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Technology Development: Wireless Sensors and Controls BT0201

Review of Energy Scavenging Schemes and Recommended Order of Investigation

JG DeSteese LA Schienbein
LC Olsen

September 2004

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RL01830

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Summary

This brief report reviews the characteristics of four candidate concepts that extract and convert ambient energy to provide electrical power for wireless sensors. This review characterizes each option's general feasibility as an energy scavenger in a building environment and recommends an order in which the options should be investigated. The results are summarized in the table below with the technologies listed in the order recommended for further investigation in this project.

Technology	Technical Maturity	Technical Development Risk	Next Development Step
Thermoelectric conversion	Breadboard prototype concept tested for up to 20°C temperature difference between air and earth	Low uncertainty, high probability of success	Develop and test breadboard prototype for smaller temperature differences found in buildings
Capture and conversion of air flow and vibrational energy	Maturity varies with specific concept. Vibrational prototypes of some concepts have been developed. Fabrication, evaluation and testing are at a very early stage. Some concepts have not yet been reduced to practice in the small size and power range for sensor applications.	Piezoelectric materials are available and do not present a significant risk. Considerable research is underway on capturing electricity from vibrations. Capturing electricity from vibrations in air flows is much less developed and scaling to the micro-level and low Re presents moderate risk.	Development of simple, robust and highly integrated devices that capture both continuous structural vibration energy and air-flow-induced vibration energy.
Photovoltaic concepts	Many years of research and development of photovoltaic cells.	Moderate risk.	Scaling to practical size for sensor power and device development.
Electromagnetic energy conversion	Least developed for both collection/conversion of ambient electromagnetic energy and beaming of power.	Greatest technical risk of the four generic concepts.	Concept development and demonstration.

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1.0 Background

For nearly a decade, Pacific Northwest National Laboratory (PNNL)[1] has recognized and investigated the potential of scavenging/harvesting free energy from ambient sources to energize devices with modest electric power demands. PNNL has evaluated many sources of ambient energy including radio waves, electric power line induction, and wind, water, solar and human power (DeSteese et al. 2000).

In buildings, adjacent zones existing at different temperatures could be tapped for thermal energy. Flowing air and fluids possess mechanical energy. The electromagnetic (EM) fields surrounding conventional electrical wiring are potential sources of ambient energy and energy in the form of EM radiation (radio waves and higher frequencies) could be beamed to power low-demand devices. In general, there has been, until quite recently, little effort to exploit ambient energy to power sensors that manage the inside environment of buildings. Such options are gaining recognition by those active in the energy scavenging field (Roundy et al. 2004).

The goal for each ambient energy harvester concept is to generate between tens of microwatts and several hundred milliwatts to supply one or more wireless sensors and their associated data acquisition, storage and transmitting electronics. An energy storage subsystem such as a supercapacitor[2] or rechargeable battery would be required, in addition, when the availability of the ambient energy source is not constant.

Wireless sensors and controls are the focus of a technology development project that PNNL is conducting as a contribution to the U. S. Department of Energy Commercial Buildings Program. The purpose of Task 3 in this project is to establish the feasibility and integration potential of ambient energy harvesting and conversion devices that would power wireless sensors and data communications in advanced building management systems. Intercepting and then converting ambient energy to low-level electrical power is an approach to facilitate the maintenance-free deployment of sensors without: 1) a need for batteries or wired connections to conventional power supplies, 2) the associated cost of batteries and hard wiring, and 3) system complexity.

The planned approach in this task is to evaluate four candidate energy conversion concepts that are potentially capable of powering wireless sensors. One is a recent PNNL development that exploits naturally-occurring temperature differences in the vicinity of the sensor package to power thermoelectric (TE) elements. The second is the concept of suspending miniature, flexible piezoelectric films in air or fluid streams. These films would generate power as a result of continuous flexing caused by the

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[1] Operated for the U.S. Department of Energy by Battelle Memorial Institute.

[2] A supercapacitor is a capacitor with very high capacitance in a small package. A regular capacitor consists of layers of conductive foils and dry dielectric separator material, while a supercapacitor crosses into battery technology by using special electrodes and some electrolyte. Supercapacitors store and release electrical energy quickly, efficiently and reliably, and have cycle lifetimes orders of magnitude greater than those of batteries.

aerodynamic forces acting on them when operating in the turbulent air stream itself or in the wake of upstream objects. The third is the prospect of extracting power directly from radio frequency (RF) energy in the vicinity of the sensor package. A fourth alternative is using ambient light to activate photovoltaic (PV) cells that, in turn, charge supercapacitors or advanced rechargeable batteries incorporated in the wireless sensor package.

These concepts are to be evaluated sequentially over a 4-year period with the currently planned order of investigation as indicated in the preceding paragraph. We recognized early in this task that further review of the options may identify one or several considerations that would change the preferred order of the investigation. This report summarizes the review effort conducted in Subtask 3.1 to advance the characterization of the candidate concepts and reassess the order in which they should be addressed in the multi-year task plan.

2.0 Thermoelectric Ambient Energy Harvester

The first building-oriented demonstration in the current plan is the thermoelectric ambient energy harvester. The configuration to be used is the recent PNNL invention of a radically new TE generator design specifically suited for harvesting thermal energy from sources that differ in temperature by only a few degrees C.

2.1 Technology

This concept, as illustrated in Figure 1, uses an assembly of ultra-thin thermocouples deposited on a flexible polyimide film with the potential capability of exploiting small (>2°C) naturally-occurring temperature differences in the environment such as those inside and outside building walls and heating, ventilation and air conditioning (HVAC) ductwork. Individual thermocouples, which are typically 1-cm high, 1.5-cm wide and only a few micrometers thick, are deposited in a linked “chain” onto a thin, flexible plastic substrate using a sputtering technique developed by PNNL. This plastic substrate is coiled around a spool enabling up to several thousand thermocouples to be assembled as a compact cylindrical generator capable of producing tens of microwatts or more.

