of the stack architecture (Feenstra et al. 2008). They are therefore employed where high pressures are available or are otherwise coupled to mechanical force amplifiers (Toprak and Tigli 2014).

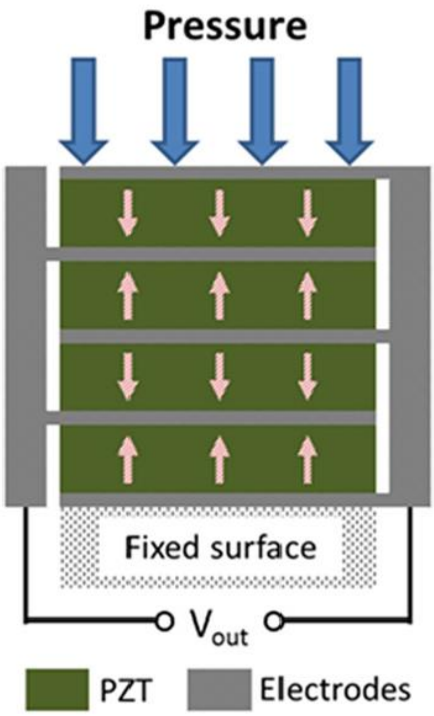


Figure 3-13: Schematic View of a Pressure-Based PEH Device in d_{33} Mode (Source: Xu et al. 2013)

3.2.2 ELECTROMAGNETIC ENERGY HARVESTING

Magnetic energy harvesting, in which a changing magnetic field is produced by an AC current-carrying wire, has already been discussed. There exists another scenario, however, in which a permanent magnet, producing a constant, static magnetic field, is set in motion relative to the coil. Although from the perspective of the magnet, the magnetic field around it does not vary in time, from the perspective of the coil, the magnet is in motion, and the magnetic flux therefore varies in time. Figure 3-14 depicts two common forms of electromagnetic harvesters:

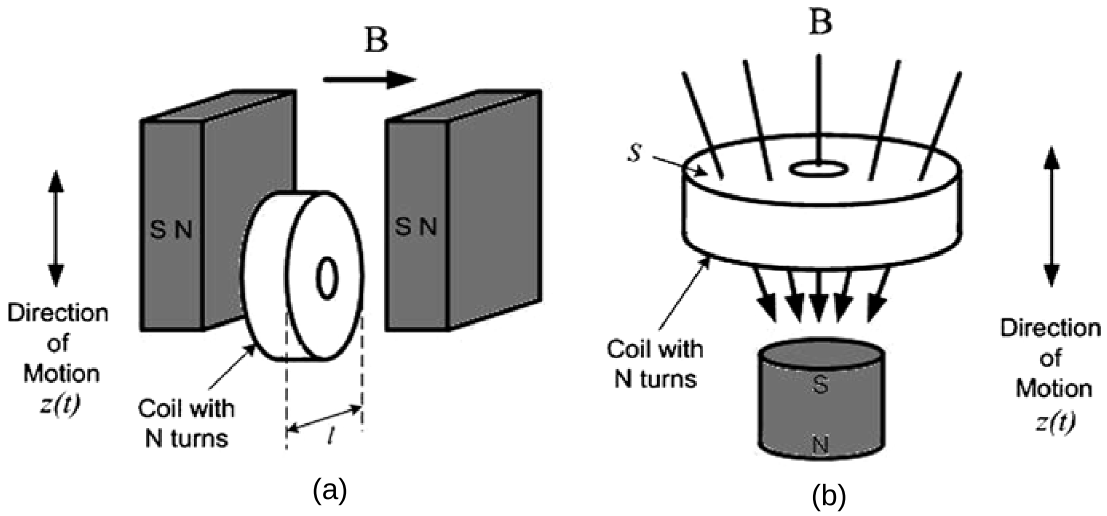


Figure 3-14: Electromagnetic Generators (Source: Zhu and Beeby 2011)

The magnetic field in Figure 3-14(a) is uniform and the coil is allowed to rotate at will. The voltage of such a device is given by:

$$V = -N \cdot l \cdot B \cdot \frac{dz}{dt}, \tag{3.9}$$

where *N* is the number of coil rotations, *l* denotes the length of the coil, *B* represents the flux density going through the coil and *dz/dt* is the relative velocity between the coil and the permanent magnet.

In Figure 3-14(b), the magnetic fields varies with distance from the magnet. In this case, induced voltage is given by:

$$V = -N \cdot S \cdot \frac{dB}{dz} \cdot \frac{dz}{dt}, \tag{3.10}$$

where *S* is the area of the magnet and *dB/dz* represents the gradient of the magnetic flux density in the direction of motion between the magnets and the coil.

One of the most promising methods of electromechanical energy harvesting is producing electromagnetic induction by means of, in addition to a permanent magnet and coil, a cantilever beam (Beeby et al. 2006). Although in theory, either the magnet or coil may be mounted on the beam of a cantilever while the other remains fixed, in practice it is generally preferable to attach the magnet to the beam, which then acts as an inertial mass, as in Figure 3-14(a) and illustrated in greater detail below (Beeby et al. 2006).

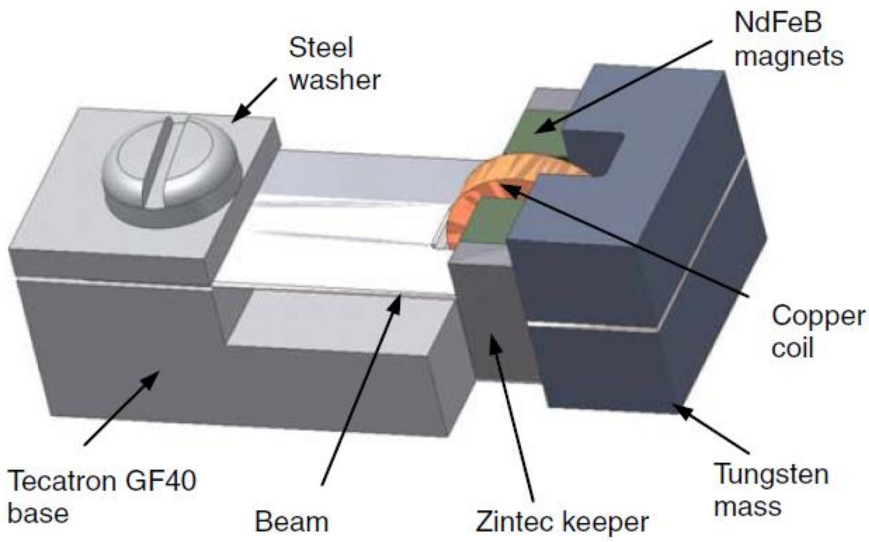


Figure 3-15: Micro Cantilever Electromagnetic Energy Harvester (Source: Beeby et al. 2006)

Electromagnetic energy harvesters work much better in the micro- as opposed to macro-scale (Zhu and Beeby 2011). Rare earth magnets, such as neodymium (NdFeB), are most commonly used in micro-scale electromagnetic (mechanical) energy harvesters. The structure of the device can be fashioned from a wide range of materials, including silicon (Si), copper (Cu), nickel (Ni), steel, berillyium copper (BeCu), gallium arsenide (GaAs) and styrene (C_8H_8), among others (Koukharenko et al. 2006; Ching et al. 2002; Saha et al. 2006; Wang et al. 2009; Glynne-Jones et al. 2004; Beeby et al. 2006; Torah et al. 2008; Williams et al. 2001; Klahand and Najafi 2008).

3.2.3 COMPARISON OF MECHANICAL ENERGY-HARVESTING DEVICES

Piezoelectric energy harvesters (PEHs) offer the simplest approach to mechanical energy harvesting. Ambient vibrations are very easily converted into voltage by attaching electrodes to the piezoelectric material (Beeby et al. 2006). The simplicity of this design lends itself well to microenegineering (Beeby et al. 2006). At only low voltages, the piezoelectric harvesting method is able to output comparatively high voltages (Beeby et al. 2006). Moreover, piezoelectric materials are readily available in the environment (Beeby et al. 2006). Constant direct strain does however limit the lifetime of piezoelectric devices. In addition, the transduction efficiency of a PEH is dependent upon the piezoelectric material itself, although the output impedance is generally quite high (>100 kΩ) (Beeby et al. 2006).

Electromagnetic energy harvesters offer a tried-and-tested method of electricity generation employed already in many applications. A number of spring-magnet combinations are available in various materials, all of which have been thoroughly tested in situations of cyclical stress (Beeby et al. 2006). Furthermore, relatively high current output levels are achievable at low voltages (<1 V) (Beeby et al. 2006). Micro-scale applications are challenging to implement however due to limitations in the number of turns the coil can make, as well as fabrication challenges at the sub-millimetre level (Beeby et al. 2006).

Table 3-6: Comparison of Piezoelectric and Electromagnetic Energy-Harvesting Devices

PARAMETERS OF COMPARISON	PIEZOELECTRIC	ELECTROMAGNETIC
Complexity of Design	Simple	Well-Established (Simple)
Power Output	0.24 μW – 4000 μW	0.4 nW – 4000 μW
Transduction Efficiency	Dependent upon the material	Dependent upon device design
Scalability	Easily scaled down for application at the micro-scale	Application at the micro-scale remains a challenge

3.6 ENERGY-HARVESTING METHODS AND PERFORMANCE PARAMETERS

The final section of this chapter provides an overview and comparison of the energy-harvesting devices discussed above, with emphasis on their performance parameters, in particular power output. Of primary interest is the large span in power output available from many energy-harvesting devices, highlighting the importance of device design. In particular, available ambient harvesting frequencies for devices harvesting mechanical and magnetic energy must be taken into account. It is also clear that solar energy, above all other forms of energy harvesting discussed here, has the greatest potential for power output. One could argue that the power density of solar harvesting is such that even when using PV cells for small-scale application, their potential lies far outside the domain of so-called “micropower” energy harvesting.

