

# Power Sources for Wireless Sensor Networks

**Abstract.** Wireless sensor networks are poised to become a very significant enabling technology in many sectors. Already a few very low power wireless sensor platforms have entered the marketplace. Almost all of these platforms are designed to run on batteries that have a very limited lifetime. In order for wireless sensor networks to become a ubiquitous part of our environment, alternative power sources must be employed. This paper reviews many potential power sources for wireless sensor nodes. Well established power sources, such as batteries, are reviewed along with emerging technologies and currently untapped sources. Power sources are classified as energy reservoirs, power distribution methods, or power scavenging methods, which enable wireless nodes to be completely self-sustaining. Several sources capable of providing power on the order of  $100 \mu\text{W}/\text{cm}^3$  for very long lifetimes are feasible. It is the authors' opinion that no single power source will suffice for all applications, and that the choice of a power source needs to be considered on an application-by-application basis.

## 1 Introduction

The vast reduction in size and power consumption of CMOS circuitry has led to a large research effort based around the vision of ubiquitous networks of wireless sensor and communication nodes [1-3]. As the size and cost of such wireless sensor nodes continues to decrease, the likelihood of their use becoming widespread in buildings, industrial environments, automobiles, aircraft, etc. increases. However, as their size and cost decrease, and as their prevalence increases, effective power supplies become a larger problem.

The issue is that the scaling down in size and cost of CMOS electronics has far outpaced the scaling of energy density in batteries, which are by far the most prevalent power supply currently used. Therefore, the power supply is usually the largest and most expensive component of the emerging wireless sensor nodes being proposed and designed. Furthermore, the power supply (usually a battery) is also the limiting factor on the lifetime of sensor node. If wireless sensor networks are to truly become ubiquitous, replacing batteries in every device every year or two is simply cost prohibitive.

The purpose of this paper, then, is to review existing and potential power sources for wireless sensor networks. Current state of the art, ongoing research, and theoretical limits for many potential power sources will be discussed. One may classify possible methods of providing power for wireless nodes into three groups: store energy on the node (i.e. a battery), distribute power to the node (i.e. a wire), scavenge available ambient power at the node (i.e. a solar cell). Power sources that fall into each of these three categories will be reviewed.

A direct comparison of vastly different types of power source technologies is difficult. For example, comparing the efficiency of a solar cell to that of a battery is not very useful. However, in an effort to provide general understanding of a wide variety of power sources, the following metrics will be used for comparison: power density, energy density (where applicable), and power density per year of use. Additional considerations are the complexity of the power electronics needed and whether secondary energy storage is needed.

## **2 Power Consumption**

Several small low power wireless platforms are available commercially and are being developed in the research community. The most common devices currently in the market are based on the BlueTooth standard. A new, lower power, lower data rate standard (IEEE 802.15.4 or Zigbee) is currently under development. Small companies providing platforms based on their own specifications include Dust Inc. [4], Crossbow [5], Xsilog [6], and Ember [7]. Finally, numerous platforms have been developed in the research community. A few of these include Mote projects from Culler and colleagues [3], the PicoRadio project by Rabaey *et al* [1], the  $\mu$ Amps project from Chandrakasan and colleagues [8], and the GALORE project from Estrin and colleagues [9].

The power needed to operate these platforms (or specifications) depends on how and where they are used. BlueTooth radios use around 40 – 60 mW. The Zigbee standard aims to cut this power consumption by a factor of 3. The power consumption of other commercial and academic platforms varies depending on their usage scenarios. Based on the authors' investigations, they generally operate at about 1 order of magnitude lower than BlueTooth (in the range of 5 – 10 mW depending on the usage environment). Platforms still in the research stage are approaching overall power consumption in the hundreds of microwatts [10-11].

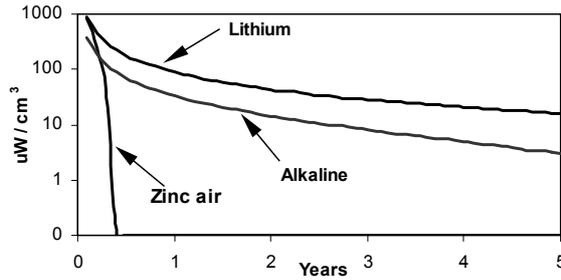
## **3 Energy Reservoirs**

### **3.1 Macro-scale Batteries**

Electrochemical batteries have been the dominant form of power storage and delivery for electronic devices over the past 100 years, thus their consideration for use in wireless sensor networks is natural. Primary batteries are perhaps the most versatile of all small power sources. The main metric of interest for macro-scale batteries is energy density. Table 1 shows the energy density for a few common primary battery chemistries. Figure 1 shows the average power available from these battery chemistries versus lifetime. Note that while zinc-air batteries have the highest energy density, their lifetime is very short.

Chemistry	Zinc-air	Lithium	Alkaline
Energy (J/cm <sup>3</sup> )	3780	2880	1200

**Table 1.** Energy density of three primary battery chemistries.



**Fig. 1.** Continuous power per cm<sup>3</sup> vs. lifetime for three primary battery chemistries.

Because batteries have a fairly stable voltage, electronic devices can often be run directly from the battery without any intervening power electronics. While this may not be the most robust method of powering the electronics, it is often used and is advantageous in that it avoids the extra power consumed by power electronics.

Macro-scale secondary (rechargeable) batteries are commonly used in consumer electronic products such as cell phones, PDA's, and laptop computers. Table 2 gives the energy density a few common rechargeable battery chemistries.

Chemistry	Lithium	NiMHd	NiCd
Energy (J/cm <sup>3</sup> )	1080	860	650

**Table 2.** Energy density of three secondary battery chemistries.

It should be remembered that rechargeable batteries are a *secondary* power source. Therefore, in the context of wireless sensor networks, another primary power source must be used to charge them. In most cases it would be cost prohibitive to manually take a recharger to each device. More likely, an energy scavenging source on the node itself, such as a solar cell, would be used to recharge the battery. One item to consider when using rechargeable batteries is that electronics to control the charging profile must often be used. These electronics add to the overall power dissipation of the device. However, like primary batteries, the voltages are stable and power electronics between the battery and the load electronics can often be avoided.