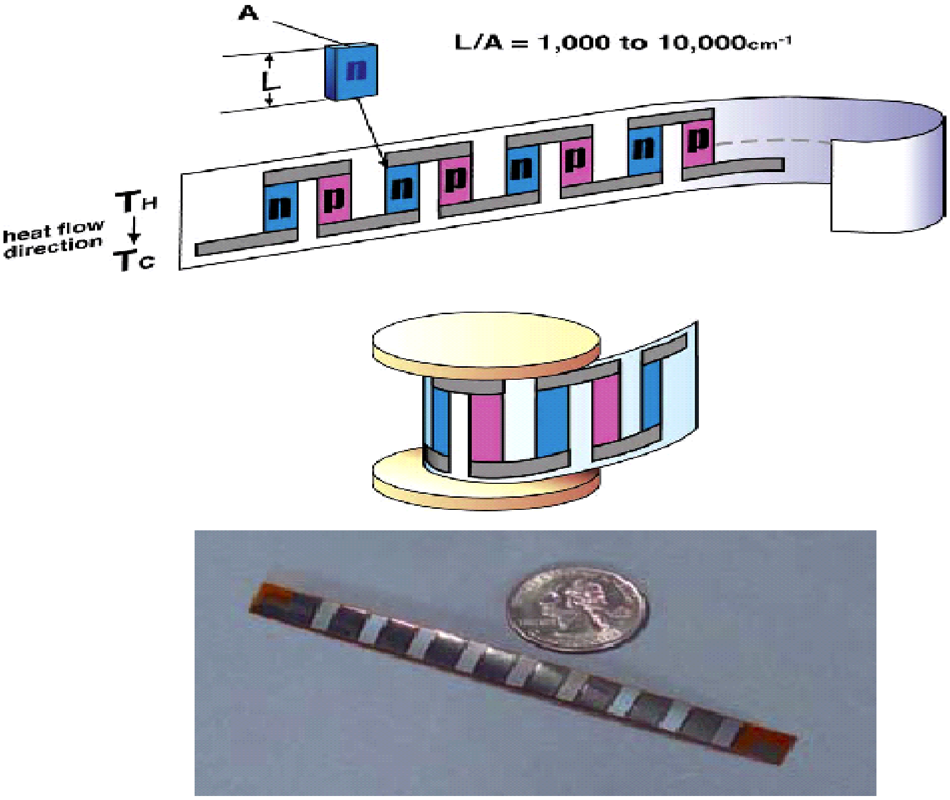

Figure 1: Principal components of a thin-film thermoelectric generator.

Heat-gathering and heat-rejecting subsystems, such as heat pipes containing condensable fluids, can be coupled to the hot and cold ”shoes” of the TE generator to extend its thermal “reach” by up to 20 cm into areas where temperature differences may be larger than those found in the device’s immediate environment. One or both sides of the generator can be heated or cooled by other heat transport methods such as conduction, convection, or radiation. Additionally, the generator can work both ways: i.e., if the cold shoe of the harvester becomes hotter than the original hot shoe as driven by environment conditions, the generator’s electrical output is maintained. Electronic power conditioning automatically manages the reversed polarity of the resulting output.

The generator produces electricity as a result of the Seebeck effect, which is common to all thermoelectric devices. This effect directly converts heat into electricity when the junctions of dissimilar metals or p- and n-type semiconductors are maintained at different temperatures. To obtain useful voltages (≥1 V) from a TE generator exposed to small temperature differences requires a large number of thermocouples in the assembly. Commercial-off-the-shelf (COTS) TE generators are assembled from discrete elements. Because they are freestanding and brittle, the practical ratio of the elements’ length to cross section (L/A) is typically in the range 10 to 30 cm^{-1}. Voltages of 1 V or higher are usually needed to activate the silicon-based semiconductors that power sensors and associated microprocessors and circuitry. As illustrated in Figure 2, conventional discrete-element TE devices with L/A ratios under 30 cm $^{-1}$ cannot provide adequate voltage for such applications when the activating temperature differences are only a few degrees C.

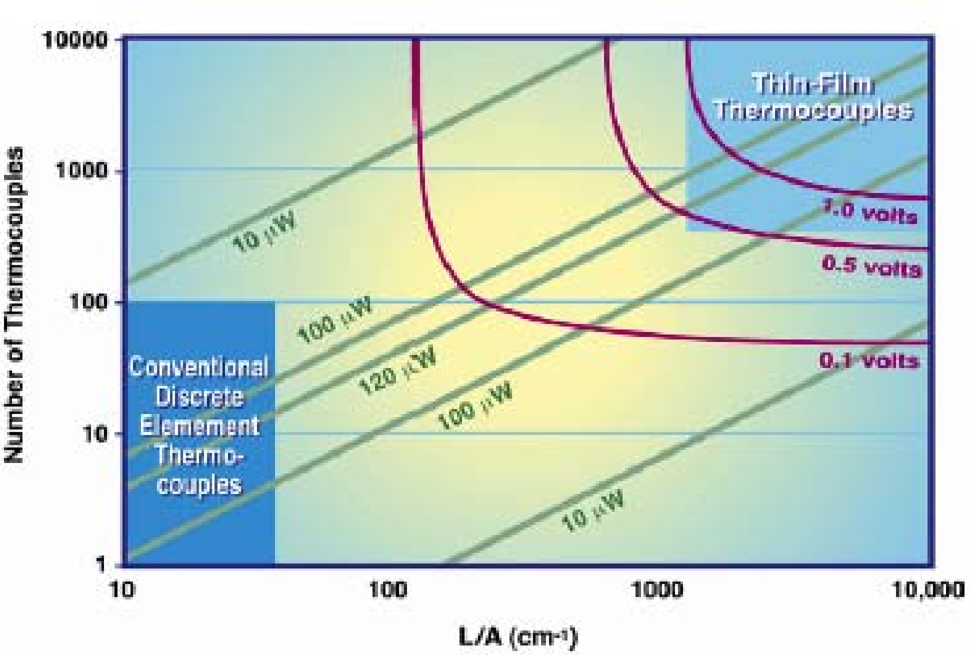

Figure 2: The number of thermocouples is shown versus the length to cross-sectional area (L/A) ratio for bismuth telluride with input heat flux of 0.1 W/cm^2. The graph shows power levels and voltages achieved as number of thermocouples and L/A increase and illustrates that thermocouples with high L/A are needed to provide voltage levels suitable to drive conventional electronic circuitry.

In contrast, the PNNL generator is constructed from thermocouples deposited on a supportive substrate allowing them to be made extremely thin in comparison to their length and height. In this manner, we achieve the high L/A ratio (in the range of 1,000 to 10,000 cm^{-1}) necessary to produce useful output voltages, as shown in Figures 1 and 2.

2.2 Technology Maturity and Risk

The deposited thermocouples are composed of p- and n-type elements based on well characterized alloys of bismuth telluride and antimony telluride. The deposition is conducted with high integrity in a clean noble gas (argon) environment and initially processed under high vacuum conditions. The substrate provides a convenient way to handle and bundle large numbers of thermocouples. It also provides other benefits in terms of reliability and production simplicity. It provides a continuous physical support for each thermocouple and the connections between the thermocouples. This contrasts with the technology of conventional discrete-element thermocouples, where connections for the brittle, upright thermocouples must be made as a separate step in the manufacturing process. These connections are themselves more fragile and susceptible to deterioration.