Table 3-7: Overview of Energy-Harvesting Device Parameters

	POWER OUTPUT/ DENSITY	VOLTAGE (V)	EFFICIENCY (η)	REFERENCE
Photovoltaic				
Monocrystalline Silicon (SPR-E20-327 and SPR E19-320) for outdoor installation	327 W or 209 W/m^2	54.7 V	19.9 % – 20.4 %	http://us.sunpower.com/
Amorphous Silicon (Indy4500) for indoor installation	90 mW (at 200 lux) – 465 mW (at 100 lux)	1.8 V – 2.0 V (at P_{MPP})	—	http://www.linear.com/solutions/1786
Thermoelectric				
Bi_2Te_3	2.5 W	3.3	4.5 (η_{TE})	http://www.hi-z.com
Electromagnetic (Magnetic)				
Air Core	5.68 x 10^{-17} W (at 60 Hz and 1 *N*)	—	—	Thomas et al. 2006
Ferromagnetic Core	5.68 x 10^{-11} W (at 60 Hz and 1 *N*) – 56.8 W (at 60 Hz and 100 *N*)	—	—	Thomas et al. 2006
Piezoelectric				
Mode d_{31}	0.24 μW (at 184 Hz) – 4000 μW (at 100 Hz)	—	—	Shen et al. 2009; Reilly et al. 2011
Mode d_{33} (shoe inserts)	1300 μW at 0.9 Hz	—	—	Kymissis et al. 1998
Electromagnetic (Mechanical)				
GaAs	0.3 μW (at 4400 Hz)	—	—	Williams et al. 2001
Steel	180 μW (at 322 Hz) – 4000 μW (at 100 Hz)	—	—	Glynne-Jones et al. 2004; www.perpetuum.co.uk
Silicon	0.4 nW (at 9500 Hz) – 0.5 μW (at 700 Hz)	—	—	Mizuno and Chetwynd 2003; Beeby et al. 2005
Copper/Brass	10 μW (at 64 Hz) – 830 μW (at 110 Hz)	—	—	Ching et al. 2002; Scherrer et al. 2005

4. FIELDS OF APPLICATION IN INDUSTRIALIZED NATIONS

In the developed world, energy-harvesting devices can be applied in a wide variety of sectors and situations, from domestic and personal use to industry and manufacturing. Essentially, energy-harvesting devices perform two main functions. First, they can replace or augment the lifetime of battery-powered devices (e.g. consumer products, household appliances, measurement and monitoring systems, etc.). Second, they can provide power to wireless sensor networks, or WSNs, in inaccessible or infrequently accessed locations. This chapter therefore explores the myriad avenues of implementation, broken down according to five of the most promising fields of application, in addition to the leading manufacturers and suppliers of energy-harvesting solutions. These include energy-harvesting solutions for industrial and manufacturing sectors, transportation, buildings and “smart homes”, personal use, such as mobile phones and automobiles, and medical applications.

4.1 ENERGY HARVESTING IN INDUSTRY AND MANUFACTURING

Energy-harvesting devices can be applied in a wide variety of industries and provide wireless support for many manufacturing processes, including power generation, waste and wastewater treatment, chemical refinement, transportation of freight, infrastructural enhancement and process manufacturing (Perpetuum 2016a). Several companies already offer energy-harvesting solutions for the industrial sectors listed above. Among the most successful in the field are Perpetuum, EnOcean, Micropelt, Linear Technology and CHERRY.[1] Only those companies that offer the most detailed device specifications and installation/application requirements are reviewed below.

As cables and lines are becoming ever more complicated and costly to lay inside walls and on rotating parts and battery replacements are a financial burden, energy harvesting can provide a wireless, intervention-free way in which to circumvent both issues in an industrial setting (Boisseau et al. 2012). In effect, energy harvesting in industry often involves the deployment of many small, wireless sensor nodes, referred to commonly in North America as motes, in order to collect and transmit data. These WSNs can be then used to monitor and transmit information regarding the status of various mechanical and industrial operations (Mitcheson et al. 2008). As with all possible sensor-network-based fields of application, WSNs for use in industry are

[1] Note that CHERRY Electrical Products is to be rebranded as of 1 January 2017 by ZF Friedrichshafen AG, who acquired the company in 2008. All CHERRY products will therefore be sold under ZF’s Industrial Solutions product line.

attractive only insofar as well-characterized ambient energy sources are amply available for harvesting (Mitcheson et al. 2008).

Figure 4-1 illustrates the principle behind WSNs capable of sensing and transmitting data for further processing remotely:

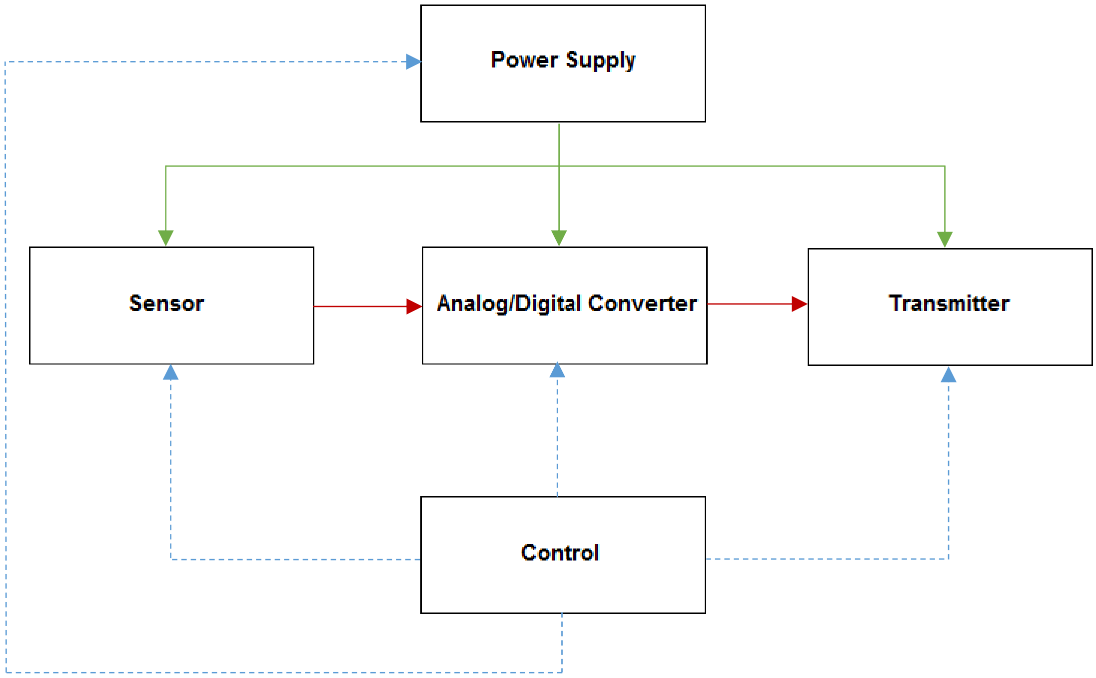


Figure 4-1: Basic Representation of a Wireless Sensor Network (after Mitcheson et al. 2008)

Today, the power requirements for each device in the network can be estimated from state-of-the-art academic research and devices commercially available primarily from those manufacturers listed above. Nevertheless, a typical WSN sensor's power consumption can be estimated. Values for different modes of operation are presented in Table 4-1.

Table 4-1: Typical Power Consumption of a WSN Sensor Node (after Boisseau et al. 2012)

POWER CONSUMPTION (µW)	MODE OF OPERATION
1–5 µW	Standby mode power consumption
500 µW	Active mode power consumption
50 mW	Transmission power peak
50–500 µJ	Total energy needed to perform complete measurement and transmit data wirelessly

The energy-harvesting device, while the WSN sensor node is in standby mode, must then harvest up to 5 µW to compensate for the sensor's consumption (Boisseau et al.

2012). A bit more energy (50–500 μJ) then has to be accumulated for storage in either a capacitor or battery (Boisseau et al. 2012).

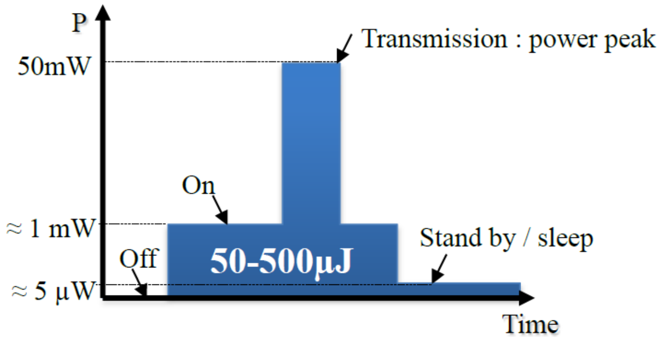
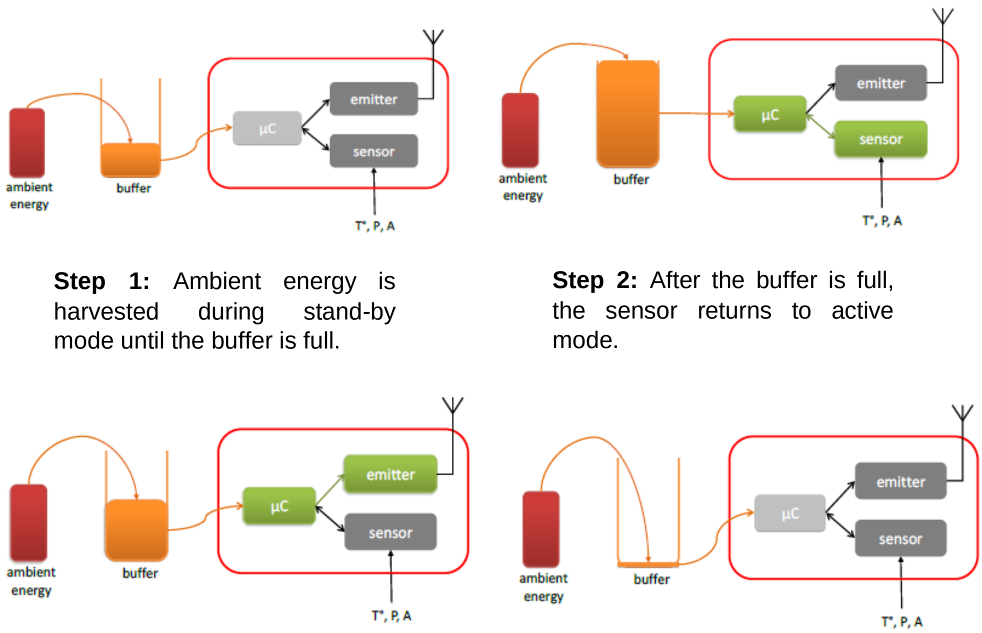


Figure 4-2: WSN Sensor Node's Power Consumption Depicted Graphically (Source: Boisseau et al. 2012)

As is clear from Table 3-7, the majority of energy-harvesting devices, excluding in some cases PV modules, are not yet able to sustain the power levels required to fully power a sensor while in operation. Due to the ultra-low power standby mode available for modern-day sensors, however, the energy that the harvester is able to store in a capacitor or battery during standby can then power the sensor while in measurement mode (Boisseau et al. 2012). Afterwards, the system returns to standby mode and begins the storage cycle in anticipation of its next measurement cycle. Consequently, energy harvesting is currently a viable option for WSN systems.