### 3.2 Micro-scale Batteries

The size of batteries has only decreased mildly when compared to electronic circuits that have decreased in size by orders of magnitude. Thus, whereas a battery for an analog transceiver of the 1920's may have occupied 5% of the device volume, the Crossbow mica mote [5] is powered by two AA size batteries that occupy 90% of

the device volume. At an operational duty cycle of 10%, the batteries must be changed every week.

Unlike capacitors or micro-fuel cells, the main stumbling block to reducing the size of microbatteries is not capacity but rather power output due to surface area limitations of microscale devices.

Since much infrastructure exists for battery development, the challenge of maintaining (or increasing) performance while decreasing size is being addressed on multiple fronts. Bates *et al* at Oak Ridge National Laboratory have created a process by which a primary thin film lithium battery can be deposited onto a chip [12]. The thickness of the entire battery is on the order of 10's of  $\mu\text{m}$ , but the areas studied are in the  $\text{cm}^2$  range. This battery is in the form of a traditional Volta pile, with alternating layers of Lithium Manganese Oxide (or Lithium Cobalt Oxide), Lithium Phosphate Oxynitride and Lithium metal. Maximum Potential is rated at 4.2 V with Continuous/Max current output on the order of 1  $\text{mA}/\text{cm}^2$  and 5  $\text{mA}/\text{cm}^2$  for the  $\text{LiCoO}_2 - \text{Li}$  based cell. A schematic of a battery fabricated with this process is shown in Figure 2.

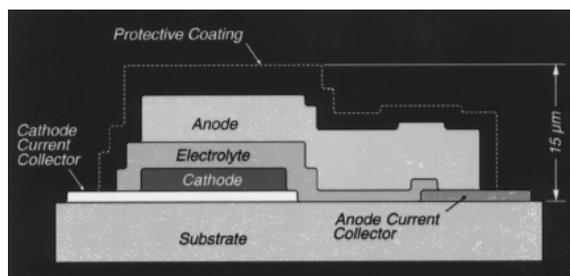


Fig. 2. Primary Lithium on chip battery proposed by Bates *et al* [12].

Work is also being done towards micro- primary batteries. Harb *et al* [13] are investigating “thick film” batteries of Ni/Zn with an aqueous NaOH electrolyte. Thick films are on the order of .1 mm, but overall thicknesses are minimized by use of three-dimensional structures. While each cell is only rated at 1.5 V, geometries have been duty-cycle optimized to give acceptable power outputs at small overall theoretical volumes (4 mm by 1.5 mm by .2 mm) with good durability demonstrated by the electrochemical components of the battery. The main challenges lie in maintaining a microfabricated structure that can contain an aqueous electrolyte. Harb is also investigating thick film lithium secondary systems.

Radical three dimensional structures are being investigated to maximize power output. Dunn *et al* [14] have theorized a three dimensional battery made of series alternating cathode and anode rods suspended in a solid electrolyte matrix. Theoretical power outputs for a three dimensional microbattery are shown to be many times larger than a two dimensional battery of equal size (with far lower ohmic ionic transport distances, thus lower ohmic losses).

For example, a 1  $\text{cm}^2$  thin film battery similar to the one proposed by Dunn *et al*, with each electrode having a thickness of 22  $\mu\text{m}$  and a 5  $\mu\text{m}$  electrolyte, would have a maximum current density on the order of 5 mA. If the battery is restructured to have

the same total volume, with square packing electrode rods of 5  $\mu\text{m}$  radius with 5  $\mu\text{m}$  surface to surface distance, geometry dictates that the energy capacity is 39% of the thin film capacity (due to a higher volume percentage of electrolyte for the thin film battery). However, while the energy density is lower for the 3D battery, the power density is higher due to a higher surface area. In fact, the three dimensional battery would have a total electrode area of 3.5  $\text{cm}^2$ , an increase of 350%. The increase in surface area alone improves the current density to 17.5 mA. Moreover, the ionic transport scale in the 2D structure is about 350% longer than the 3D case because the electrodes for the 3D case are much thinner. Therefore, decreased ohmic losses could further improve the maximum throughput to 20 mA at 4.2 volts.

However, the inherent non-uniformities in current distribution in three dimensional batteries (exacerbated by the particular complexity of this cell) may lead to difficulties with regard to device reliability on primary battery systems and cycle life in secondary battery systems.

### 3.3 Micro-fuel Cells

Hydrocarbon based fuels have very high energy densities compared to batteries. For example, methanol has an energy density of 17.6  $\text{kJ}/\text{cm}^3$ , which is about 6 times that of a lithium battery. Therefore, fuel cells are potentially very attractive for wireless sensor nodes that require high power outputs for hours to days. Fuel cells operate on the same principle as batteries, electrochemically converting energy, but are “open” systems where the reactor size and configuration determine the energy and power output.

Toshiba [15] plans on releasing fuel cells to power laptop computers and cell phones that have total volumes (storage and reactor) on the order of  $\text{cm}^3$ . This particular fuel cell is capable of powering a standard laptop computer for 5 hours continuous off 50 cc of high concentration methanol. Holloday's [16] research level fuel cell reactor, shown in Figure 3, is on the order of  $\text{mm}^3$ .

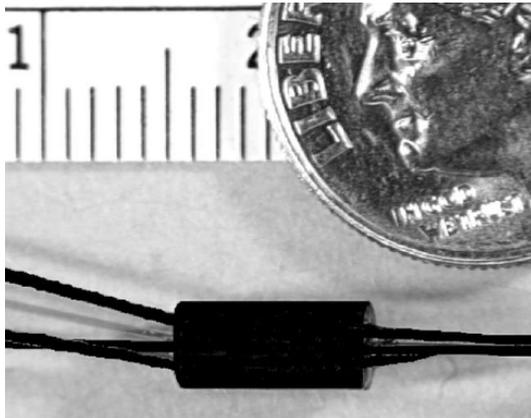


Fig. 3. Small fuel cell reactor by Holloday [16].