PNNL has assembled several operable thin film generators during the course of developing the deposition technique. Additionally, we have demonstrated an operating sensor system breadboard activated by the natural difference in temperature (up to 20°C) between outdoor ambient air and earth. This assembly included commercial, off-the-shelf (COTS) thermoelements, electronic interfacing, energy storage, a temperature sensor and a radiofrequency (RF) transmitter.

In fiscal year 2004, Task 3 of this project (the subject of this report) focuses on the feasibility of adapting our demonstrated thin film TE concept to the smaller differences in temperature that are typically found between adjacent zones in buildings (e.g., inside and outside an HVAC duct). The current plan is to design a new wireless sensor breadboard that demonstrates a thin film TE generator with sufficient power derived from ambient building conditions to operate a sensor and onboard data storage, and to provide periodic RF data transmission to a remote receiver.

Among the candidate concepts, PNNL has more experience in the design and construction of thin film TE devices and more experimentally acquired performance data and information than with the other concepts. These assets suggest this application of the thin film TE generator represents less technological uncertainty and the highest chance of early success in meeting task objectives. For these reasons, we recommend that the TE ambient energy harvester remain the first candidate to be investigated in Task 3 of the FY2004 project.

3.0 Energy Scavenging from Air Flow and Vibrating Sources

In building HVAC air ducts, typical air flow speeds range from 3 to 15 m/s (Vent-Axia Ltd. 2004), depending on the type of building application and whether the duct is a main/branch or supply/return. Flow rates in this range represent significant ambient energy potential. The lower flow rates typically found in building open spaces may also be useful as a source of harvestable energy.

3.1 Air Flow Energy Conversion

A number of conventional and unconventional power converter approaches are candidates in this category. A review of the literature and the fundamentals of aerodynamics in the range of Reynolds Number (Re) and flow rates of interest indicates that at least six approaches are technically feasible, as discussed below.

Piezoelectric and Microcapacitor Conversion - An attractive feature of the first four approaches identified below is that air flow to electric energy conversion is accomplished by causing piezoelectric or similar elements to vibrate as a result of their interaction with the air stream. Significant variants of this concept are:

- Circular (or other shape) rods supported at both ends vibrating laterally because of vortex shedding or experiencing "flutter" (see Figure 3). Multiple micro-scale rods could form an energy conversion array similar to the configuration of a solar photovoltaic module.

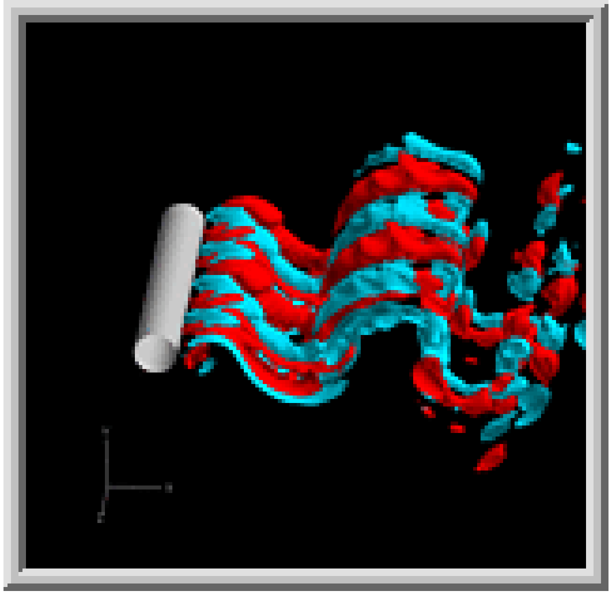

Figure 3: Vortex shedding and the instantaneous streamwise vorticity behind a circular cylinder for Re=300. Red indicates positive vorticity, and blue identifies negative vorticity. (Figure used with permission from Center for Turbulence Research, Stanford University.)

- A circular (or other shape) cantilever supporting a rod or rods that vibrate laterally because of vortex shedding. For example, harvesting energy from a small scale "soft mounted" vortex flow meter to power the meter itself may be feasible.

- Beams vibrating in torsion as a result of aeroelastic "flutter". Research and testing of this concept, developed at Clarkson University, has been relatively extensive and is current and on-going (Schmit et al. 1999; Schmit et al. 2004). The "Aeroelastic Wind Energy Converter" was first proposed by Professor Ahmadi of Clarkson University in 1979 (Ahmadi 1979, 1983). An "H" shaped beam cross section seems to be favored (see Figure 4).

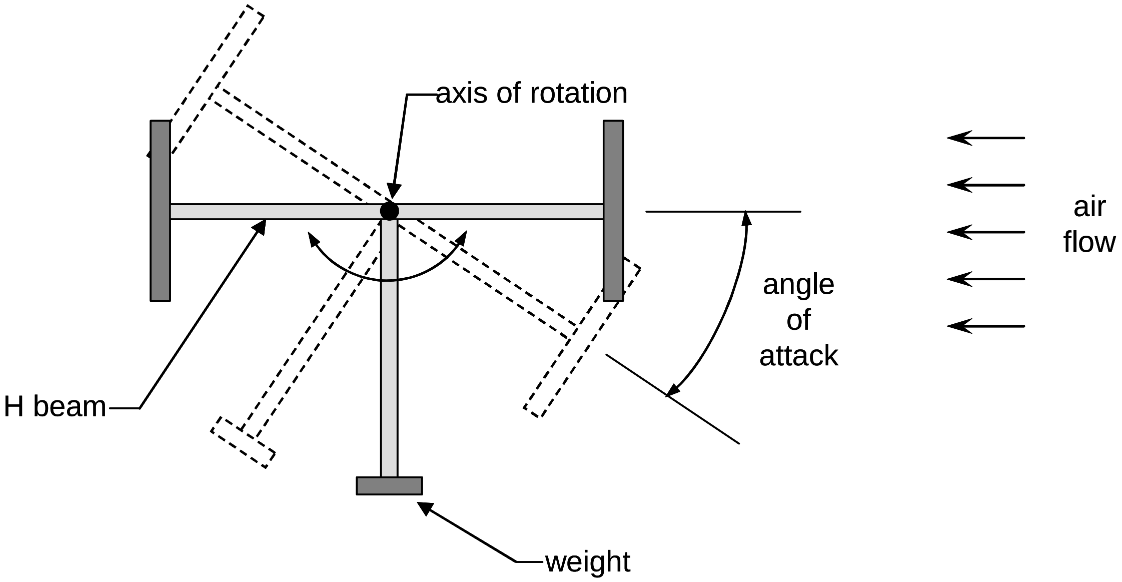

Figure 4: The H-shaped cross section aeroelastic converter of Schmit et al. (1999, 2004).