Step 1: Ambient energy is harvested during stand-by mode until the buffer is full.

Step 2: After the buffer is full, the sensor returns to active mode.

Step 3: Remaining energy stored in the buffer is used to transmit the gathered data wirelessly.

Step 4: The sensor returns to stand-by mode and ambient energy is harvested to re-fill the buffer.

Figure 4-3: Step-by-Step Process of Energy Harvesting for WSNs (after Boisseau et al. 2012)

4.1.1 INDUSTRIAL WIRELESS POWER SOLUTIONS

Perpetuum offers electromagnetic vibration energy harvesters (VEHs) that act as a perpetual source of power for WSNs. The VEHs operate at 27 mW at 6 V or 24 mW at 8 V and can function for a decade before requiring maintenance (Perpetuum 2016b). Moreover, they are easy to install, specially designed for use in demanding industrial environments and economic, not only because they reduce material and upkeep costs, but also because they free up skilled labourers to attend to other more vital operations (Perpetuum 2016b). Perpetuum's VEHs fulfill two roles. First, they act as monitors of equipment health. Second, they monitor various process parameters, for example, temperature, pressure and flow (Perpetuum 2016b).

Figure 4-4: Perpetuum (Electromagnetic) Vibration Energy Harvester (Source: Perpetuum 2016b)

Without access to energy-harvesting technologies, wiring for sensor networks would comprise 80 % of total installation costs (Freeland 2012). Batteries, which have for many years been the go-to power sources for WSNs, are also troublesome. They require constant maintenance, are hazardous and therefore difficult to dispose of properly after use, and will not last the entire lifespan of the WSN (Freeland 2012). Energy harvesters can therefore act as substitute for batteries, but nevertheless minimizing power consumption is crucial. This is done in industrial settings by reducing the frequency of reporting (Freeland 2012). Sensor nodes monitoring the conditions of machinery, for example, ought not to be transmitting data continuously but should rather send reports only on a periodic basis (Freeland 2012). In addition, the WSN can analyze the parameters under investigation and notify its operators in case of an emergency.

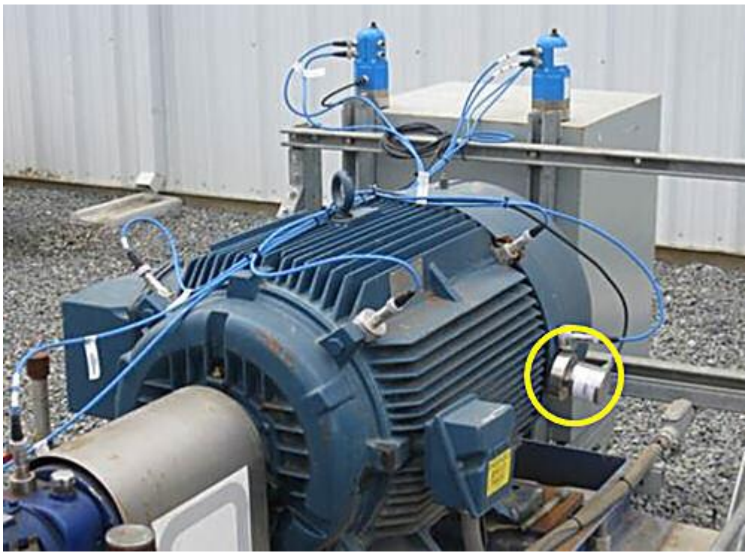


Figure 4-5: A Perpetuum (Electromagnetic) Vibration Energy Harvester "At Work" (Source*:* Perpetuum 2016c)

To better summarize the points above, Table 4-2 outlines more clearly the advantages of VEHs in industry over battery-powered devices:

Table 4-2: Comparison of VEHs and Batteries for Use in Industry (after Perpetuum 2011a)

PARAMETERS OF COMPARISON	VEHS	BATTERIES
Inexhaustible power delivery	Yes	No
Maintenance-free	Yes	No
Temperature compensated	Yes	No
Can power multiple WSNs simultaneously	Yes	No
Support for alternate energy-harvesting power options	Yes	No
Environmentally friendly	Yes	No
Affected by the environment	No	Yes
Stocking and replacement costs	No	Yes
Transport restrictions	No	Yes
Disposal logistics and costs	No	Yes
Deterministic lifespan	>200 years	Variable
Impact on internal WSN deployment cost factor	None	Large
Large-scale WSN deployment cost factor	Minimum	Large
Fully operational in target environment	Unrestricted	Limited

Ability to increase data-cycle rates	No effect	Limits lifespan
Supports additional WSN features	No effect	Limits lifespan
Intrinsically safe	By design	Only if specially designed

To demonstrate the cost-effectiveness of VEH-based solutions in industry, Figure 4-6 plots the number of sensor of nodes in relation to costs and management effort required for the installation and oversight of WSNs en masse:

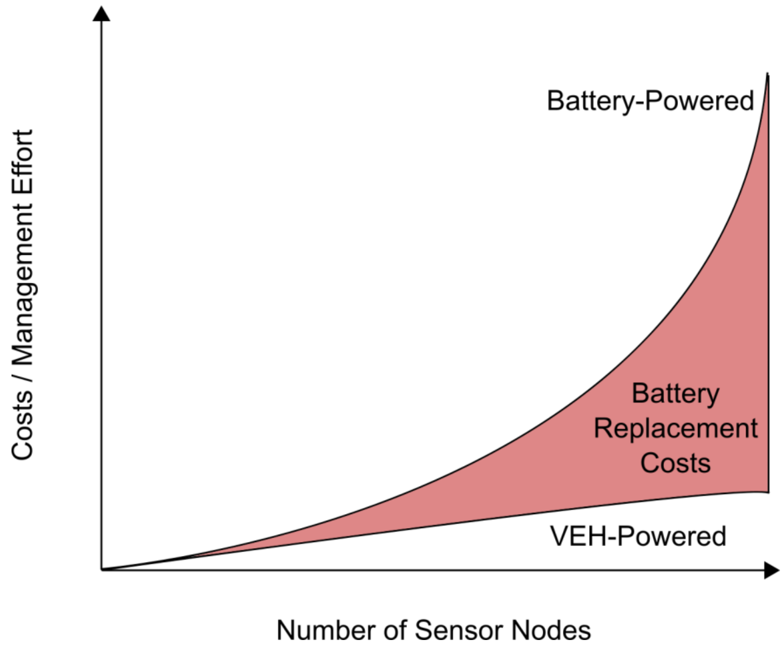


Figure 4-6: Scalability of VEH- vs. Battery-Powered Sensor Nodes (after Perpetuum 2011b)

From Figure 4-6, it is clear that battery-powered devices are neither a cost-effective, nor scalable solution for industrial WSN applications. The costs of VEHs, on the other hand, do not increase exponentially with the number of sensor nodes deployed, but rather they level out after the installation of around 100 nodes and thereafter stabilize.

The Freiburg-based start-up, Micropelt, manufactures thin-film thermoelectric generators for condition monitoring and use as WSNs. The Micropelt MPG-D655 is designed to output power in the mW range and suited for small thermo-gradients of less than 30 K (Micropelt 2016a). Figure 4-7 below displays the available output power in relation to change in temperature (ΔT) between the hot and cold side of the device:

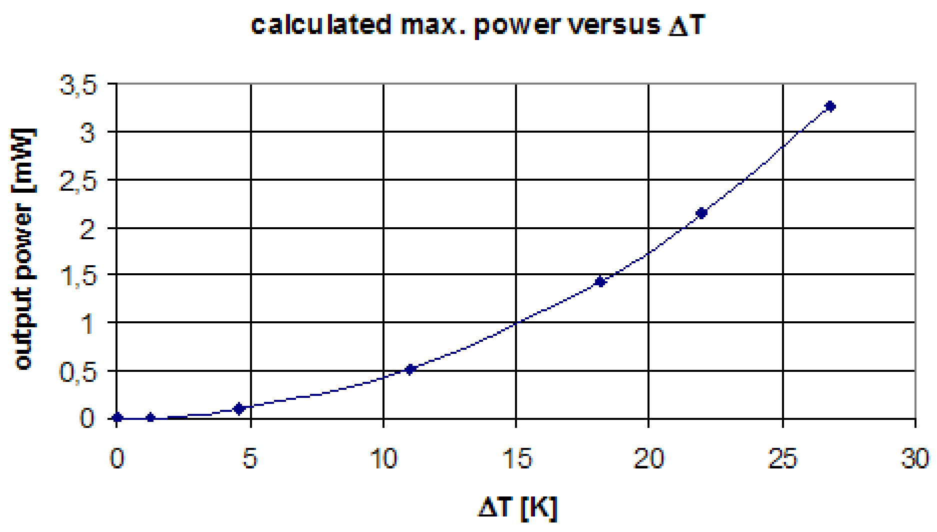


Figure 4-7: Output Power of Micropelt Thermogenerators in Relation to *ΔT* (Source: Micropelt 2016a)

Micropelt also manufactures a sensor node, mNODE, powered by stray AC energy from current-carrying industrial equipment. mNODE offers precise monitoring of electrical infrastructure by identifying defects at an early stage of development via trend analysis (Micropelt 2015). Defects in power generation systems and electrical infrastructure generally present themselves in the form of higher-than-normal temperatures. Typical causes of overheating in an industrial setting include deterioration of cable material and erosion, bad cable junctions and problems with torque at busbar joints (Micropelt 2015).