An issue with fuel cells, however, is the high temperature the reformers must work at to obtain high efficiencies. For example, Holladay's best reactor is capable of 99% conversion above 320°C at 300 milliseconds, however, at 270°C conversion is less than 60%. At higher temperature, conversion times decrease. In larger wireless sensors these high temperatures may be feasible as the microelectronics can be well insulated from the reactor, but millimeter scale computing is most likely incompatible with fuel cells that require such high temperatures.

### **3.4 Ultracapacitors**

Ultracapacitors represent a compromise of sorts between rechargeable batteries and standard capacitors. Capacitors can provide significantly higher power densities than batteries, however their energy density is lower by about 2 to 3 orders of magnitude. Ultracapacitors (also called supercapacitors or electrochemical capacitors) achieve significantly higher energy density than standard capacitors, but retain many of the favorable characteristics of capacitors, such as long life and short charging time.

Rather than just storing charge across a dielectric material, as capacitors do, ultracapacitors store ionic charge in an electric double layer to increase their effective capacitance. By introducing an electrolyte researchers hope to limit ionic diffusion between plates, trading power generation for longer running times. However, this is still an area of technical difficulty. The energy density of commercially available ultracapacitors is about 1 order of magnitude higher than standard capacitors and about 1 to 2 orders of magnitude lower than rechargeable batteries (or about 50 to 100 J/cm<sup>3</sup>). Because of their increased lifetimes, short charging times, and high power densities, ultracapacitors could be very attractive in some wireless sensor node applications. Corporations working on such ultracapacitors include NEC [17] and Maxwell [18].

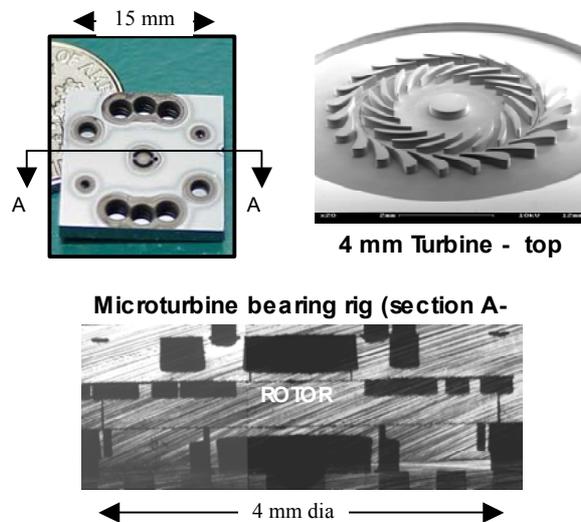
### **3.5 Micro Heat Engines**

At large scales, fossil fuels are the dominant source of energy used for electric power generation, mostly due to the low cost per joule, high energy density, abundant availability, storability and ease of transport. Power plants typically convert the chemical energy of the fuel into thermal energy through combustion, then convert thermal to mechanical power by driving a heat engine that implements a thermodynamic cycle (such as gas turbines or internal combustion engines). The engine then entrains a magnetic generator to produce the electrical power. To date, the complexity and multitude of components involved in such a process have hindered the miniaturization of heat engines and power generation approaches based on combustion of hydrocarbon fuels. As the scale of a mechanical system is reduced, the tolerances must reduce accordingly and the assembly process becomes increasingly challenging. This results in increasing costs per unit power and/or deteriorated performance.

The extension of silicon microfabrication technology from microelectronics to micro-electromechanical systems (or MEMS) is changing this paradigm. Complex microsystems that integrate mechanical, chemical, thermal, fluidic, and electromagnetic functions on-chip, can be batch fabricated with micron-scale

precision using photolithography, etching, and other microfabrication techniques. In the mid-1990's, Epstein *et al* proposed that microengines, i.e. dime-size heat engines, for portable power generation and propulsion could be fabricated using MEMS technology [19]. The initial concept consisted of using silicon deep reactive ion etching, fusion wafer bonding, and thin film processes to microfabricate and integrate high speed turbomachinery, with bearings, a generator, and a combustor within a cubic centimeter volume. An application-ready power supply would also require auxiliary components, such as a fuel tank, engine and fuel controller, electrical power conditioning with short term storage, thermal management and packaging. Expected performance is 10-20 Watt of electrical power output at thermal efficiencies on the order of 5-20%. Figure 4 shows a microturbine test device used for turbomachinery and air bearing development.

Multiple research groups across the globe have also undertaken the development of various micro heat engine-based power generation approaches. On-going microengine projects include micro gas turbine engines [19-20], Rankine steam turbines [21], rotary Wankel internal combustion engine [22], free and spring loaded piston internal combustion engines [23-24], and thermal-expansion-actuated piezoelectric power generators [25-26], to name a few. In addition, various static approaches to convert heat into electricity are in development for small scales, including thermoelectric [27-28], thermionic [29], and thermophotovoltaic [30] components coupled with a heat source.



**Fig. 4.** – Micro-turbine development device, which consists of a 4 mm diameter single crystal silicon rotor enclosed in a stack of five bonded wafers used for micro air bearing development.

Most of these and similar efforts are at initial stages of development and performance has not been demonstrated. However, predictions range from 0.1-10W of electrical power output, with typical masses ~1-5 g and volumes ~1 cm<sup>3</sup>. Microengines are not expected to reduce further in size due to manufacturing and

efficiency constraints. At small scales, viscous drag on moving parts and heat transfer to the ambient and between components increase, which adversely impacts efficiency.

The main system level parameter that emerges for wireless sensor applications is the energy conversion efficiency,  $\eta$  (ratio of output electrical power to what is available from the fuel). For a duration,  $t$ , and average power level,  $P$ , the mass of fuel required is simply the product of duration and average power level, divided by the fuel heating value,  $h_{fuel}$ , and efficiency:  $m_{fuel} = (t * P) / (h_{fuel} * \eta)$ . Typical values of expected fuel requirements are presented in Table 3 for 10 year mission consuming an average power of 1 mW (efficiency of 10% is assumed). The fuel requirement tends to dominate the envelope of the complete system, given the small engine size and mass. If refueling is possible during the mission, then the overall size of the power supply is dramatically reduced, and tends toward the size of the engine and auxiliary components for short autonomous periods.

