Power Sources for Wireless Sensor Networks

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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 $\mu W/cm^3$ 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 sources 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 a 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 Energy Reservoirs

Energy storage, in the form of electrochemical energy stored in a battery, is the predominant means of providing power to wireless devices today. However, several other forms of energy storage may be useful for wireless sensor nodes. Regardless of the form of the energy storage, the lifetime of the node will be determined by the fixed amount of energy stored on the device. The primary metric of interest for all forms of energy storage will be usable energy per unit volume (J/cm^3). An additional issue is that the instantaneous power that an energy reservoir can supply is usually dependent on its size. Therefore, in some cases, such as micro-batteries, the maximum power density (μW/cm^3) is also an issue for energy reservoirs.

2.1 Macro-scale Batteries

Primary batteries are perhaps the most versatile of all small power sources. Table 1 shows the energy density for a few common primary battery chemistries. Note that while zinc-air batteries have the highest energy density, their lifetime is very short, and so are most useful for applications that have constant, relatively high, power demands.

Table 1. Energy density of three primary battery chemistries.

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

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 of a few common rechargeable 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.

Table 2. Energy density of three secondary battery chemistries.

Chemistry	Lithium	NiMHd	NiCd
Energy (J/cm^3)	1080	860	650

2.2 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. One of the main stumbling blocks to reducing the size of micro-batteries is power output due to surface area limitations of micro-scale devices. The maximum current output of a battery depends on the surface area of the electrodes. Because micro-batteries are so small, the electrodes have a small surface area, and their maximum current output is also very small.

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 [4]. The thickness of the entire battery is on the order of 10's of µm, but the areas studied are in the 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 mA/cm^2 and 5 mA/cm^2 for the $LiCoO_2$ – Li based cell.

Work is being done on thick film batteries with a smaller surface area by Harb *et al* [5], who have developed micro-batteries of Ni/Zn with an aqueous NaOH electrolyte. Thick films are on the order of 0.1 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 0.2 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.

Radical three dimensional structures are also being investigated to maximize power output. Hart *et al* [6] 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 because of higher electrode surface area to volume ratios and lower ohmic losses due to lower ionic transport distances. However, it should be noted that the increased power density comes at a lower energy density because of the lower volume percentage of electrolyte.

2.3 Micro-fuel Cells

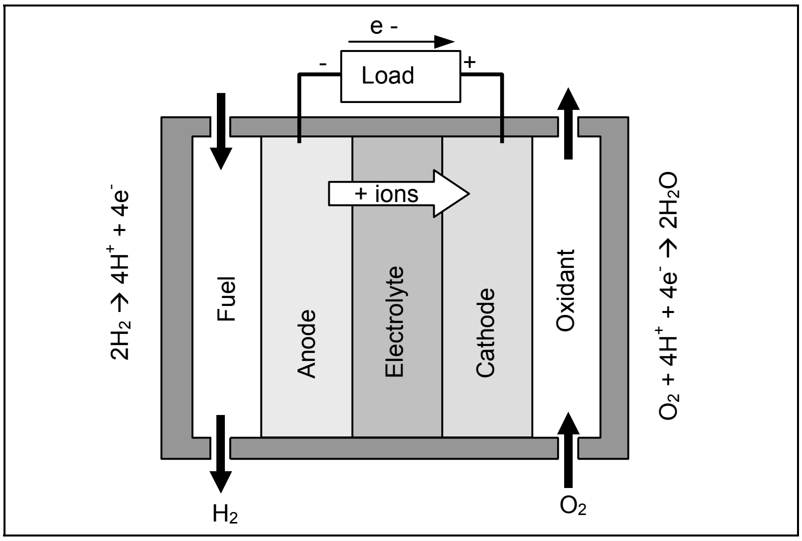


Fig. 1. Illustration of how a standard hydrogen fuel cell works.

Hydrocarbon based fuels have very high energy densities compared to batteries. For example, methanol has an energy density of 17.6 kJ/cm^3, which is about 6 times that of a lithium battery. Like batteries, fuel cells produce electrical power from a chemical reaction. A standard fuel cell uses hydrogen atoms as fuel. A catalyst promotes the separation of the electron in the hydrogen atom from the proton. The proton diffuses through an electrolyte (often a solid membrane) while the electron is available for use by an external circuit. The protons and electrons recombine with oxygen atoms on the other side (the oxidant side) of the electrolyte to produce water molecules. This process is illustrated in Figure 1. While pure hydrogen can be used as a fuel, other hydrocarbon fuels are often used. For example, in Direct Methanol Fuel Cells (DFMC) the anode catalyst draws the hydrogen atoms out from the methanol.