4.1.2 INDUSTRIAL TRANSPORT SOLUTIONS

As freight railcars lack direct access to power, energy-harvesting devices offer a battery-less, low-maintenance way in which to monitor cargo while in transit. Perpetuum's electromagnetic VEHs can be deployed to detect wheel flats and bearing degradation, as well as temperature in the cargo hold, pressure, leakage and security breaches (Perpetuum 2016d). Data can be collated and transmitted lengthy distances via GPRS to a central hub, or a WSN can be installed to transmit all data directly to the locomotive cab on-board (Perpetuum 2016d).

4.2 ENERGY-HARVESTING APPLICATIONS FOR THE PUBLIC SECTOR, COMMERCIAL USE AND CIVIL SOCIETY

Energy-harvesting devices can be of benefit to both the governments' of industrialized nations and their citizens. This section therefore explores energy-harvesting applications intended to streamline key infrastructural functions, in particular public transit and roadways. It also examines energy-harvesting devices for commercial and civil-sector use.

4.2.1 COMMERCIAL APPLICATIONS, INFRASTRUCTURE AND PUBLIC TRANSPORTATION

Pavegen Systems, a UK-based company, has patented a piezoelectric tile technology designed to harvest the kinetic energy of footfalls. These tiles can be installed on a large-scale in schools, subways and railway stations and along major roads with each 50 cm x 50 cm tile outputting 5 W continuous power from footsteps. The energy harvested from pedestrian footfalls can then be used to power stop lights, monitor pedestrian congestion at high-density intersections and provide traffic management for airports and even marketing professionals monitoring consumer activity at shopping centres (Dervojeda et al. 2015). Moreover, Pavegen's footfall technology can connect directly to social media, and the floor tiles themselves can act as an advertising medium, powering interactive messages, signage and billboards (Pavegen 2016).

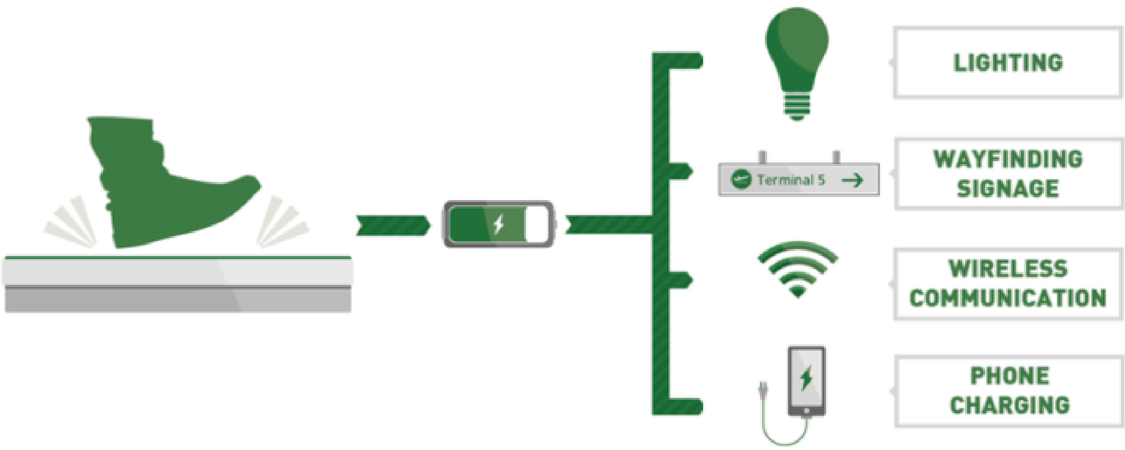


Figure 4-8: Overview of Possible Applications of Pavegen Footfall Technology (Source: Dervojeda et al. 2015)

In addition to supplying industrial transport solutions, Perpetuum also offers battery-free VEH sensor nodes designed to enhance safety and security on passenger trains. The sensors are installed directly on-board ensuring better quality of data and monitoring of track conditions (Perpetuum 2016b). The sensor nodes can therefore predict potential emergencies and lessen the impact of adverse events on both passengers and travel times (Perpetuum 2016b).

Thermoelectric modules are perfect for insertion into the tailpipes of commercial automobiles where thermal gradients are large enough to power automated systems. As thermoelectric devices can offer a direct conversion pathway between waste heat and electricity, conventional vehicles can achieve increased fuel economy by using the extra electricity to decrease alternator loads or to power accessory applications such as power steering (Smith and Thornton 2009; Smith and Thornton 2007a). Hybrid automobiles can also benefit by using the extra power to assist directly with vehicle propulsion (Smith and Thornton 2007b).

The current target is to improve fuel economy by more than 5 % using TEG technology (Fairbanks 2013). Although increased fuel efficiency levels of 5 % sound low, at even 1 % automobiles and light-duty trucks can save an estimated EUR 4.5 billion per year on fuel whereas heavy-duty trucks used for commercial purposes can save around EUR 1.3 billion (Fairbanks 2013). At fuel efficiency levels of 5 %, autos and light-duty trucks will save approximately EUR 22.3 billion per year on fuel and commercial trucks will save EUR 6.2 billion (Fairbanks 2013). Furthermore, if figures of merit greater than three are reached, replacing internal combustion engines with a thermoelectric hybrid combustor would become possible (Fairbanks 2008).

4.2.2 BUILDING AUTOMATION AND "SMART HOMES"

EnOcean specializes in energy-harvesting technologies for use primarily in building and "smart home" automation, although they also offer energy-harvesting solutions for industry, transportation and logistics. EnOcean boasts a wide range of harvesting devices, including electromagnetic kinetic converters, small solar cells and thermoelectric converters (EnOcean 2016a). Their modules combine micropower converters for ultra-low power applications and reliable wireless communication, enabling customers to install self-powered wireless sensor solutions (Dervojeda 2015).

The ECO 200 for kinetic energy harvesting functions like a mini-dynamo, harvesting energy from a switching operation via button pressure (see 3.2.2). With a total power output of 120 μW, it can perform more than 300,000 switch cycles (up to 1,000,000 under ideal conditions). The harvesters can be used in miniaturized switches and sensors in buildings but are used currently to control remote control key fobs, wireless key card switches and door sensors (EnOcean 2010).

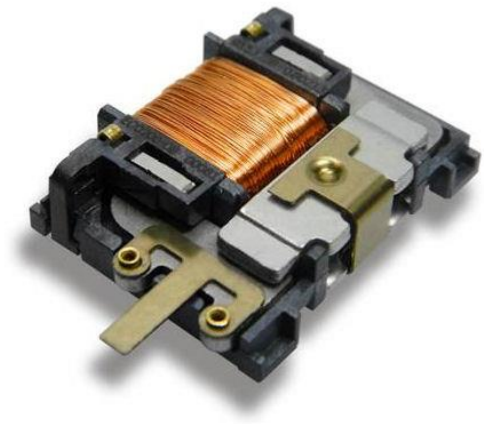


Figure 4-9: EnOcean's ECO 200 Kinetic Energy Harvester (Source: EnOcean 2016b)

The ECS 300/ECS 310 miniaturized solar modules are specifically designed to harvest ambient light indoors. If they are in use briefly every fifteen minutes, 3.6 hours of charging and 200 lux, which correlates to ambient levels of light available outside during an extremely stormy day around noontime, are sufficient for continuous operation (EnOcean 2016c). Power output of the ECS 300 and ECS 310 amounts to approximately 13.5 μW and 33 μW, respectively, at 25 °C and 200 lux. Once fully charged, the modules are operable for several days in complete darkness (EnOcean 2015). They can be used to power temperature sensors, as well as window and door contacts, and to measure humidity, light level, occupancy and even the indoor concentration of CO/CO_2 (EnOcean 2015).

Figure 4-10: EnOcean's ECS 300/ECS 310 Solar Harvesting Cells (Source: EnOcean 2016a)

EnOcean’s ECT 310 DC/DC converter, combined with a Peltier element, can act as a thermoelectric energy-harvesting device powered by heat dissipation. With an input voltage of 20 mV or more, at about a 2 K temperature differential, an output voltage of more than 3 V is generated. At a temperature gradient of around 7 K, approximately 100 µW can be produced (EnOcean 2016c).

Figure 4-11: EnOcean's ECT 310 Perpetuum – Thermo Energy Harvester (Source: EnOcean 2016a)

Micropelt has developed a thermal energy-harvesting radiator valve, or iTRV, fully wireless and battery free, which is capable of controlling a single room and offers energy savings of up to 30 % (Micropelt 2015).[2] Once installed, it communicates with “smart” thermostats for maintenance-free climate control. The iTRV’s internal thermal generator converts the temperature gradient between ambient room temperature and the radiator into useable electricity (Micropelt 2016b). It produces power from temperature differences as small as 4 K (Micropelt 2016b).

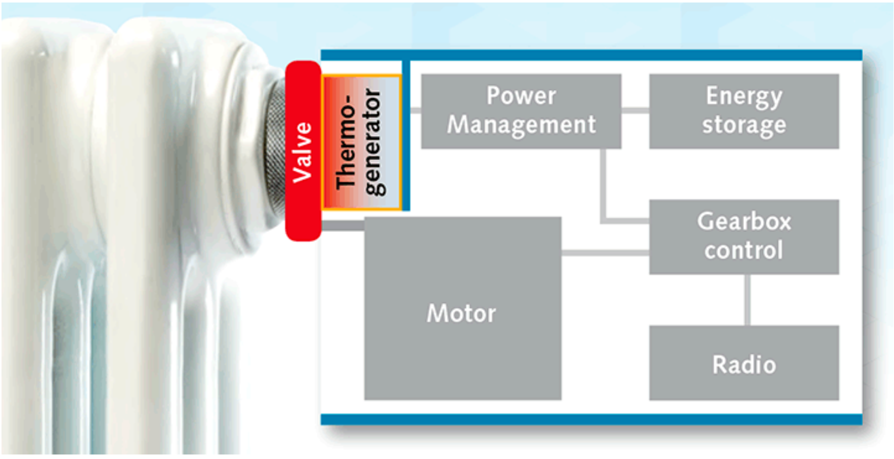


Figure 4-12: Working Principle of Micropelt's iTRV (Source: Micropelt 2015b)

All of the abovementioned can be used for building automation. By definition, building automation using energy-harvesting devices entails the installation of self-powered switches, sensors and controls to for an energy-efficient, safe and comfortable building environment (EnOcean 2016d). Energy-harvesting devices for building automation can

[2] iTRV stands for “intelligent Thermostatic Radiator Valve”.

control and monitor temperature levels, control air conditioning and heating, control lighting and dimming, adjust temperature and lighting when rooms are not in use and switch off HVAC systems when windows are opened (EnOcean 2016d). This can ultimately amount to 15 % lower construction costs and accrue an energy savings of up to 40 % (EnOcean 2016d). In the context of "smart homes", energy harvesters offer functionality similar to building automation, simply on a smaller, more personalized scale (EnOcean 2016e).