Fuel	Net specific energy ( $h_{fuel} * \eta$ )	Fuel mass	Fuel volume
Gasoline	1324 Whr/kg	66 g	94 cm <sup>3</sup>
Butane	1270 Whr/kg	69 g	99 cm <sup>3</sup>
Hydrogen	3337 Whr/kg	26 g	972 cm <sup>3</sup>

**Table 3.** Fuel for 10 year mission at 1 mW average power provided by a 10% efficient micro heat engine.

Alternatively, if high quality (temperature) heat is available from the surroundings, the engine could scavenge it instead of burning fuel. Examples of such sources include waste heat from large engines and solar irradiation. Lower efficiencies are however expected if the heat source temperatures are lower than those created by combustion products (1000-1500K). This situation is considered further in the section on Power Scavenging.

Given the relatively large power level, a single microengine would only need to operate at low duty-cycles (less than 1% of the time) to periodically recharge a battery. The total operating time is therefore on the order of hundreds of hours, which alleviates lifetime issues for the engine. It should also be noted that the inefficiency of a heat engines will result in heat rejection to its surroundings. For example, an engine with 1W output power operating at 10% efficiency is consuming 10W from the fuel and rejecting 9 W of heat during periods of operation. Specific applications must allow release of this heat. Combining micro heat engines with thermoelectrics that convert some of this waste heat would lead to greater overall efficiency, but with a cost and size penalty of adding such components.

Overall, the greatest benefits of micro heat engines are their high power density (0.1-2 W/g, without fuel) and their use of fuels allowing high density energy storage for compact, long duration power supplies. For long missions, the power density is not as important as efficiency. Microengines will therefore require many years of development before to reaching the expected efficiencies and being applicable for real life applications.

### 3.6 Radioactive power sources

Radioactive materials contain extremely high energy densities. As with hydrocarbon fuels, this energy has been used on a much larger scale for decades. However, it has not been exploited on a small scale as would be necessary to power wireless sensor networks. The use of radioactive materials can pose a serious health hazard, and is a highly political and controversial topic. It should, therefore, be noted that the goal here is neither to promote nor discourage investigation into radioactive power sources, but to present their potential, and the research being done in the area.

The total energy emitted by radioactive decay of a material can be expressed as in equation 1.

$$E_t = A_c E_e T \quad (1)$$

where  $E_t$  is the total emitted energy,  $A_c$  is the activity,  $E_e$  is the average energy of emitted particles, and  $T$  is the time period over which power is collected. Table 4 lists several potential radioisotopes, their half-lives, specific activities, and energy densities based on radioactive decay. It should be noted that materials with lower activities and higher half-lives will produce lower power levels for more time than materials with comparatively short half-lives and high specific activities. The half-life of the material has been used as the time over which power would be collected. Only alpha and beta emitters have been included because of the heavy shielding needed for gamma emitters. Finally, uranium 238 is included for purposes of comparison only.

Material	Half-life (years)	Activity volume density (Ci/cm <sup>3</sup> )	Energy density (J/cm <sup>3</sup> )
<sup>238</sup> U	4.5 X 10 <sup>9</sup>	6.34 X 10 <sup>-6</sup>	2.23 X 10 <sup>10</sup>
<sup>63</sup> Ni	100.2	506	1.6 X 10 <sup>8</sup>
<sup>32</sup> Si	172.1	151	3.3 X 10 <sup>8</sup>
<sup>90</sup> Sr	28.8	350	3.7 X 10 <sup>8</sup>
<sup>32</sup> P	0.04	5.2 X 10 <sup>5</sup>	2.7 X 10 <sup>9</sup>

**Table 4.** Comparison of radio-isotopes.

While the energy density numbers reported for radioactive materials are extremely attractive, it must be remembered that in most cases the energy is being emitted over a very long period of time. Second, efficient methods of converting this power to electricity at small scales do not exist. Therefore, efficiencies would likely be extremely low.

Recently, Li and Lal [18] have used the <sup>63</sup>Ni isotope to actuate a conductive cantilever. As the beta particles (electrons) emitted from the <sup>63</sup>Ni isotope collect on the conductive cantilever, there is an electrostatic attraction. At some point, the cantilever contacts the radioisotope and discharges, causing the cantilever to oscillate. Up to this point the research has only demonstrated the actuation of a cantilever, and not electric power generation. However, electric power could be generated from an oscillating cantilever. The reported power output, defined as the change over time in the combined mechanical and electrostatic energy stored in the cantilever, is 0.4 pW

from a 4mm X 4mm thinfilm of  $^{63}\text{Ni}$ . This power level is equivalent to  $0.52 \mu\text{W}/\text{cm}^3$ . However, it should be noted that using  $1 \text{ cm}^3$  of  $^{63}\text{Ni}$  is impractical. The reported efficiency of the device is  $4 \times 10^{-6}$ .

## 4 Power Distribution

### 4.1 Electromagnetic (RF) Power Distribution

The most common method (other than wires) of distributing power to embedded electronics is through the use of RF (Radio Frequency) radiation. Many passive electronic devices, such as electronic ID tags and smart cards, are powered by a nearby energy rich source that transmits RF energy to the passive device. The device then uses that energy to run its electronics. [32-33]. This solution works well, as evidenced by the wide variety of applications where it is used, if there is a high power scanner or other source in very near proximity to the wireless device. It is, however, less effective in dense ad-hoc networks where a large area must be flooded with RF radiation to power many wireless sensor nodes.