Most single fuel cells tend to output open circuit voltages around 1.0 – 1.5 volts. Of course, like batteries, the cells can be placed in series for higher voltages. The voltage is quite stable over the operating lifetime of the cell, but it does fall off with increasing current draw. Because the voltage drops with current, it is likely that some additional power electronics will be necessary if replacing a battery with a fuel cell.

Large scale fuel cells have been used as power supplies for decades. Recently fuel cells have gained favor as a replacement for consumer batteries [7]. Small, but still macro-scale, fuel cells are likely to soon appear in the market as battery rechargers and battery replacements [8].

The research trend is toward micro-fuel cells that could possibly be closely integrated with wireless sensor nodes. Like micro-batteries, a primary metric of comparison in micro-fuel cells is power density in addition to energy density. As with micro-batteries, the maximum continuous current output is dependent on the electrode surface area. Efficiencies of large scale fuel cells have reached approximately 45% electrical conversion efficiency and nearly 90% if cogeneration is employed [9]. Efficiencies for micro-scale fuel cells will certainly be lower. The maximum obtainable efficiency for a micro-fuel cell is still uncertain. Demonstrated efficiencies are generally below 1% [10].

Many research groups are working on microfabricated partial systems that typically include an electrolyte membrane, electrodes, and channels for fuel and oxidant flow. Recent examples include the hydrogen based fuel cells developed by Hahn *et al* [11] and Lee *et al* [12]. Both systems implement microfabricated electrodes and channels for fuel and oxidant flow. The system by Hahn *et al* produces power on the order of 100 mW/cm^2 from a device 0.54 cm^2 in size. The system by Lee *et al* produces 40 mW/cm^2. It should be noted that the fundamental characteristic here is power per unit area rather than power per unit volume because the devices are fundamentally planar. Complete fuel storage systems are not part of their studies, and therefore an energy or power per unit volume metric is not appropriate. Fuel conversion efficiencies are not reported.

Hydrogen storage at small scales is a difficult problem that has not yet been solved. Primarily for this reason, methanol based micro-fuel cells are also being investigated by numerous groups. For example, Holloday *et al* [10] have demonstrated a methanol fuel processor with a total size on the order of several mm^3. This fuel processor has been combined with a thin fuel cell, 2 cm^2 in area, to produce roughly 25 mA at 1 volt with 0.5% overall efficiency. They are targeting a 5% efficient cell.

Given the energy density of fuels such as methanol, fuel cells need to reach efficiencies of at least 20% in order to be more attractive than primary batteries. Nevertheless, at the micro scale, where battery energy densities are also lower, a lower efficiency fuel cell may still be attractive. Finally, providing for sufficient fuel and oxidant flows is a very difficult task in micro-fuel cell development. The ability to microfabricate electrodes and electrolytes does not guarantee the ability to realize a micro-fuel cell. To the authors' knowledge, a self-contained, on-chip fuel cell has yet to be demonstrated.

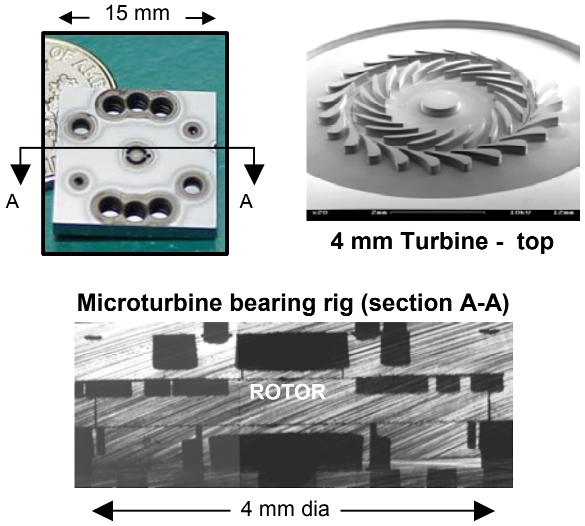
2.4 Micro Heat Engines

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 (gasoline has an energy density of 12.7 kJ/cm^3), abundant availability, storability and ease of transport. To date, the complexity and multitude of components involved 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. 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 [13]. 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 2 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 generators. Approaches ranging from micro gas turbine engines to thermal-expansion-actuated piezoelectric generators and micro-thermophotovoltaic systems are being investigated [13–20].

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^3. 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. 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.



4 mm Turbine - top

Microturbine bearing rig (section A-A)

Fig. 2. – 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.

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 low power applications, the power density is not as important as efficiency. Microengines will therefore require many years of development before reaching the expected efficiencies and being applicable for wireless sensor network applications.

2.6 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.

$$E_t = A_c E_e T \tag{1}$$

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 3 lists several potential radioisotopes, their half-lives, specific activities, energy densities, and power densities based on radioactive decay. The half-life of the material has been used as the time over which power would be collected.

Table 3. Comparison of radio-isotopes.