- The "Energy Harvesting Eel," shown in Figure 5, has been proposed by Allen and Smits (2001). The piezoelectric membrane (the "eel") is placed in the wake of a bluff body. The vortex street trailing this body induces oscillations of the membrane. The properties of the membrane are "tuned" for maximum energy conversion. Oscillations result in the capacitive buildup of charge on the membrane thereby causing the membrane to become a voltage source. Work for flowing water applications, supported by the Office of Naval Research and the Defense Advanced Research Projects Agency (DARPA) in 2001-2002 and performed by Ocean Power Technologies, Inc., is summarized in DARPA 2004. A student group at MIT (Jenket et al. 2004) recently reported on its design and testing of 2 cm x 12 cm single and series connected energy harvesting eels in an air stream.

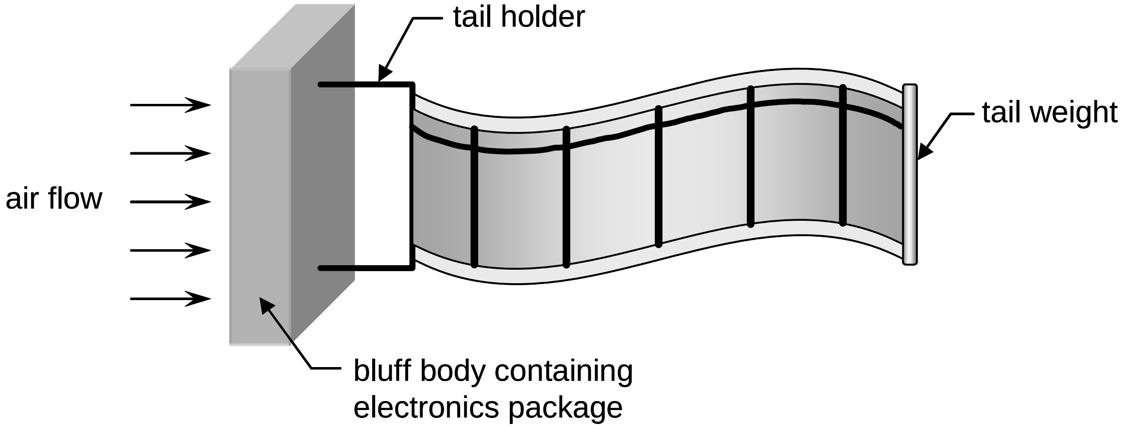

Figure 5: The “Energy Harvesting Eel” extracts energy from the von Karman vortex street behind a bluff body. A piezoelectric membrane oscillating in the vortex street converts mechanical energy of the flow into electrical energy, which is harnessed by electronics inside the bluff body. The small strip of electrodes at the top of the “eel” serve as sensors while the larger electrodes are used to harvest power.

Micro Wind Turbines - Roundy et al. (2004) comment favorably on the potential for micro machines capable of converting air flow energy, noting that power densities and power conversion efficiencies are quite promising, even at relatively low flow rates, when compared to large-scale wind energy converters. Scaled down versions of conventional multi-blade rotating wind turbines include: 1) vertical axis systems and 2) horizontal axis systems. We are not aware of any published work describing the development of miniature multi-bladed turbines that are specifically intended to convert air flow energy to electric power. It should be noted that rotational speeds would need to be very high for such machines. For example, a 100 mm^2 horizontal axis multi-blade air flow energy collector producing 10 mW (with overall energy conversion efficiency of 25% at an air speed of 9 m/s) would have a rotor diameter of about 11 mm and a rotational speed of about 125,000 rpm. However, an air flow power converter rated at 100 mW (assuming the same efficiency and air speed) would require a rotor diameter of about 36 mm. This is about the size of the rotors used in COTS hand held (“pocket”) anemometers. Thus, it should be relatively easy to design a practical, horizontal axis energy harvester derived from existing commercial technology.

Oscillating/Flapping Wings - Other approaches to scavenging air flow energy include, but are not limited to, oscillating wing energy conversion (there is a substantial base of research in this area, albeit at much larger scale) (McKinney and DeLaurier 1981) and flapping wing energy recovery (Jones, Davids and Platzer 1999; Jones and Platzer 1997). The second approach involves “reversing” the use of flapping wings to extract flow energy rather than converting this energy to provide propulsion. A significant body of research exists for the latter at the scales of interest as a result of renewed interest in applying and adapting the propulsion and lift aerodynamics used by larger insects and small birds (Michelson and Naqvi 2003; Kamakoti et al. 2000; Usherwood and Ellington 2002).

3.2 Technical Considerations in Air Flow Energy Conversion

The effective collector area of air flow power generators is a function of air speed, air density, power output required, and expected energy conversion efficiency. Considering conventional horizontal axis wind turbine generators, for example, the effective collector area is the area of the circle swept by the blade tips. Figure 6 shows the effective collector area required for three power output levels as a function of air speed, assuming standard sea level air density and an overall efficiency of 25%. It is evident that for an electrical power output of 100 μW, the required collector area is in the micro device domain, i.e., about 1 mm^2 for an air speed of 9 m/s.