4.2.3 ENERGY HARVESTING FOR PERSONAL MOBILE ELECTRONIC DEVICES

Energy harvesting for personal mobile devices, in the context of this thesis, refers to energy-harvesting devices used to power small electronics nowadays considered integral to life in industrialized nations. For most portable electronic devices, the variability of battery life often inconveniences users. In such cases, energy-harvesting solutions must be selected to suit each device's design architecture, which is typically dependent on the following four parameters: 1) Power consumption of the device; 2) the size of the device; 3) typical patterns of use; 4) the type of motion to which the device is subjected (only in the case of mechanical energy harvesting) (Mitcheson et al. 2008).

Desktop computers and laptops, for example, are currently unappealing candidates for harvesting as they consume significant power (10–40 W for laptops and 80–250 W for PCs), are in use for significant periods of time without interruption and are in low-motion environments during idle periods (Mitcheson et al. 2008). Nevertheless, laptop-compatible energy-harvesting solutions have been proposed and developed. One such design suggests harvesting the keystrokes of a laptop's keyboard while typing (see Fig. 4-13). The depression of the keys could then be coupled to a piezoelectric harvester (Kalyanaraman and Babu 2010). Power harvested in this way could be used in case of emergency if/when access to traditional power supplies is not available (Kalyanaraman and Babu 2010).

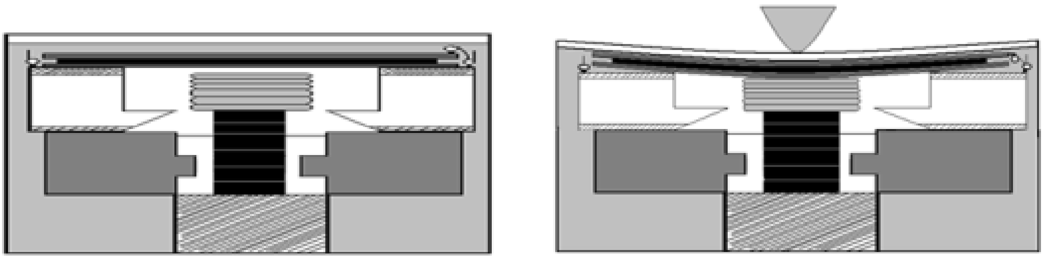


Figure 4-13: State of PEH Before and After Key Depression (Source: Kalyanaraman and Babu 2010)

Cellular phones and other mobile devices (e.g. DAPs, PDAs, smart watches, tablets, etc.), on the other hand, offer more promising prospects.[3] First, they are carried oftentimes close to the body, which means that passive human power can be harnessed to charge mobile devices while on-the-go (Mitcheson et al. 2008). Second, they are generally in use for only short periods, with plenty of downtime. Admittedly, however, this depends largely on each person's pattern of usage (Mitcheson et al. 2008). Today's smartphones, for example, consume only 320 mW while in audio-playback mode, in video-playback mode aggregate power consumption (excluding backlight) is 453.5 mW, average power required for a voice call is 1054.3 mW, the power breakdown for sending an SMS is 302.2 mW and power consumption while sending an e-mail amounts to 610 mW (via GPRS) or 432.4 mW (via WiFi) (Caroll and Heiser 2010).

Mobile devices therefore lend themselves well to piezoelectric energy-harvesting devices. Specifically, pressure- and impact-sensitive piezoelectric generators can be designed to harvest the kinetic energy of movement to charge mobile devices on-the-go. Only recently has such technology become commercially available, albeit on a much larger-scale than would be ideal for personal use. Pavegen floor tiles are also able to harvest the energy of footfalls for mobile charging (refer to Fig. 4-8). Additionally, piezoelectric plates constructed out of PVDF, around 1 mm thick, have been developed and tested in a laboratory setting for integration into the soles of shoes (Paulo and Gaspar 2010). The energy conversion of such an approach is not particularly efficient, with shoe inserts producing around 8.3 mW from heel pressure and 1.3 mW from walking on one's toes at a walking speed of 0.8 Hz (Shenck and Paradiso 2001).

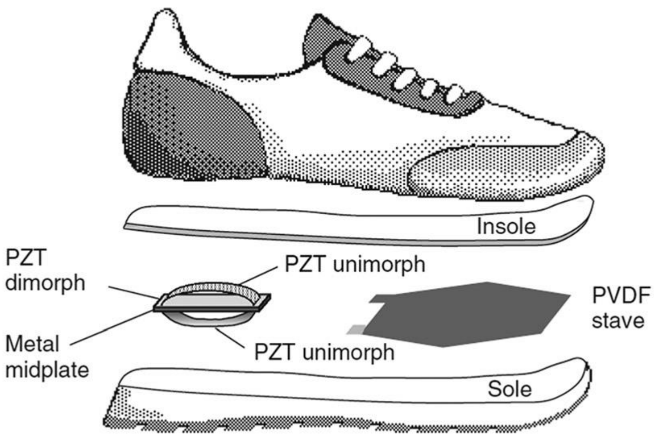


Figure 4-14: PVDF Shoe Inset Energy-Harvesting Scheme (Toprak and Tigli 2014)

[3] Energy-harvesting devices must naturally be adapted to suit the context and usage patterns of each mobile electronic device. Even where small-scale electronic devices are concerned, a "one-device-fits-all" approach is not possible.

4.2.4 ENERGY HARVESTING FOR WEARABLE AND IMPLANTABLE MEDICAL DEVICES

In the past, healthcare has focused largely on sporadic periods of treatment as opposed to long-term care and monitoring (Wanless 2002). Many chronically ill patients could experience better care and enjoy longer life expectancies if their biological signs could be continuously monitored (Mitcheson et al. 2008). For example, in case of hypertension, medical compliance can be improved via frequent monitoring of the patient’s blood pressure, real-time processing of electrocardiographs is effective in identifying the early stages of heart disease and automated “closed-loop” insulin control systems, in which insulin is measured and administrated throughout the day and night, could significantly reduce the risk of hypoglycemia in patients with diabetes (Flowerday and Smith 2004; Needham and Gamlyn 2004; Heller 2005).

Medical monitoring also reduces health-care costs by regulating medicinal dosages more efficiently and pre-empting prolonged hospital visits. Implantable and wearable medical devices are only attractive, however, if they are non-intrusive both in terms of use and maintenance (Bauer et al. 2000; Lo and Yang 2005). Non-renewable power sources ought, in particular, to be avoided (Görge et al. 2001). Ideally, therefore, both implantable and wearable medical devices should last the lifetime of the intended application. This has led to a fast-growing sector of research into body sensor networks (BSNs) (Mitcheson et al. 2008).

BSNs can be powered internally by mechanical energy, such as cardiac contractions and the flow of bodily fluids (Gaspar et al. 2013). The heart contracts approximately 1.8 billion times during the average seventy-year lifespan, providing an extremely reliable mechanical energy source, especially for pacemakers whose power consumption is a mere 8 μW (Gaspar et al. 2013). Moreover, thermoelectric generators can be implanted at the skin’s surface or subcutaneously to monitor various biological processes. Temperature gradients of between 1 and 5 K are abundantly available within the fatty tissue of the human body (Yang et al. 2007). Thermoelectric devices have also been proposed for use with pacemakers, but issues regarding the possible toxicity of Bi_2Te_3 persist. Although toxicity is low, when the device corrodes, Bi_2Te_3 can, in large enough quantities, cause kidney damage and fatality (Paulo and Gaspar 2010).

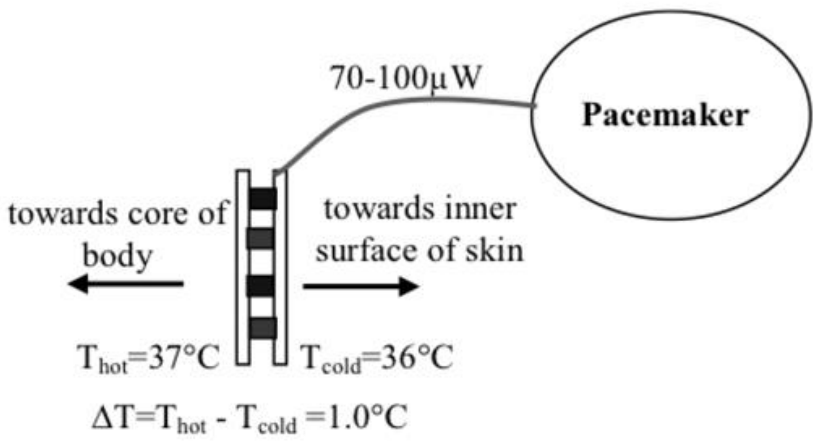


Figure 4-15: Schematic of Thermoelectric-Powered Pacemaker (Source: Suzuki et al. 1999)

In terms of near-future commercial availability, technology readiness levels between 2008 and future projections for the year 2023 are summarised below:

Table 4-3: Technology Readiness Level of Various Energy-Harvesting Devices (after Gaspar et al. 2013)

ENERGY-HARVESTING METHOD	2008	2013	2018	2023
Piezoelectric	4	5	5	6
Electromagnetic	5	6	7	8
Thermoelectric	6	7	7	8

Table 4-4: Breakdown of the Various Stages of Technological Readiness (after Gaspar et al. 2013)

LEVEL	DESCRIPTION
1	Basic principles observed and reported.
2	Technological concept and/or application formulated
3	Analytical and experimental critical function and/or characteristics
4	Component and/or broadboard validation in laboratory setting
5	Component and/or broadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in relevant environment
7	System prototype demonstration in an operational environment
8	Actual system completed and “flight qualified” through testing and demonstration
9	Actual system completed and “flight proven” through successful mission operation

As is clear from the tables above, electromagnetic (mechanical) energy harvesting for use in medical devices will be relatively close to commercial applicability by 2023. Other forms of energy harvesting for use in wearable or implantable medical devices may take quite a bit longer to mature. In particular, progress with piezoelectric energy harvesting appears to have stagnated around the halfway mark. Thermoelectric harvesting from thermal gradients at skin-level or within the body appears most promising with a steady upward trajectory observable in the fifteen years between 2008 and 2023.