Material	Half-life (years)	Activity volume density (Ci/cm^3)	Energy density (J/cm^3)	Power density (mW/cm^3)
^{238}U	4.5 X 10^9	6.34 X 10^{-6}	2.23 X 10^{10}	1.6 X 10^{-4}
^{63}Ni	100.2	506	1.6 X 10^8	50.6
^{32}Si	172.1	151	3.3 X 10^8	60.8
^{90}Sr	28.8	350	3.7 X 10^8	407
^{32}P	0.04	5.2 X 10^5	2.7 X 10^9	2.14 X 10^6

While the energy density numbers reported for radioactive materials are extremely attractive, it must be remembered that 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 [21] have used the ^{63}Ni isotope to actuate a conductive cantilever. As the beta particles (electrons) emitted from the ^{63}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}Ni. This power level is equivalent to 0.52 μW/cm^3. However, it should be noted that using 1 cm^3 of ^{63}Ni is impractical. The reported efficiency of the device is 4 X 10^{-6}.

3 Power Distribution

In addition to storing power on a wireless node, in certain circumstances power can be distributed to the node from a nearby energy rich source. It is difficult to characterize the effectiveness of power distribution methods by the same metrics (power or energy density) because in most cases the power received at the node is more a function of how much power is transmitted rather than the size of the power receiver at the node. Nevertheless an effort is made to characterize the effectiveness of power distribution methods as they apply to wireless sensor networks.

3.1 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 [22-23]. 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 [24].

$$P_r = \frac{P_0 \lambda^2}{4\pi R^2} \tag{2}$$

where P_o is the transmitted power, λ 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 μW, which is probably on the borderline of being really useful for wireless sensor nodes. 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.

3.2 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 approximately 1 μW/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.

4 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.

4.1 Photovoltaics (Solar cells)

At midday on a sunny day, the incident light on the earth's surface has a power density of roughly 100 mW/cm^2. Single crystal silicon solar cells exhibit efficiencies of 15% - 20% [25] under high light conditions, as one would find outdoors. Common indoor lighting conditions have far lower power density than outdoor conditions. Common office lighting provides about 100 μW/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 [25]. 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 mW/cm^2 at midday outdoors to 10 μW/cm^2 indoors.

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 3. Unlike the voltage, current densities are directly dependent on the light intensity.

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.

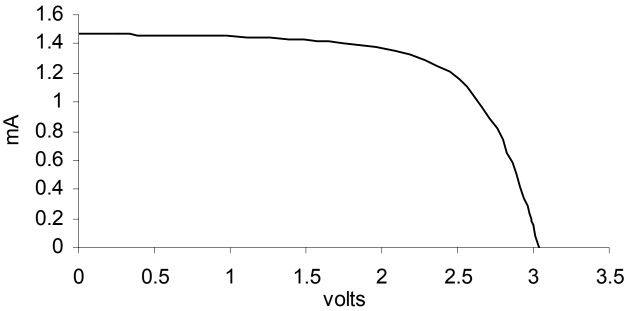


Fig. 3. Typical I-V curve from a cadmium telluride solar array (Panasonic BP-243318).

4.2 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.

$$\eta = \frac{T_{high} - T_{low}}{T_{high}} \tag{3}$$

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.

$$q' = k\frac{\Delta T}{L} \tag{4}$$

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^2. If Carnot efficiency could be obtained, the resulting power output would be 117 mW/cm^2. 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. For example Stordeur and Stark [26] have demonstrated a micro-thermoelectric generator capable of generating 15 µW/cm^2 from a 10 ºC temperature differential. 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 ºC temperature differential using a device 0.5 cm^2 in area and a few millimeters thick [27]. The output voltage of the device is approximately 1 volt. The thermal-expansion actuated piezoelectric generator referred to earlier [17] has also been proposed as a method to convert power from ambient temperature gradients to electricity.

4.3 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 [28]. 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 [29]. This research has led to the development of piezoelectric shoe inserts capable of producing an average of 330 µW/cm^2 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 to generate power other than what they would normally do. 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 [30] 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.

4.4 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.

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

where P is the power, ρ 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 kg/m^3. Figure 4 shows the power per square centimeter versus air velocity.

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 4 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.

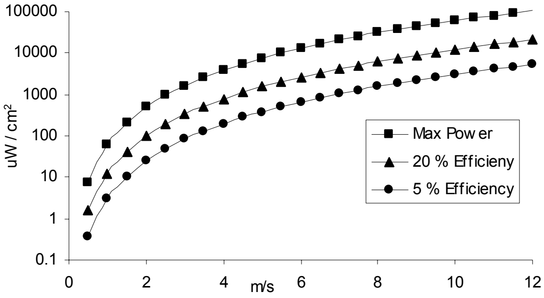


Fig. 4. Maximum power density from air flow. Power density assuming 20% and 5% conversion efficiencies are also shown.