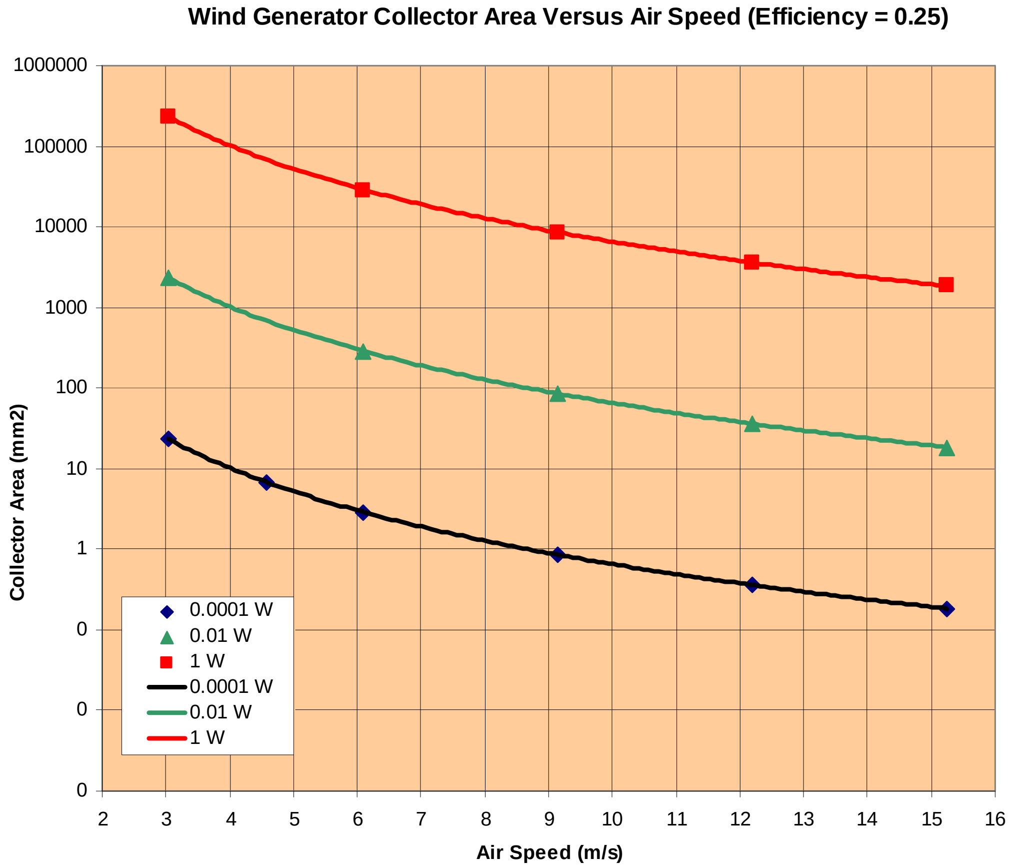

Figure 6: Effective collector area required at three power output levels as a function of air speed and standard sea level air density with an overall 25% conversion efficiency.

Reynolds Number (Re) effects must be carefully taken into account because the forces applied to the air flow energy converter active elements (e.g., torsional beams) as a result of their interaction with the air stream depend heavily on Re. For the power converter described in the previous paragraph, and assuming that it is configured with a single active element having a rectangular cross section and a 10:1 aspect ratio, the Re based on the minimum dimension (0.1 mm) at standard sea level air density is about 60.[1]

The latter Re value lies within the so-called "intermediate" or transition flow regime situated between the creeping flow regime, where viscous forces dominate (Re < 1) and the higher Re regime, where dynamic forces are predominant. The sensitivity of aerodynamic forces to Re can be demonstrated, for example, by the fact that the drag coefficient of a circular cylinder at Re = 60 is about 1.5 times the drag coefficient at Re = 1000. Significantly, a Re of 60 is also about the value at which eddies circulating behind the circular cylinder begin to oscillate and break off, traveling downstream in what is called a "vortex street."

Thus, the Re is also important in determining whether an air flow energy converter can operate effectively using the mechanism of vortex-induced oscillations.

It may not be possible to design practical, very small scale air flow power converters with overall maximum efficiencies exceeding 5 to 10%. This is because the efficiency of rotating and vibrating air flow energy converters depends fundamentally on: 1) maximizing the resultant aerodynamic force (the "lift") that moves the active element in the desired maximum power producing pattern, and 2) minimizing the resultant aerodynamic force that acts in opposition. These forces are Re dependent. However, even within this range of efficiency, the power density can be quite large. For example, Roundy et al. (2004) show an expected power density of 380 μW/cm^3 for an air flow converter at an air speed of 5 m/s and 5% conversion efficiency. Significantly, they also show a demonstrated power density of 300 μW/cm^3 for a vibrational energy source.

3.3 Vibration Source Energy Conversion

Vibrating energy sources are widespread within buildings and include appliances and machine-powered tools, in addition to load bearing elements (floors and decks, for example) and non-load bearing elements such as doors and windows. Converting vibrational energy using microcapacitors and piezoceramic elements, for example, in vibrating structures constitutes a simple and potentially highly reliable approach that has already been the subject of considerable research (Meninger et al. 2001, Roundy et al. 2002, Kasyap et al. 2002). This approach also falls neatly within the broader category of energy harvesting from a wide range of vibrating sources including the walls of HVAC ducts.

The walls of HVAC ductwork may vibrate continuously (even when air flow is turned off) as a result of continuous excitation by other sources in a building. Thus piezoelectric-based flow energy converter systems could be designed to act in concert with converters of a similar type responding to wall vibrations. The individual converter devices could be co-located and, indeed, might be manufactured as a single unit using many common components. This combined system could yield continuous electric power output from either or both sources at a sufficiently high level such that the amount of energy storage required to activate the associated wireless sensor and data processing system would be minimal (see further discussion in section on Energy Storage). This highly integrated concept could be a

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[1] To gain an appreciation of the significance of this value, it should be noted that Re for a gliding butterfly, based on its wing chord, is about 7000.

particularly challenging design problem but may yield commensurate rewards. For example, tuning energy conversion elements to couple optimally with the energy distribution of typical vibration frequency spectra could require a very different design from that of converter elements that maximize conversion efficiency using vibrations induced by air flow.

3.4 Technology Maturity and Risk

Piezoelectric devices that convert air-flow energy to electric power can be built using existing technologies. Laboratory test articles have been manufactured and tested for some of the concepts in this category. However, the fabrication, testing and evaluation of preproduction commercial prototypes, if they are occurring at all, are likely at a very early stage of development.

We believe that near micro scale multi-blade rotating wind energy converters have not been the subject of research and development with the intent to commercialize within the power range of interest, although reliable high speed rotor and bearing assemblies (capable of >100,000 rpm) could probably be fabricated using existing micro technology techniques, shaft power to electrical power converters (electric power generator) based on electromagnets, for example, could present a considerable development challenge. However, derivatives of commercially available hand-held anemometers could be the jumping off points for practical and reliable air flow energy converters meeting the needs of a fairly large portion of the 100 μW to 1 W power range.

Given the commercial availability of proven piezoelectric materials and devices and the robust research and development activity and demonstration that continues in micro scale vibration energy power conversion based on piezoelectrics, development risk for this part of the energy conversion system is considered low to moderate. Achieving reasonable overall energy conversion efficiencies for very small wind energy converters, operating at extremely low Re, may present the greatest development risk. This is because the size of converters required may become unacceptably large for the application. However, HVAC duct sizes in many commercial, industrial and office buildings may be large enough to accommodate substantially larger devices than those having micro scale dimensions with no measurable impact on the efficiency of the air distribution system.

The potential for developing simple, robust and highly integrated devices that capture both continuous structural vibration energy and air-flow-induced vibration energy appears to be real and is the basis for retaining evaluation of such devices as our second priority in the 4-year project plan.

4.0 Energy Scavenging from Electromagnetic Fields

The power requirements of sensors and communication equipment have been reduced in recent years to levels that can be supplied by intercepting human generated (i.e., non-solar) electromagnetic (EM) energy in the environment. The space that buildings occupy is typically bathed in radio frequency (RF) radiation from such sources as radio and television broadcasting, cell phones, RF tags and monitors, and microwave communication systems. Among communication media, radio is potentially the most powerful and pervasive and, therefore, was an option previously assessed by PNNL as an ambient energy source (DeSteese et al. 2000). In addition, an abundance of power-frequency EM fields are associated with building wiring and appliances.