5. FIELDS OF APPLICATION IN DEVELOPING COUNTRIES

Energy harvesting as a field of both research and application is still very much in its infancy. Total market value remains low, when compared to other forms of renewable energy technologies, and the technological readiness level of many devices is insufficient for large-scale application.[1] For this reason, very little in the way of research into possible fields of application in developing countries has been carried out. This chapter therefore examines three common development scenarios in which the implementation of energy-harvesting devices could be of substantial benefit.

Applications suited to least develop countries (LDCs), in which access to electricity remains limited and rural electrification rates are near non-existent, are considered first, followed by remote and isolated regions where laying powerlines would be impossible and middle income countries (MICs), in which rolling blackouts and sporadic downtimes remain common. Any additional discussion of new fields of application is eschewed as only the most practical of the most promising applications discussed above can be feasibly adapted to suit the country contexts of developing nations.

5.1 ENERGY HARVESTING IN LEAST DEVELOPED COUNTRIES

The United Nations defines LDCs as those countries that exhibit the lowest indicators of socioeconomic development, characterized by weak human and institutional capacities, low income and a general scarcity of resources (UN-OHRLLS 2016). A significant portion of the world's population lives in Sub-Saharan Africa (SSA) and other LDCs. Approximately 630 million, out of a total population of 824 million, living in LDCs and 560 million, out of 777 million, in SSA were without access to electricity in 2009 (Legros et al. 2009). Total electrification rates were only 21 % in LDCs and 26 % in SSA (Legros et al. 2009). As illustrated in Figure 5-1, 80 % of people without access to electricity are located in SSA, even though SAA comprises a mere 14 % of the total population of developing countries (Legros et al. 2009).

Figure 5-1 also highlights the marked regional disparity between those with and without access to electricity. In SSA, for example, more than 90 % of people lack access to electricity in Chad, Liberia and Burundi (all LDCs), whereas only around 25 % of the population lacks electricity access in South Africa (Legros et al. 2009). Naturally,

[1] For example, investment in wind farms totalled EUR 52 billion in 2013 and is projected to reach EUR 83 billion by 2023 (Deloitte 2014).

energy access in rural areas is also a great deal lower in LDCs than access in urban city centres (Legros et al. 2009).

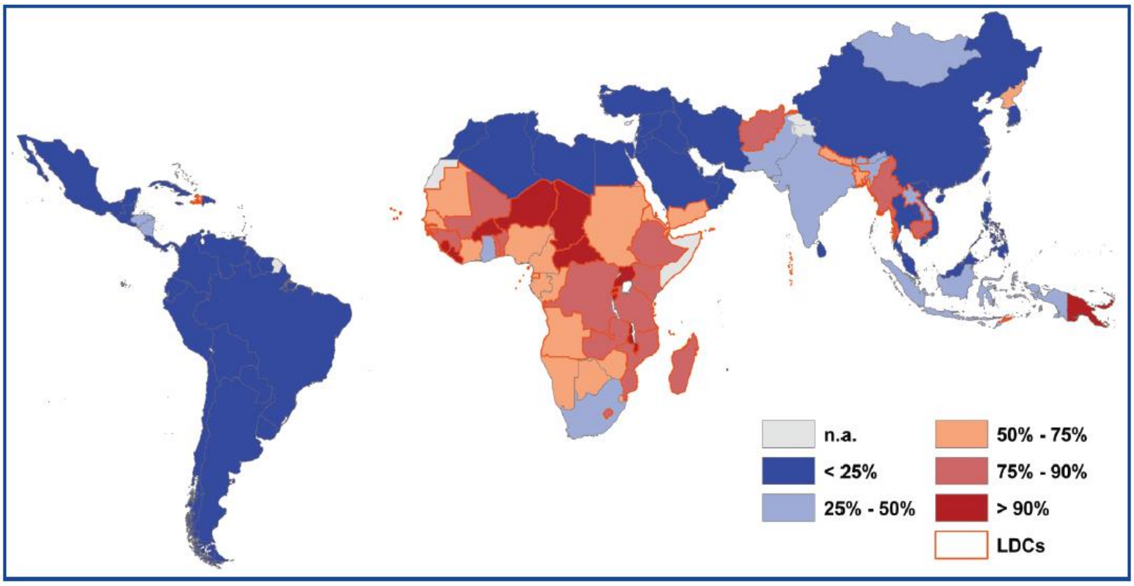


Figure 5-1: Percentage of People without Access to Electricity in 2009 (Legros et al. 2009)

In conditions such as those described above, substituting conventional fuel sources for small-scale, decentralized power generation can help to improve the livelihoods of women and children, who are among those primarily affected by biomass gathering and kerosene poisoning. Battery-powered lanterns also pose a health hazard in such situations as batteries are often disposed of improperly. In such situations, due to insufficient infrastructure, conventional methods of electrification cannot be economically justified.

Ambient energy harvesting therefore circumvents the need for grid-based electrification by providing power for essential services, including light for education, medical clinics and small business. More specifically, mechanical and optical energy can be harvested to charge the mobile phones of extra-urban residents and to power other small electronic devices. Optical and mechanical energy can also be harnessed to power lanterns for use in schools, clinics and marketplaces. Small-scale solar energy harvesting already exhibits significant potential with regard to water-pumping and irrigations systems, as well as refrigeration. Standalone, decentralized energy-harvesting systems therefore hold significant promise for use in un-electrified peri-urban and rural areas. Moreover, following the widespread advent of wearable and implantable medical devices powered by energy-harvesters, advances in the quality of healthcare may become possible as device costs decrease.

5.2 ENERGY HARVESTING IN REMOTE AND ISOLATED REGIONS

Communities or sojourners in remote and isolated developing regions of the world are unlikely to have any access to electricity. Although difficult to qualify, the general distinction between LDCs and remote locations is the ability, even theoretically, to provide access to power. LDCs are unable to provide power to all but their capital or largest cities as it is not yet infrastructurally or economically feasible to electrify towns and villages in which the majority of the nation’s residents reside. In remote and isolated locales, however, the possibility of laying lines and building up a conventional power grid is impossible due often to physical and climatic constraints. Nevertheless, it should be noted that in many least-developed regions of the world, rural communities can be considered synonymous with remote and isolated locations in that, due to some intrinsic environmental factor, it would be impossible to power the community via conventional centralized means.

In remote areas, where access to vital, life-saving amenities is limited, energy harvesting can provide power for emergency satellite phones, radios and lighting for medical services. Pressure-sensitive piezoelectric devices may be of use in communities where traversing long distances is common, and PV-powered solutions may be better suited to arid areas in which solar potential is quite high. Due to the remote nature of isolated areas and oftentimes severe weather patterns and harsh environmental conditions, energy-harvesting solutions must, above be all, be designed specifically to suit the best available ambient energy sources of each isolated community. New WSN applications are also an option in remote areas. They can monitor temperature trends, water flow in rivers exhibiting hydro-potential and a variety of other environmental indices in order to better serve nearby communities.

5.3 ENERGY HARVESTING IN MIDDLE INCOME COUNTRIES

Middle income countries (MICs) are those nations currently exhibiting the most rapid growth, both in terms of population and key human development and economic indicators (UNDP et al. 2012). Severe inequality and poverty remain a persistent issue, however, despite fast-growing economies and trade liberalization (UNDP et al. 2012). In many MICs, where electrification is significantly more advanced than in LDCs, energy security remains a pervasive obstacle to development. Load-shedding and blackouts are commonplace, leaving parts of the country without access to electricity for extended periods of time. Heavy reliance on fossil fuels for industrial and economic development likewise remains a problem, and measures to ensure efficient use of energy are often not implemented.

South Africa, for instance, although accorded upper-middle-income status by the World Bank and promoted to the rank of major emerging national economy in 2010, alongside Brazil, Russia, India and China, has a long history of rolling blackouts (World Bank 2016). The country's primary electricity provider, Eskom, must keep the power system balanced at 50 Hz, the international standard, in order to prevent a nationwide blackout (Eskom 2016). If the grid comes under pressure, Eskom reduces demand by reducing the load (Eskom 2016). This involves load curtailment, in which industrial users are instructed to restrict their usage, as well as complete load shedding (Eskom 2016).

In MICs, the potential for energy harvesting is slightly greater than in LDCs. First, many MICs, especially those on the upper end of the scale, are industrializing or newly-industrialized. Industries and rising middle-class home-owners, pressured by power generation companies to curtail their electricity usage, may therefore find WSNs a cost-effective way in which to more efficiently distribute energy between integral systems such as climate-control, manufacturing equipment and usage of indoor illumination. In addition, PV- and piezo-powered lanterns can provide lighting to households during power outages and to rural areas still without access to electricity. Energy-harvesting devices can similarly ensure that traffic lights, wayfinding signage and other essentials remain operational long enough for electricity providers to restore power.