Using a very simple model neglecting any reflections or interference, the power received by a wireless node can be expressed by equation 2 [34].

$$P_r = \frac{P_0 \lambda^2}{4\pi R^2} \quad (2)$$

where  $P_0$  is the transmitted power,  $\lambda$  is the wavelength of the signal, and  $R$  is the distance between transmitter and receiver. Assume that the maximum distance between the power transmitter and any sensor node is 5 meters, and that the power is being transmitted to the nodes in the 2.4 – 2.485 GHz frequency band, which is the unlicensed industrial, scientific, and medical band in the United States. Federal regulations limit ceiling mounted transmitters in this band to 1 watt or lower. Given a 1 watt transmitter, and a 5 meter maximum distance the power received at the node would be  $50 \mu\text{W}$ , which is probably on the borderline of being really useful. However, in reality the power transmitted will fall off at a rate faster than  $1/R^2$  in an indoor environment. A more likely figure is  $1/R^4$ . While the 1 watt limit on a transmitter is by no means general for indoor use, it is usually the case that some sort of safety limitation would need to be exceeded in order to flood a room or other area with enough RF radiation to power a dense network of wireless devices.

### 4.2 Wires, Acoustic, Light, Etc.

Other means of transmitting power to wireless sensor nodes might include wires, acoustic emitters, and light or lasers. However, none of these methods are appropriate for wireless sensor networks. Running wires to a wireless communications device defeats the purpose of wireless communications. Energy in the form of acoustic waves has a far lower power density than is sometimes assumed. A sound wave of 100 dB in sound level only has a power level of  $0.96 \mu\text{W}/\text{cm}^2$ . One could also imagine using a laser or other focused light source to direct power to each of the nodes in the sensor network. However, to do this is a controlled way, distributing

light energy directly to each node, rather than just flooding the space with light, would likely be too complex and not cost effective. If a whole space is flooded with light, then this source of power becomes attractive. However, this situation has been classified as “power scavenging” and will be discussed in the following section.

## 5 Power Scavenging

Unlike power sources that are fundamentally energy reservoirs, power scavenging sources are usually characterized by their power density rather than energy density. Energy reservoirs have a characteristic energy density, and how much average **power** they can provide is then dependent on the lifetime over which they are operating. On the contrary, the **energy** provided by a power scavenging source depends on how long the source is in operation. Therefore, the primary metric for comparison of scavenged sources is power density, not energy density.

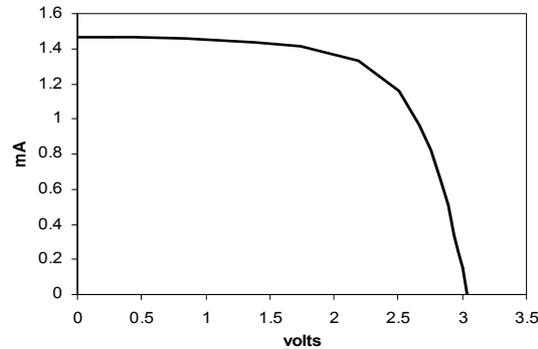
### 5.1 Photovoltaics (Solar cells)

At midday on a sunny day, the incident light on the earth’s surface has a power density of roughly  $100 \text{ mW/cm}^2$ . Single crystal silicon solar cells exhibit efficiencies of 15% - 20% [35] under high light conditions, as one would find outdoors. Common indoor lighting conditions have far lower power density than outdoor light. Common office lighting provides about  $100 \text{ } \mu\text{W/cm}^2$  at the surface of a desk. Single crystal silicon solar cells are better suited to high light conditions and the spectrum of light available outdoors [35]. Thin film amorphous silicon or cadmium telluride cells offer better efficiency indoors because their spectral response more closely matches that of artificial indoor light. Still, these thin film cells only offer about 10% efficiency. Therefore, the power available from photovoltaics ranges from about  $15 \text{ mW/cm}^2$  outdoors to  $10 \text{ } \mu\text{W/cm}^2$  indoors. Table 4 shows the measured power outputs from a cadmium telluride solar cell (Panasonic BP-243318) at varying distances from a 60 watt incandescent bulb.

Distance	8 in.	12 in.	18 in.	Office light
Power ( $\mu\text{W/cm}^2$ )	503	236	111	7.2

**Table 5.** Power from a cadmium telluride solar cell at various distances from a 60 watt incandescent bulb and under standard office lighting conditions.

A single solar cell has an open circuit voltage of about 0.6 volts. Individual cells are easily placed in series, especially in the case of thin film cells, to get almost any desired voltage needed. A current vs. voltage (I-V) curve for a typical five cell array (wired in series) is shown below in Figure 5. Unlike the voltage, current densities are directly dependent on the light intensity.



**Fig. 5.** Typical I-V curve from a five cell cadmium telluride solar array (Panasonic BP-243318).

Solar cells provide a fairly stable DC voltage through much of their operating space. Therefore, they can be used to directly power electronics in cases where the current load is such that it allows the cell to operate on high voltage side of the “knee” in the I-V curve and where the electronics can tolerate some deviation in source voltage. More commonly solar cells are used to charge a secondary battery. Solar cells can be connected directly to rechargeable batteries through a simple series diode to prevent the battery from discharging through the solar cell. This extremely simple circuit does not ensure that the solar cell will be operating at its optimal point, and so power production will be lower than the maximum possible. Secondly, rechargeable batteries will have a longer lifetime if a more controlled charging profile is employed. However, controlling the charging profile and the operating point of the solar cell both require more electronics, which use power themselves. An analysis needs to be done for each individual application to determine what level of power electronics would provide the highest net level of power to the load electronics. Longevity of the battery is another consideration to be considered in this analysis.

## 5.2 Temperature gradients

Naturally occurring temperature variations can also provide a means by which energy can be scavenged from the environment. The maximum efficiency of power conversion from a temperature difference is equal to the Carnot efficiency, which is given as equation 3.

$$\eta = \frac{T_{high} - T_{low}}{T_{high}} \quad (3)$$

Assuming a room temperature of 20 °C, the efficiency is 1.6% from a source 5 °C above room temperature and 3.3% for a source 10 °C above room temperature.