An earlier scoping evaluation performed by PNNL (Desteese et al. 2000) considered the use of simple dipole antennas to extract power from amplitude-modulated (AM) and frequency-modulated (FM) radio at distances of 1 km and 10 km from the broadcasting transmitter. The AM and FM transmitters were assumed to radiate 5 kW at 1000 kHz, and 100 kW at 100 MHz, respectively. Table 1 summarizes the calculated energy scavenging potential of the evaluated combinations and shows power capture for all except FM at 10 km being in the useful range for powering wireless sensors.

Table 1. Power Extracted from Broadcast Radio

Radio Transmission	Antenna Type	Power at 1 km	Power at 10 km
1000-kHz AM, 5 kW	1-m dipole	213 mW	2.1 mW
1000-kHz AM, 5 kW	λ/2 dipole[1]	64 mW	640 μW
100-MHz FM, 100 kW	λ/2 dipole	100 μW	1 μW

[1] λ is wave length.

Fry et al. (1997) reference work performed by Norton, a colleague at Oak Ridge National Laboratory (ORNL), who has proposed an automated means of extracting power from the strongest AM radio signal in the vicinity. The ORNL report indicates the range of available power from this source is microwatts to hundreds of milliwatts depending on distance and power of the transmitter. As shown in Table 1, the PNNL evaluation is consistent with this ORNL conclusion.

4.1 Radio Frequency Technology

In the basic concept, ambient RF fields or other sources of EM radiation induce alternating voltage and current in an antenna that are rectified to power the associated wireless sensor system. The power in watts (P) extracted from a radio wave by a receiving antenna can be expressed by:

$$P = \frac{(\varepsilon h)^2}{(R_l + R_r + R_L)}$$

where ε = root mean square (rms) field strength of radio wave (V/m)

h = effective height of antenna (m)

R_l = antenna loss resistance (Ω)

R_r = antenna radiation resistance (Ω)

R_L = load resistance (Ω).

Ideally, the maximum power extracted occurs when $R_l + R_L = R_r$ and the load reactance is equal in magnitude but opposite in sign to the reactive component of the impedance that the load sees looking toward the antenna. Under these conditions, half the energy extracted is re-radiated, and the power dissipated by R_l and R_L is $(\varepsilon h)^2/(4R_r)$. In practice, it is difficult to operate at this design point.

A 1-m dipole is physically small compared to the AM broadcast wavelength of 300 m. This results in its radiation resistance being only a few μΩ. Therefore, it is difficult to make R_l and R_L low enough to obtain efficient power extraction and at the same time supply significant power to a load. However, the 1-m dipole performs better than the half-wavelength dipole, which is not only impractically large in a building's environment but also introduces a much larger R_l term. The 3-m wavelength of the FM transmission allows the $\lambda/2$ dipole to be somewhat better than the equally practical 1-m dipole. However, the physical size requirement of both antennas is associated with a much larger value of R_r, which reduces the energy capture potential of this option below that of the AM case. Even 1-m antennas may be difficult to accommodate, especially if the wireless sensor population density is high in a given area.

A potential advantage of scavenging energy from radio transmission would be the relatively high capacity factor of the source because many stations broadcast from 14 to 24 hours a day. However, the widespread use of wireless sensors powered in this manner could require amendment of broadcast regulations, the enactment of fee structures to pay for captured energy, and controls that would prevent large buildings from casting EM shadows that affect conventional reception in their neighborhood.

Roundy et al. (2004) consider RF power scavenging in the 2.4 to 2.485 GHz frequency range, which is an unlicensed industrial, scientific and medical band available in the U.S. They point out that Federal regulations limit ceiling-mounted transmitters to 1 W or less in this band. Therefore, at a distance as short as 5 m from the source, the power coupling at a receiving node would be tens of microwatts. This power level is essentially below the borderline of usefulness. One advantage of operating in this frequency band is that antennas are compact and practical, with dimensions of only a few centimeters.

4.2 Power Frequency Induction Options

In some circumstances, EM power frequency radiation from electric lines and wiring represents a source of harvestable energy. Two opportunities in this category were evaluated by PNNL in previous work. As noted below, these evaluations focused on energy scavenging from outdoor power lines, however, the results are interpreted here as they might apply to wireless sensors in buildings.

Capacitive Coupling - An antenna insulated from ground and stretched between adjacent poles or towers of a transmission line could act as the plate of a capacitor. When charged by its proximity to the overhead conductors of the transmission system, the antenna would act as a synchronous voltage generator that could be used to energize a low-power application. The geometry investigated (DeSteese et al 2000) was a 50-m long antenna stretched between towers at a height of 6 m above the ground and 6 m below a typical three-phase, 345-kV overhead transmission system consisting of three conductors spaced 7-m apart. Analysis showed that this concept would generate only about 10 µW when supplying a properly tuned load impedance. The concept was shown not to be useful even with a high-voltage source and significant spatial separation of conductors. The effect becomes absolutely worthless when rescaled to building service voltages and closely spaced conductors. Capacitive coupling, therefore, does not appear to warrant further consideration.

Inductive Coupling - Potentially more power can be tapped by EM induction. The configuration evaluated consisted of insulated copper wires that run for some distance parallel to and on both sides of a transmission system right-of-way. The wires are connected at each end by conductors that cross under the transmission lines forming a loop. Electromagnetic induction occurs in the portions of the loop that are asymmetrical with respect to the geometry of the three-conductor overhead system. Very little voltage is induced in the parts of the loop directly under the overhead conductors.

The energy capture potential of this concept was evaluated (DeSteese et al. 2000) by considering a loop with an active length of 50 m on the sides running parallel to the transmission line. As before, the reference transmission system is a three-phase, 345-kV overhead transmission system consisting of three conductors spaced 7-m apart and 12-m above the ground. The long parallel sides of the loop are 7 m further outside the outer transmission conductors. Total loop length of this configuration is 156 m. The concept is, in essence, a transformer in which the transmission conductors are each single, phase-separated primary turns and the ground-level loop is a single-phase secondary winding linked by magnetic flux across a very large air core.

Power output of the concept was estimated to range from about 2 W to 113 W, corresponding to root mean square (rms) phase currents in the overhead conductors of 100 A and 800 A, respectively. It appears possible that rescaling this or an equivalent configuration to 120-V circuits in buildings using acceptably small pickup coils could provide milliwatt-level power for wireless sensors. Conventional building wiring would need to be separated into single conductor segments in the vicinity of the pickup coils to realize inductive coupling. This arrangement will not meet current electrical code requirements and would likely be physically restrictive in application. The concept would have the character of being more of an engineered local source than the preferred situation of a "universal" readily installed device capable of coupling to and harvesting generally pervasive ambient energy.