4.5 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. The results of measurements performed by the authors on many commonly occurring vibration sources suggest that the dominant frequency is generally between 60 to 200 Hz at amplitudes ranging from 1 to 10 m/s^2.

A simple general model for power conversion from vibrations has been presented by Williams *et al* [31]. The final equation for power output from this model is shown here as equation 6.

$$P = \frac{m\zeta_e A^2}{4\omega(\zeta_e + \zeta_m)^2} \tag{6}$$

where P is the power output, m is the oscillating proof mass, A is the acceleration magnitude of the input vibrations, ω is the frequency of the driving vibrations, ζ_m is the mechanical damping ratio, and ζ_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.
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* [32] verify that generally the lowest frequency peak has the highest acceleration magnitude.

Figures 5 and 6 provide a range of power densities that can be expected from vibrations similar to those listed above. 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.

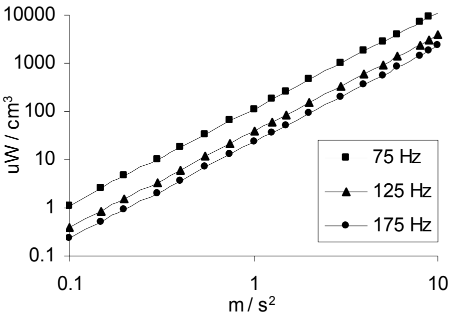


Fig. 5. Power density vs. vibration amplitude for three frequencies.

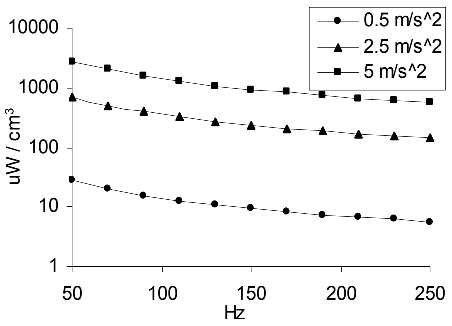


Fig. 6. Power density vs. frequency of vibration input for three amplitudes.

Several researchers have developed devices to scavenge power from vibrations [31-34]. 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 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 *et al* [35] have demonstrated a piezoelectric power converter of 1cm^3 in size that produces 200 μW from input vibrations of 2.25 m/s^2 at 120 Hz. Both Roundy *et al* and Ottman *et al* [34-35] have demonstrated wireless transceivers powered from vibrations. Figure 7 shows the generator, power circuit, and transceiver developed by Roundy *et al*.

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. 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.

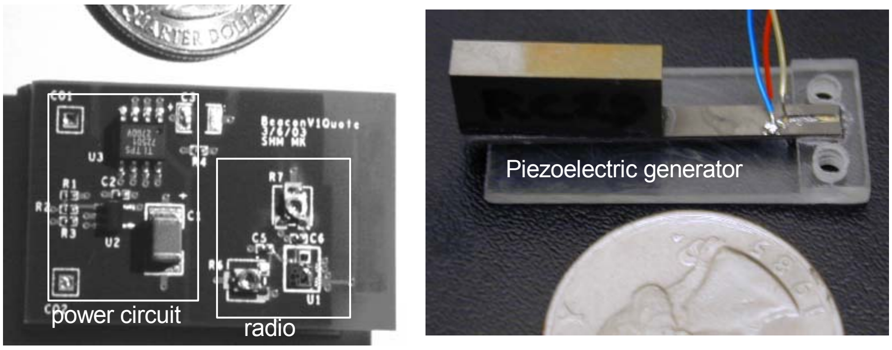


Fig. 7. Piezoelectric generator, power circuit, and radio powered from vibrations of 2.25 m/s^2 at 120 Hz.

5 Summary

An effort has been made to give an overview of the many potential power sources for wireless sensor networks. Because some sources are fundamentally characterized by energy density (such as batteries) while others are characterized by power density (such as vibrations) 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 4. Note that power density is listed as µW/cm^3, however, it is understood that in certain instances the number reported really represents µW/cm^2. Such values are marked with a "*". Note also that, with only one exception, values listed are numbers that have been demonstrated or are based on experiments rather than theoretical optimal values. The one exception is power from air flow, which has been italicized to indicate that it is a theoretical value. In many cases the theoretical best values are explained in the text above.

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.

Table 4. Comparison of various potential power sources for wireless sensor networks. Values shown are actual demonstrated numbers except in one case which has been italicized.

Power Source	P/cm^3 (µW/cm^3)	E/cm^3 (J/cm^3)	P/cm^3/yr (µW/cm^3/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
Heat engine	-	3346	106	Yes	Yes	No
Radioactive(^{63}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	*380 ††*	-	-	Yes	Yes	No
Vibrations	200	-	-	Yes	Yes	No

* 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.

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