A reasonable estimate of the maximum amount of power available can be made assuming heat conduction through silicon material. Convection and radiation would

be quite small compared to conduction at small scales and low temperature differentials. The amount of heat flow (power) is given by equation 4.

$$q' = k \frac{\Delta T}{L} \quad (4)$$

where  $k$  is the thermal conductivity of the material and  $L$  is the length of the material through which the heat is flowing. The conductivity of silicon is approximately 140 W/mK. Assuming a 5 °C temperature differential and a length of 1 cm, the heat flow is 7 W/cm<sup>2</sup>. If Carnot efficiency could be obtained, the resulting power output would be 117 mW/cm<sup>2</sup>. While this is an excellent result compared with other power sources, one must realize demonstrated efficiencies are well below the Carnot efficiency.

A number of researchers have developed systems to convert power from temperature differentials to electricity. The most common method is through thermoelectric generators that exploit the Seebeck effect to generate power. This is the same principle on which thermocouples work. For example Stordeur and Stark [36] have demonstrated a micro-thermoelectric generator capable of generating 15 μW/cm<sup>2</sup> from a 10 °C temperature differential. Furthermore, they report a technology limit of about 30 μW/cm<sup>2</sup> for the technology used. Recently Applied Digital Solutions have developed a thermoelectric generator soon to be marketed as a commercial product. The generator is reported as being able to produce 40 μW of power from a 5 °C temperature differential using a device 0.5 cm<sup>2</sup> in area and a few millimeters thick. [37] The output voltage of the device is approximately 1 volt. The thermal-expansion actuated piezoelectric generator referred to earlier [25] has also been proposed as a method to convert power from ambient temperature gradients to electricity.

### 5.3 Human power

An average human body burns about 10.5 MJ of energy per day. (This corresponds to an average power dissipation of 121 W.) Starner has proposed tapping into some of this energy to power wearable electronics [38]. For example watches are powered using both the kinetic energy of a swinging arm and the heat flow away from the surface of the skin [39].

The conclusion of studies undertaken at MIT suggests that the most energy rich and most easily exploitable source occurs at the foot during heel strike and in the bending of the ball of the foot [40]. This research has led to the development of piezoelectric shoe inserts capable of producing an average of 330 μW/cm<sup>2</sup> while a person is walking. The shoe inserts have been used to power a low power wireless transceiver mounted to the shoes. While this power source is of great use for wireless nodes worn on a person's foot, the problem of how to get the power from the shoe to the point of interest still remains.

The sources of power mentioned above are passive power sources in that the human doesn't need to do anything other than what they would normally do to generate power. There is also a class of power generators that could be classified as active human power in that they require the human to perform an action that they would not normally perform. For example Freeplay [41] markets a line of products

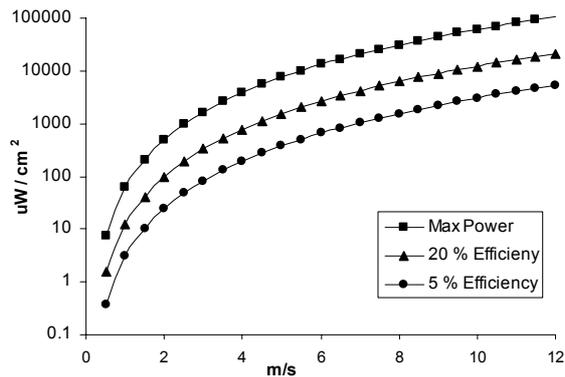
that are powered by a constant force spring that the user must wind up. While these types of products are extremely useful, they are not very applicable to wireless sensor networks because it would be impractical and not cost efficient to individually wind up every node.

#### 5.4 Wind / air flow

Wind power has been used on a large scale as a power source for centuries. Large windmills are still common today. However, the authors' are unaware of any efforts to try to generate power at a very small scale (on the order of a cubic centimeter) from air flow. The potential power from moving air is quite easily calculated as shown in equation 5.

$$P = \frac{1}{2} \rho A v^3 \quad (5)$$

where P is the power,  $\rho$  is the density of air, A is the cross sectional area, and v is the air velocity. At standard atmospheric conditions, the density of air is approximately  $1.22 \text{ kg/m}^3$ . Figure 6 shows the power per square centimeter versus air velocity.



**Fig. 6.** Maximum power density from air flow. Power density assuming 20% and 5% conversion efficiencies are also shown.

Large scale windmills operate at maximum efficiencies of about 40%. Efficiency is dependent on wind velocity, and average operating efficiencies are usually about 20%. Windmills are generally designed such that maximum efficiency occurs at wind velocities around 8 m/s (or about 18 mph). At low air velocity, efficiency can be significantly lower than 20%. Figure 6 also shows power output assuming 20% and 5% efficiency in conversion. As can be seen from the graph, power densities from air velocity are quite promising. As there are many possible applications in which a fairly constant air flow of a few meters per second exists, it seems that research leading to the development of devices to convert air flow to electrical power at small scales is warranted.

### 5.5 Pressure variations

Variations in pressure can be used to generate power. For example one could imagine a closed volume of gas that undergoes pressure variation as the daily temperature changes. Likewise, atmospheric pressure varies throughout the day. The change in energy for a fixed volume of ideal gas due to a change in pressure is simply given by

$$\Delta E = \Delta PV \quad (6)$$

where  $\Delta E$  is the change in energy,  $\Delta P$  is the change in pressure, and  $V$  is the volume. A quick survey of atmospheric conditions around the world reveals that an average atmospheric pressure change over 24 hours is about 0.2 inches Hg or 677 Pa, which corresponds to an energy change of 677  $\mu\text{J}/\text{cm}^3$ . If the pressure cycles through 0.2 inches Hg once per day, for a frequency of  $1.16 \times 10^{-5}$ , the power density would then be 7.8  $\text{nW}/\text{cm}^3$ .