4.3 Technology Maturity and Risk

From the foregoing we conclude that EM induction at both power and RF frequencies is currently marginal as a harvestable ambient energy source; however, the concept cannot be ruled out entirely. There are several longer term issues that deserve more attention. For example, RF scavenging may be capable of better performance with innovations in antenna design that were either not evaluated in previous studies or are yet to be developed. There are innovations in building design that may enable locally generated RF power beaming and the use of HVAC ductwork, for example, as a waveguide for such a concept. In addition, not all opportunities for power-frequency induction appear to have been fully evaluated.

In consideration of the above, we recommend that EM energy harvesting from the environment remain as a candidate option in this project but that it be currently assigned the lowest rank in order of interest and likelihood of near-term success. Deferring further consideration of this concept class to the fourth year will also exploit the results of ongoing research and development in EM field effects, conversion technologies and antennas that collectively could improve the out-year feasibility of this option.

5.0 Photovoltaics for Powering Wireless Communications

Two basic approaches appear possible as photovoltaic (PV) solutions for powering wireless sensors and communications. Solar cells could utilize ambient room illumination directly or receive illumination from an external source through optical fibers.

5.1 Technology

Photovoltaic devices produce electrical power directly from light absorption. Although most applications utilize solar illumination, PV devices can generate power with photons from any source to generate electrical power as long as the incident photons have energies greater than the electron band gap characteristic of the PV cell material. Considerable progress has been made in solar cell development over the last 20 to 30 years. PV modules are being produced for installation on homes and for large power plants. Modules are being fabricated using single crystal silicon and three thin film polycrystalline materials. These modules typically convert solar illumination to electrical power with an efficiency of 10 to 12%. Single crystal silicon and gallium arsenide cells have been fabricated with efficiencies greater than 25%, and devices based on monolithic stacks of three cells designed to utilize the solar spectrum in an optimum manner have exhibited efficiencies to greater than 30%. Although further efficiency improvements are expected, the most significant advances in future PV development will likely be in the area of reduced manufacturing cost.

Photovoltaic devices could be used to supply power for wireless communications in two basic ways. Power can be produced from conversion of ambient room light, or from ambient light external to the building (or from another space within the building) conducted by optical fibers or light tubes. Table 2 indicates the estimated electrical output of GaAs cells illuminated by: 1) typical room lighting intensity provided by conventional fluorescent bulbs and 2) 1-mW laser beams.

Table 2. Estimated Power from 1-cm^2 GaAs Cell

Light Source	Cell Configuration	Current (µA)	Voltage (V)	Power (µW)
Fluorescent	Single Cell	40	0.7	28
Fluorescent	Two 0.5-cm^2 cells in series	20	1.4	28
1-mW, 820-nm Laser	Single cell	60	0.72	43
1-mW, 820-nm Laser	Two 0.5-cm^2 cells in series	30	1.44	43

It is expected that results obtained with light being transmitted through optical fibers from a flood lamp would be similar to that given for 820-nm laser light.

A key issue to be considered when using solar cells to power wireless sensors concerns the voltage at which the power is produced. If a single GaAs cell with an area of 1-cm^2 is used, then power will be produced at 0.7 or 0.72 V for the cases described in Table 2. On the other hand, if two cells of one-half this area are connected in series, the same power is supplied at 1.4 or 1.44 V. Thus, to achieve voltages necessary to activate silicon-based electronic circuitry, cell designs will need to be developed that consist of two or more cells connected in series.

5.2 Technology Maturity and Risk

Silicon solar cells were first fabricated in the late 1950s to early 1960s. Crystalline silicon solar cells still constitute the backbone of the PV industry. Whereas silicon cells were typically 2 cm x 2 cm in size in 1960, they can now be as large as 20 cm in diameter today. Other cell technologies have emerged over the last 30 years, however. GaAs and related cells based on III-V compounds are more efficient than those based on silicon, but are also more expensive. These cells are particularly appropriate for space applications.

Another class of cells is referred to as thin film solar cells. These consist of devices based on CdTe, $CuInSe_2$ and amorphous silicon. Although thin film PV modules still cost more than those based on single crystal silicon, they are expected to eventually be produced at lower cost. A particularly unique feature of thin film solar cells is that they are more readily produced as an array of individual cells connected in series. This property could be particularly important for providing PV power sources for wireless communications. It will be important that PV devices can be produced cheaply and with a design that produces power at voltages greater than 1 V. Thin film photovoltaic technology will be particularly important for the wireless communication application. It is expected that this technology will eventually allow large-scale production of PV devices at reduced cost relative to silicon and gallium arsenide. Furthermore, thin film technology will allow production of miniature, high voltage devices.

PNNL is well equipped to investigate PV options for powering wireless sensors with a staff that has extensive experience in solar cell development, including fabrication of cells based on silicon, GaAs and thin film technologies. The possibilities of the PV alternative appear to be nearer at hand than those of energy harvesting from ambient electromagnetic fields. Therefore, we recommend that the PV evaluation be elevated in priority and be conducted in the third year of this project.

6.0 Energy Storage

Each of the concepts, with the exceptions noted above, will require a significant amount of energy storage to compensate for periods when ambient sources supply less than design energy capture or when temporary demand peaks occur. For example, the power required for RF data transmission may exceed the average power output of the ambient harvester by orders of magnitude, but this demand lasts typically for less than 1 second. It would be generally inefficient to design ambient energy harvesters to provide peak outputs of this nature on demand.

Most of the candidate concepts can be successfully interfaced with sensors and data processing electronics using supercapacitors as the energy storage element. This configuration is analogous to current practice with much larger scale, commercially available distributed power generators. In these systems (for example, solar-PV standalone units), the generator typically delivers DC electrical energy to a battery and is, thereby, buffered from the load. This configuration is often termed a “battery node” system and features minimal power conditioning (ideally a simple DC voltage regulator) between the generator and the energy storage device. Additional power conditioning, if any, is installed “downstream” of the energy storage unit. The power generator therefore does not “see” the peaks and valleys of the output load profile but supplies instead the average energy needs of the system. Today’s wireless sensor systems including RF transmission represent an average load in the 40 μW to 100 μW range (from experience with such systems fabricated at PNNL). The largest component of this is energy required to maintain the “sleep” mode of the system between periodic cycles of data acquisition, processing and transmission. Sensor systems of the future may be able to operate at an order of magnitude lower than average power. Such a development will allow use of less powerful energy harvesters but place higher differential demands on the capabilities of the energy storage component.