6. CONCLUSION AND DISCUSSION OF RESULTS

Having identified and characterized the most abundantly available forms of ambient energy for harvesting and carefully reviewed both state-of-the-art and commercially available devices designed to harvest each form of energy, as well as their potential applications, the following conclusions can be drawn:

1) WSNs are currently the most promising avenue of application insofar as energy-harvesting devices are concerned. Although only one of many potential applications, WSNs can help private and industrial consumers lower their electricity bills and operating costs, respectively, by reducing over-consumption of electricity occasioned by improper moderation of indoor climate systems and lighting, in the case of houses, and by preventing machine and device failure, in the case of manufacturing.
2) Fields of application outside of WSNs, including the harvesting of ambient energy to power mobile electronics and even medical devices, are still struggling due to low device efficiencies and power outputs too insignificant to make any great dent in the overall energy consumption of the consumer.
3) Some energy-harvesting technologies exhibit more promise than others. For example, cantilever-based PEHs are not yet marketable, although certain pressure-based systems are; thermoelectric modules are struggling to overcome low *ZT*s and device efficiencies but show significant near-future potential in the area of medical technology and waste-heat harvesting from automobiles; electromagnetic energy harvesting is already quite promising in the industrial sector and shows promise for application in medical devices; PV modules on the whole exhibit perhaps the most potential of any energy-harvesting technique discussed in this thesis, nevertheless micropower PV cells currently on the market, although adapted to suit ill-lit areas and rooms, are designed to harvest only enough energy to power a sensor.
4) It is undeniable that should these device deficiencies be overcome, as they are projected to in the near future, the potential to save on material and installation costs, energy consumption for households and industries, and automotive fuel consumption would be substantial. Already, simply by installing harvester-powered WSN systems, efficiency gains at the household level are significant (promising energy savings of up to 40 % and a 15 % reduction in construction costs).

Table 6-1 systematically breaks down each form of energy-harvesting technology, its field(s) of potential application(s), estimated technological readiness level (ETRL) and material-saving/cost-saving/energy-saving potential:

Table 6-1: Energy-Harvesting Potential, ETRL and Cost-Saving Potential

ENERGY-HARVESTING DEVICE	**APPLICATIONS IN INDUSTRIALIZED COUNTRIES**	**APPLICATIONS IN DEVELOPING COUNTRIES**	**(COST-)SAVING POTENTIAL**	**ENERGY-HARVESTING COMPANY/ COMPANIES**	**ETRL**
OPTICAL ENERGY					
Micropower PV Cells	➢ Temperature Sensors ➢ Monitor window and door contacts ➢ Measure humidity, light level, occupancy and concentration of CO/CO_2	➢ Mobile phone charging stations ➢ Provide hazard-free light ➢ Assist in water-pumping and irrigation ➢ Power small refrigerators	**Industrialized Nations:** ➢ Energy efficiency savings (less power required from a wall-socket) ➢ Material and installation savings ➢ EUR/W savings may be jeopardized by short lifetime of devices **Developing Countries:** ➢ Improved quality of life in LDCs ➢ Economic benefits to local business owners who are able to keep longer hours	➢ EnOcean	➢ Commercially available

ENERGY-HARVESTING DEVICE	APPLICATIONS IN INDUSTRIALIZED COUNTRIES	APPLICATIONS IN DEVELOPING COUNTRIES	(COST-)SAVING POTENTIAL	ENERGY-HARVESTING COMPANY/ COMPANIES	ETRL
THERMAL ENERGY					
Thermoelectric Generators	➢ Power WSNs in industry ➢ Reclaim waste-heat in tailpipe of automobiles to power automated systems ➢ Power WSNs in “smart homes”/ climate control ➢ Implantable medical devices	➢ Insertion into tailpipes of automobiles	**Industrialized Nations:** ➢ Energy efficiency savings (less power required from a wall-socket) ➢ Material and installation savings ➢ EUR/W savings not there yet for non-WSN applications **Developing Countries:** ➢ Reduction of fuel consumption and associated emissions in MICs	➢ Micropelt (industrial applications only)	➢ Model and demonstrable prototypes available (medicine and waste-heat reclamation) ➢ Commercially available for use in WSNs

ENERGY-HARVESTING DEVICE	APPLICATIONS IN INDUSTRIALIZED COUNTRIES	APPLICATIONS IN DEVELOPING COUNTRIES	(COST-)SAVING POTENTIAL	ENERGY-HARVESTING COMPANY/ COMPANIES	ETRL
MAGNETIC ENERGY					
Electromagnetic Generators	➢ Monitoring of electrical infrastructure (e.g. temperature) via trend analysis	➢ N/A	**Industrialized Nations:** ➢ Material and installation savings (prevents industrial malfunction before it occurs)	➢ Micropelt (industrial applications only)	➢ Commercially available for use in WSNs in industry
MECHANICAL ENERGY					
Piezoelectric Energy Harvesters	➢ Power lighting, including stop lights, monitor pedestrian congestion ➢ Monitoring activity in public places (e.g. shopping centres) ➢ Powering interactive messages, signage and billboards ➢ Charge/power electronic mobile devices (e.g. laptop, mobile phones, etc.) ➢ Implantable medical devices	➢ Power mobile phones in LDCs via pressure-base piezoelectric devices ➢ Power traffic lights in MICs during blackouts	**Industrialized Nations:** ➢ Energy efficiency savings (no centralized power required) ➢ Enhance public infrastructure **Developing Countries:** ➢ Improved quality of life in LDCs ➢ Enhanced public infrastructure in MICs	➢ Pavegen (large-scale, outdoor application requiring continuous footfalls)	➢ Commercially available for large-scale use ➢ Model and demonstrable prototypes available (e.g. shoe inserts) ➢ Component validation only for medical devices

ENERGY-HARVESTING DEVICE	APPLICATIONS IN INDUSTRIALIZED COUNTRIES	APPLICATIONS IN DEVELOPING COUNTRIES	(COST-)SAVING POTENTIAL	ENERGY-HARVESTING COMPANY/ COMPANIES	ETRL
MECHANICAL ENERGY					
Electromagnetic Energy Harvesters	➢ Monitor equipment health in industry ➢ Measure various process parameters: flow, temperature and pressure ➢ Detect wheel flats and bearing degradation, temperature in cargo hold, pressure, leakage and security onboard freight trains ➢ Monitoring of track conditions for public transit ➢ Can power miniaturized switches and sensors in buildings, control remote control key fobs, wireless key card switches and door sensors ➢ Implantable medical devices	➢ Same as industrialized nations	**Industrialized Nations:** ➢ Energy efficiency savings (less power required from a wall-socket) ➢ Material and installation savings **Developing Nations:** ➢ Industrial applications in MICs to reduce energy consumption and machine failure (especially in the case of antiquated machinery)	➢ Perpetuum (industrial applications only) ➢ EnOcean (building and house automation only)	➢ Commercially available and cost-effective options for WSNs in industry and building/ “smart homes”/ public and freight transportation ➢ Demonstrable system prototypes only for use in BSNs

Figures 6-1 to 6-5 illustrate more fully the near-future readiness levels of each energy-harvesting device, broken down according to all five areas of potential application identified in Chapter 4. The definitions of each level of technological readiness, outlined in Table 6-2, are adapted to suit this context from the work of Gaspar et al.

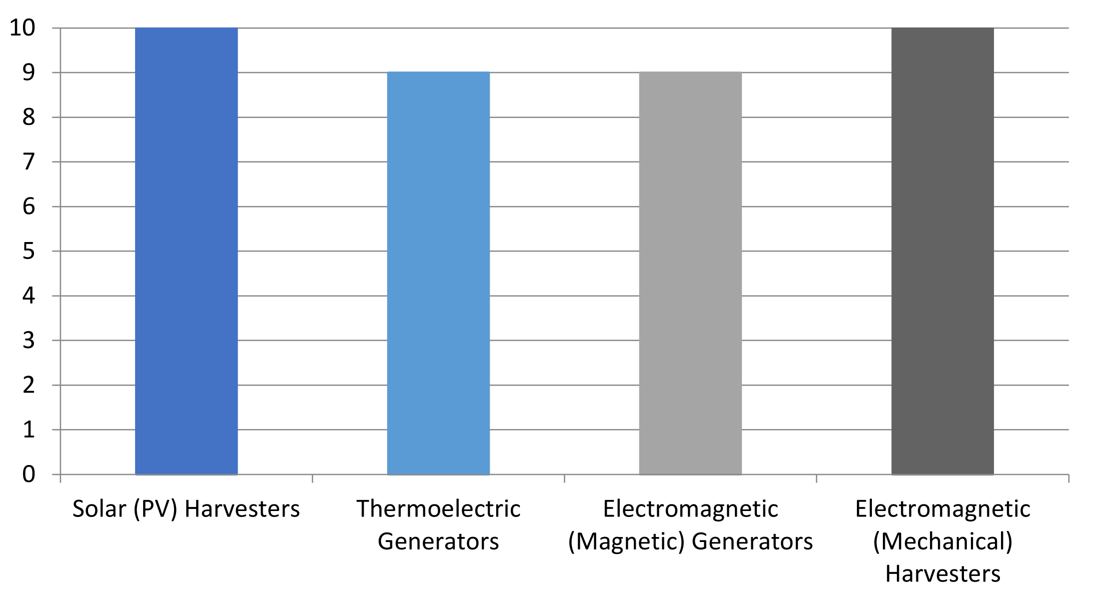


Figure 6-1: Estimated Technological Readiness Levels of Energy Harvesters for Use in Industry and Manufacturing

In Figure 6-1, the conclusions drawn at the outset of this section are well-illustrated. In particular, PV and electromagnetic (mechanical) harvesters are commercially available for use in WSNs. In particular, electromagnetic harvesters provide cost-effective coverage in an industrial setting in which very low levels of power output are required. Thermoelectric generators are not yet as widespread but also offer a power output suited to wireless sensor applications. Electromagnetic generators, designed to harvest magnetic energy available near current-carrying conductors, are not yet extensively available, although proof of concept is of course well-established. State-of-the-art prototypes have been discussed in the scientific literature as, for example, by Gupta et al.