An average temperature variation over a 24 hour period would be about 10 °C. The change in pressure to a fixed volume of ideal gas from a 10 °C change in temperature is given by

$$\Delta P = \frac{mR\Delta T}{V} \quad (7)$$

where  $m$  is mass of the gas,  $R$  is gas constant, and  $\Delta T$  is the change in temperature. If 1  $\text{cm}^3$  of helium gas were used, a 10 °C temperature variation would result in a pressure change of 1.4 MPa. The corresponding change in energy would be 1.4 J per day, which corresponds to 17  $\mu\text{W}/\text{cm}^3$ . While this is a simplistic analysis and assumes 100% conversion efficiency to electricity, it does give an idea of what might be theoretically expected from naturally occurring pressure variations.

To the authors' knowledge, there is no research underway to exploit naturally occurring pressure variations to generate electricity. Some clocks, such as the "Atmos clock", are powered by an enclosed volume of fluid that undergoes a phase change under normal daily temperature variations. The volume and pressure change corresponding to the phase change of the fluid mechanically actuates the clock. However, this is on a large scale, and no effort is made to convert the power to electricity.

### 5.6 Vibrations

Low level mechanical vibrations are present in many environments. Examples include HVAC ducts, exterior windows, manufacturing and assembly equipment, aircraft, automobiles, trains, and small household appliances. Table 6 shows results of measurements on several different vibrations sources performed by the authors. It will be noticed that the primary frequency of all sources is between 60 and 200 Hz. Acceleration amplitudes range from about 1 to 10  $\text{m}/\text{s}^2$ .

Vibration Source	Peak Acc. (m/s <sup>2</sup> )	Freq. (Hz)
Base of 3-axis machine tool	10	70
Kitchen blender casing	6.4	121
Clothes dryer	3.5	121
Door frame just as door closes	3	125
Small microwave oven	2.25	121
HVAC vents in office building	0.2 – 1.5	60
Wooden deck with foot traffic	1.3	385
Breadmaker	1.03	121
External windows (size 2 ft X 3 ft) next to a busy street	0.7	100
Notebook computer while CD is being read	0.6	75
Washing Machine	0.5	109
Second story floor of a wood frame office building	0.2	100
Refrigerator	0.1	240

**Table 6.** Summary of several vibration sources.

A simple general model for power conversion from vibrations has been presented by Williams *et al* [41]. The final equation for power output from this model is shown here as equation 8.

$$P = \frac{m\zeta_e A^2}{4\omega(\zeta_e + \zeta_m)^2} \quad (8)$$

where  $P$  is the power output,  $m$  is the oscillating proof mass,  $A$  is the acceleration magnitude of the input vibrations,  $\omega$  is the frequency of the driving vibrations,  $\zeta_m$  is the mechanical damping ratio, and  $\zeta_e$  is an electrically induced damping ratio. In the derivation of this equation, it was assumed that the resonant frequency of the oscillating system matches the frequency of the driving vibrations. While this model is oversimplified for many implementations, it is useful to get a quick estimate on potential power output from a given source. Three interesting relationships are evident from this model.

1. Power output is proportional to the oscillating mass of the system.
2. Power output is proportional to the square of the acceleration amplitude of the input vibrations.
3. Power is inversely proportional to frequency.

Point three indicates that the generator should be designed to resonate at the lowest frequency peak in the vibrations spectrum provided that higher frequency peaks do not have a higher acceleration magnitude. Many spectra measured by Roundy *et al* [42] verify that generally the lowest frequency peak has the highest acceleration magnitude.

Figures 7 through 9 provide a range of power densities that can be expected from vibrations similar to those listed above in Table 6. The data shown in the figures are

based on calculations from the model of Williams *et al* and do not consider the technology that is used to convert the mechanical kinetic energy to electrical energy.

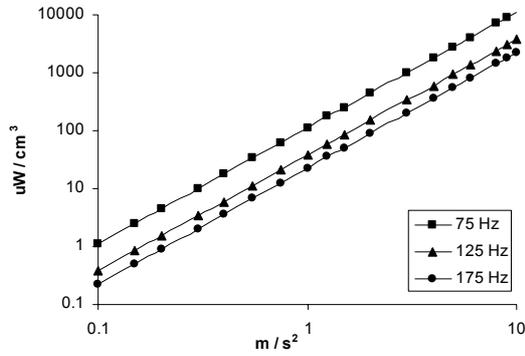


Fig. 7. Power density vs. vibration amplitude for three frequencies.

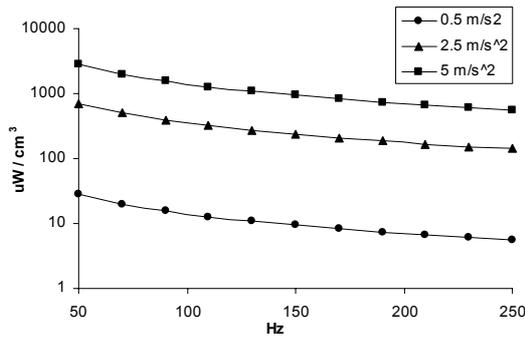


Fig. 8. Power density vs. frequency of vibration input.

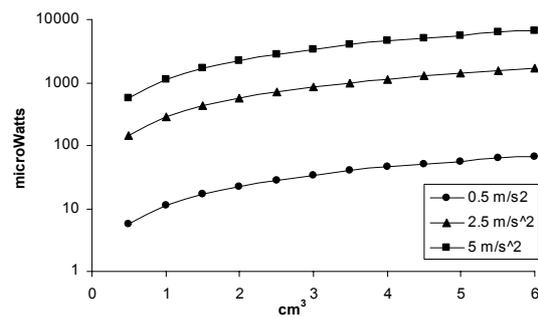
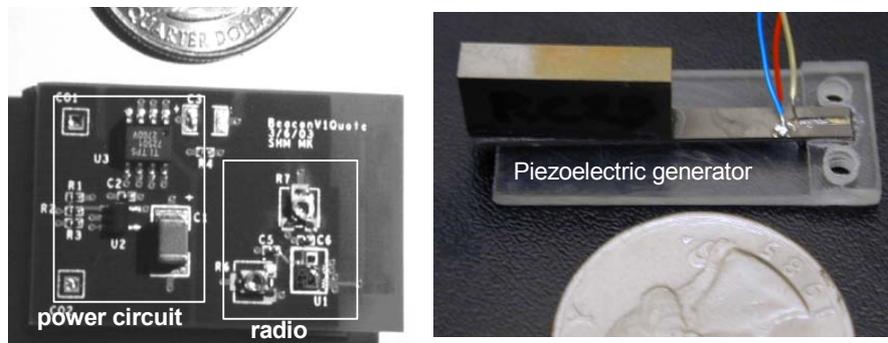


Fig. 9. Total power vs. device size. Frequency of input vibrations is 125 Hz.