7.0 Conclusions

This review confirms and expands the rationale for investigating the four ambient energy harvesting candidates proposed in the original task plan. It also provides new insight into their respective technical maturities. The results are summarized in Table 3. The product of this exercise is an improved basis for defining the topical priority of future effort planned in this task.

The revised order of investigation is recommended as follows: 1) thermoelectric conversion; 2) capture and conversion of air flow and vibrational energy; 3) photovoltaic concepts, and 4) electromagnetic energy conversion. This recommendation is consistent with the original plan with the exception that PV options will be investigated before EM concepts. This change will be reflected in a revised work plan.

Table 3: Summary of Findings

Technology	Technical Maturity	Technical Development Risk	Next Development Step
Thermoelectric conversion	Breadboard prototype concept tested for up to 20°C temperature difference between air and earth	Low uncertainty, high probability of success	Develop and test breadboard prototype for smaller temperature differences found in buildings
Capture and conversion of air flow and vibrational energy	Maturity varies with specific concept. Vibrational prototypes of some concepts have been developed. Fabrication, evaluation and testing are at a very early stage. Some concepts have not yet been reduced to practice in the small size and power range for sensor applications.	Piezoelectric materials are available and do not present a significant risk. Considerable research is underway on capturing electricity from vibrations. Capturing electricity from vibrations in air flows is much less developed and scaling to the micro-level and low Re presents moderate risk.	Development of simple, robust and highly integrated devices that capture both continuous structural vibration energy and air-flow-induced vibration energy.
Photovoltaic concepts	Many years of research and development of photovoltaic cells.	Moderate risk.	Scaling to practical size for sensor power and device development.
Electromagnetic energy conversion	Least developed for both collection/conversion of ambient electromagnetic energy and beaming of power.	Greatest technical risk of the four generic concepts.	Concept development and demonstration.

8.0 References

Ahmadi, G. 1979. "Aeroelastic Wind Energy Converter." *Energy Conversion* 18:115–120.

Ahmadi, G. 1983. "Performance of an Angular Aeroelastic Wind Energy Converter." *Journal of Energy* 7:285–288.

Allen, J. J. and A. J. Smits. 2001. "Energy Harvesting Eel." *Journal of Fluids and Structures* 15:629-640.

Center for Turbulence Research. http://ctr.stanford.edu/gallery/cylinder.html Accessed September 20, 2004. Figure reprinted with permission of Center for Turbulence Research, Stanford University, Palo Alto, California.

DARPA. 2004. *Energy Harvesting Eel Program.* Accessed September 16, 2004 at http://www.darpa.mil/dso/trans/energy/pa_opt.html.

DeSteese, J. G., D. J. Hammerstrom, and L. A. Schienbein. 2000. *Electric Power from Ambient Energy Sources.* PNNL-13336, Pacific Northwest National Laboratory, Richland, Washington.

Fry, D. N., D. E. Holcomb, J. K. Munro, L. C. Oakes and M. J. Maston. 1997. *Compact Portable Electric Power Sources.* ORNL/TM-13360, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Jenket, D., K. Li and P. Stone. 2004. "Eelectric: Electricity Harvesting Through Piezoelectric Polymers, Final Report – May 13." PowerPoint Presentation. Accessed September 16, 2004 at http://web.mit.edu/3.082/www/team4/FinalPresentation.ppt#8.

Jones, K. D. and M. F. Platzer. 1997. *Numerical Computation of Flapping-Wing Propulsion and Power Extraction.* AIAA 97-0826, presented at 35th Aerospace Sciences Meeting and Exhibit, January 6-10, 1997, Reno, NV.

Jones, K. D., S. Davids and M. F. Platzer. 1999. "Oscillating Wing Power Generation." ASME Paper 99-7050, *Proceedings of the Third ASAME/JSME Joint Fluids Engineering Conference*, July 18-23, 1999, San Francisco, CA.

Kamakoti, R., M. Berg, D Ljungqvist and W. Shyy. 2000. "A Computational Study of Biological Flapping Wing Flight." In *Transactions of the Aeronautical and Astronautical Society of the Republic of China*, Volume 32, Number 4, pp. 265-279.

Kasyap, A., Ji-Song Lim, D. Johnson, S. Horowitz, T. Nishida, K. Ngo, M. Sheplak and L. Cattafesta. 2002. "Energy Reclamation from a Vibrating Piezoceramic Composite Beam." Ninth International Congress on Sound and Vibration (ICSV9), Orlando Florida.

McKinney, W. and J. DeLaurier. 1981. "The Wingmill: An Oscillating-Wing Windmill." *Journal of Energy* 5(2):109-115.

Meninger, S., J. O. Mur-Miranda, R. Amirtharajah, A. P. Chandraskasan and J. H. Lang. 2001. "Vibration-to-Electric Energy Conversion." *IEEE Transactions on Very Large Scale Integration (VLSI) Systems* 9(1):64-76.

Michelson, R. C. and M. A. Naqvi. 2003. "Beyond Biologically-Inspired Insect Flight." Low RE Aerodynamics on Aircraft Including Applications in Emerging UAV Technology, RTO-AVT von Karman Institute for Fluid Dynamics Lecture Series, November 24-28, 2003.

Roundy, S., P. K. Wright and K. S. J. Pister. 2002. "Micro-Electrostatic Vibration-to-Electricity Converters." IMECE2002-39309, In *Proceedings of IMECE2002, ASME International Mechanical Engineering Congress and Exposition*, November 17-22, 2002, New Orleans, Louisiana.

Roundy, S., P. K. Wright, and J. M. Rabaey. 2004. *Energy Scavenging for Wireless Sensor Networks with Special Focus on Vibrations*. Kluwer Academic Publishers, Norwell, Massachusetts.

Schmit R., M. Glauser and G. Ahmadi. 1999. "Turbulent Wake Profiles of an Aeroelastic Wind Energy Converter." Presented at the American Physical Society, Division of Fluid Dynamics Meeting, November 21-23, 1999, New Orleans, Louisiana.

Schmit, R. F., M. N. Glauser and G. Ahmadi. 2004. "Flow and Turbulence Conditions in the Wake of a H-Section in Cross Flow." *Journal of Fluids and Structures* 19(2):193-207.

Usherwood, J. R. and C. P. Ellington. 2002 "The Aerodynamics of Revolving Wings – II. Propeller Force Coefficients from Mayfly to Quail." *The Journal of Experimental Biology* 205:1565-1576.

Vent-Axia Ltd. 2004. *The Vent-Axia Ventilation Handbook.* Accessed on September 10, 2004 at http://www.vent-axia.com/sharing/simpleducted.asp.

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