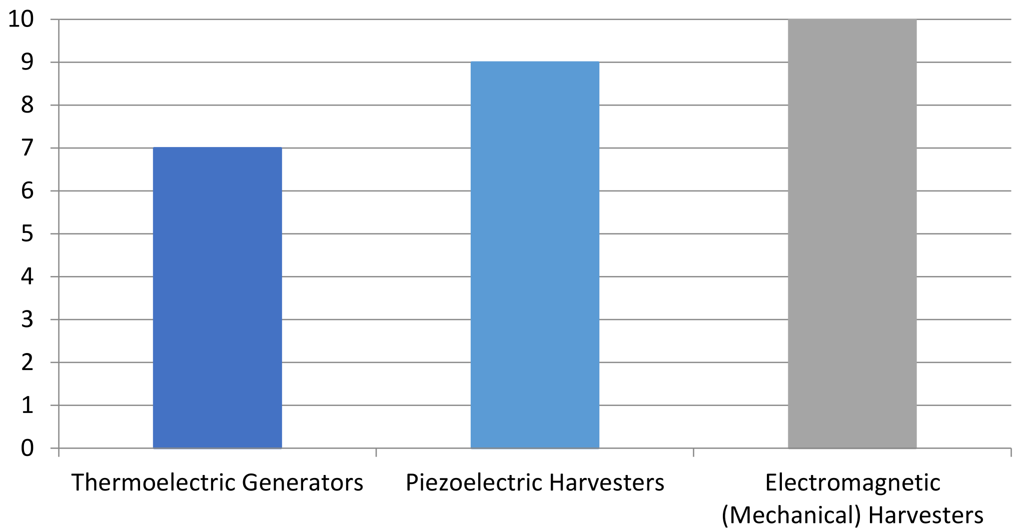


Figure 6-2: Estimated Technological Readiness Levels of Energy Harvesters for Commercial Applications, Infrastructure and Public Transportation

ETRLs in the area of commercial applications, infrastructure and transport are quite varied. At this stage, TEGs for insertion into the tailpipes of automobiles are available only as prototypes due to low *ZT*s. The piezoelectric pressure-based floor tiles offered by Pavegen are commercially available but still offer relatively low power output levels capable of powering a streetlamp for no more than thirty seconds by continuous footfalls. This implies, of course, that Pavegen's footfall technology still requires additional refinement prior to widespread distribution in developing nations. Electromagnetic (mechanical) harvesters are once again viable options for use in WSNs installed on passengers trains.

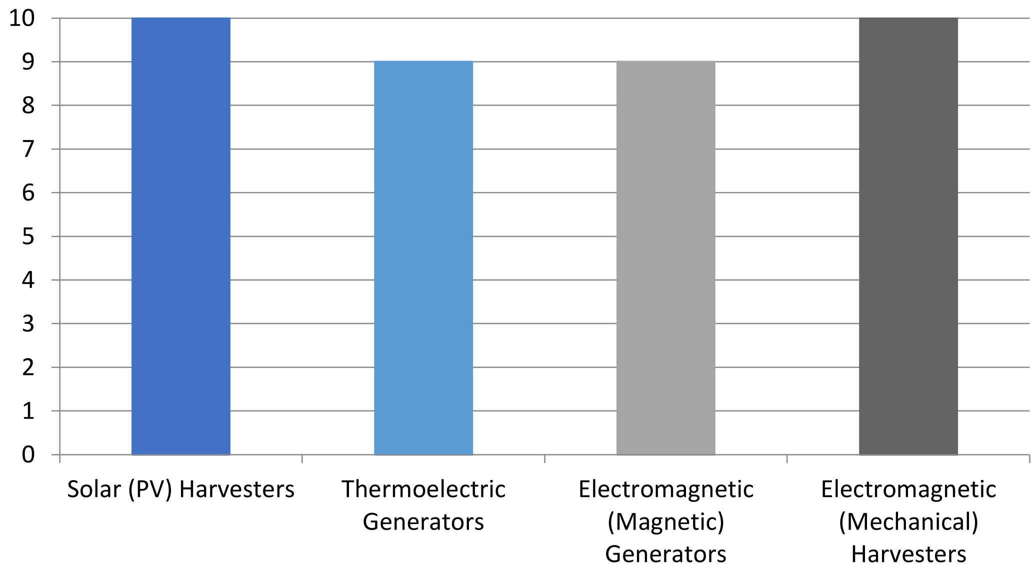


Figure 6-3: Estimated Technological Readiness Levels of Energy Harvesters for Building Automation and "Smart Homes"

In the building automation and “smart home” sector, PV harvesters once again are well-suited for use in WSNs. Thermoelectric generators are commercially available but not yet widespread, although they output power levels sufficient for use in WSNs. Electromagnetic (mechanical) harvesters are also offered by EnOcean for use in buildings and homes. Prototypes of electromagnetic (magnetic) generators for installation next to current-carrying wires embedded within the walls of a private household have been successfully implemented by Gupta et al.

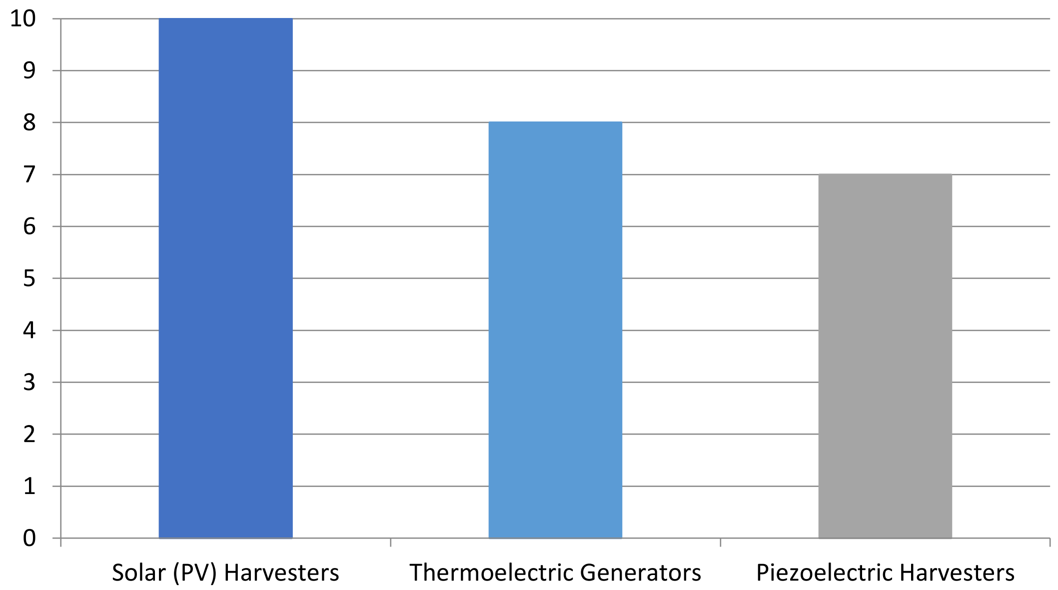


Figure 6-4: Estimated Technological Readiness Levels of Energy Harvesters for Personal Mobile Electronic Devices

For personal mobile electronic devices, ETRLs are somewhat low. Small-scale PV panels capable of charging or powering a mobile phone or radio for use mainly in the developing world have been commercially available for quite some time, hence their relative exclusion from extensive discussion in Chapter 4. Other interesting applications of up-and-coming energy-harvesting techniques are currently far from implementable on a large-scale. TEGs are struggling due to low power outputs, better suited to WSNs than powering mobile electronics. Although potential for thermoelectric-powered devices exists, piezoelectrics dominate the literature and therefore constituted the primary focus of section 4.2.3. Many prototype piezoelectric harvesters designed to charge mobile phones and laptops have been developed, but power conversion remains insubstantial.

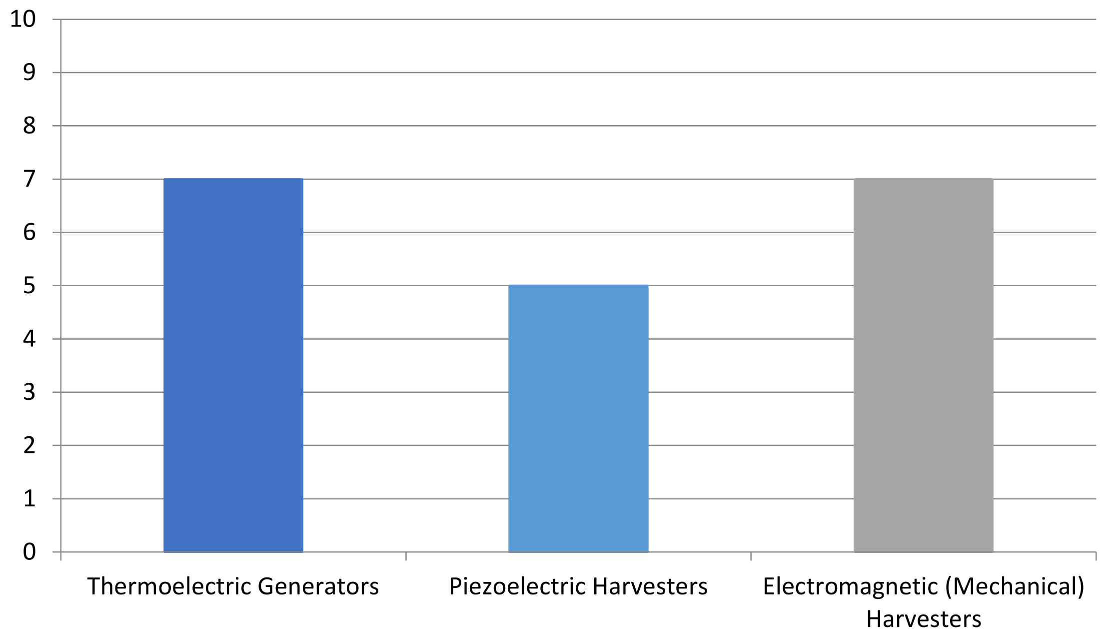


Figure 6-5: Estimated Technological Readiness Levels of Energy Harvesters for Wearable and Implantable Medical Devices

In the healthcare sector, only moderate progress in the area of wearable and implantable medical devices has been made. By current estimates, they will not be commercially available even by 2023. In particular, piezoelectric harvesters exhibit low near-future potential, whereas thermoelectric generators, some of which can operate 100,000 hours (or 10 years) without maintenance, as well as electromagnetic harvesters are both particularly appealing candidates.

Table 6-2: Description of Estimated Technological Readiness Levels

LEVEL	DESCRIPTION
1	Basic principles observed and reported.
2	Technological concept and/or application formulated
3	Analytical and experimental critical function and/or characteristics
4	Component and/or broadboard validation in laboratory setting
5	Component and/or broadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in relevant environment
7	System prototype demonstration in an operational environment
8	Actual system completed and “flight qualified” through testing and demonstration
9	Actual system completed and “flight proven” through successful mission operation
10	Actual system commercially available and cost-effectiveness (EUR/W ratio) established

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