Several researchers have developed devices to scavenge power from vibrations [41-44]. Devices include electromagnetic, electrostatic, and piezoelectric methods to convert mechanical motion into electricity. Theory, simulations, and experiments performed by the authors suggest that for devices on the order of  $1 \text{ cm}^3$  in size, piezoelectric generators will offer the most attractive method of power conversion. Piezoelectric conversion offers higher potential power density from a given input, and produces voltage levels on the right order of magnitude. Roundy [45] has demonstrated a piezoelectric power converter of  $1 \text{ cm}^3$  in size that produces  $200 \text{ } \mu\text{W}$  from input vibrations of  $2.25 \text{ m/s}^2$  at 120 Hz. Both Roundy *et al* and Ottman *et al* [44-45] have demonstrated wireless transceivers powered from vibrations. Figure 10 shows the generator, power circuit, and transceiver developed by Roundy *et al*.



**Fig. 10.** Piezoelectric generator, power circuit, and radio powered from vibrations of  $2.25 \text{ m/s}^2$  at 120 Hz.

Because vibration based power generators are almost always have fairly low damping ( $Q \sim 30$ ), it is essential that the resonant frequency of the converter match the dominant frequency of the input vibrations. In many applications the vibration spectrum is known beforehand, and the system can be designed to resonate at the appropriate frequency. However, in other applications the frequency of the input vibrations is either unknown or changes with time. Therefore, self-tuning generators would be necessary in these situations.

The power signal generated from vibration generators needs a significant amount of conditioning to be useful to wireless electronics. The converter produces an AC voltage that needs to be rectified. Additionally the magnitude of the AC voltage depends on the magnitude of the input vibrations, and so is not very stable. Typically, some sort of energy reservoir is needed along with a voltage regulator or DC-DC converter. However, the energy reservoir could be as small as a capacitor of several microfarads depending on the application. Although more power electronics are needed compared with some other sources, commonly occurring vibrations can provide power on the order of hundreds of microwatts per cubic centimeter, which is quite competitive compared to other power scavenging sources.

## 6 Summary

An effort has been made to give an overview of the many potential power sources for wireless sensor networks. Well established sources, such as batteries, have been considered along with potential sources on which little or no work has been done. Because some sources are fundamentally characterized by energy density (such as batteries) while others are characterized by power density (such as solar cells) a direct comparison with a single metric is difficult. Adding to this difficulty is the fact that some power sources do not make much use of the third dimension (such as solar cells), so their fundamental metric is power per square centimeter rather than power per cubic centimeter. Nevertheless, in an effort to compare all possible sources, a summary table is shown below as Table 7. Note that power density is listed as  $\mu\text{W}/\text{cm}^3$ , however, it is understood that in certain instances the number reported really represents  $\mu\text{W}/\text{cm}^2$ . Such values are marked with a “\*”. Note also that with only two exceptions, values listed are numbers that have been demonstrated or are based on experiments rather than theoretical optimal values. The two cases in which theoretical numbers are listed have been italicized. In many cases the theoretical best values are explained in the text above.

Power Source	P/cm <sup>3</sup> ( $\mu\text{W}/\text{cm}^3$ )	E/cm <sup>3</sup> (J/cm <sup>3</sup> )	P/cm <sup>3</sup> /yr ( $\mu\text{W}/\text{cm}^3/\text{Yr}$ )	Secondary Storage Needed	Voltage Regulation	Comm. Available
Primary Battery	-	2880	90	No	No	Yes
Secondary Battery	-	1080	34	-	No	Yes
Micro-Fuel Cell	-	3500	110	Maybe	Maybe	No
Ultra-capacitor	-	50-100	1.6-3.2	No	Yes	Yes
Heat engine	-	3346	106	Yes	Yes	No
Radioactive( <sup>63</sup> Ni)	0.52	1640	0.52	Yes	Yes	No
Solar (outside)	15000 *	-	-	Usually	Maybe	Yes
Solar (inside)	10 *	-	-	Usually	Maybe	Yes
Temperature	40 * †	-	-	Usually	Maybe	Soon
Human Power	330	-	-	Yes	Yes	No
Air flow	<i>380 ††</i>	-	-	Yes	Yes	No
Pressure Variation	<i>17 †††</i>	-	-	Yes	Yes	No
Vibrations	200	-	-	Yes	Yes	No

**Table 7.** Comparison of various potential power sources for wireless sensor networks. Values shown are actual demonstrated numbers except in two cases which have been italicized.

\* Denotes sources whose fundamental metric is power per **square** centimeter rather than power per **cubic** centimeter.

† Demonstrated from a 5 °C temperature differential.

†† Assumes air velocity of 5 m/s and 5 % conversion efficiency.

††† Based on a 1 cm<sup>3</sup> closed volume of helium undergoing a 10 °C temperature change once per day.

Almost all wireless sensor nodes are presently powered by batteries. This situation presents a substantial roadblock to the widespread deployment of wireless sensor networks because the replacement of batteries is cost prohibitive. Furthermore, a battery that is large enough to last the lifetime of the device would dominate the overall system size and cost, and thus is not very attractive. It is therefore essential that alternative power sources be considered and developed.

This paper has attempted to characterize a wide variety of such sources. It is the authors' opinion that no single alternative power source will solve the problem for all, or even a large majority of cases. However, many attractive and creative solutions do exist that can be considered on an application-by-application basis.

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