Sandia National Laboratories

(U) Overview of Harvested Power and the Need

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1. (U) Executive Summary

(U) The continued miniaturization of sensors, actuators, and communication modules is increasing the demand for small-scale power sources. The need for alternative power sources is most pressing for applications where energy density and mission duration exceed the capability of batteries. Small power systems that have been based on harvesting of chemical, thermal, electromagnetic, and mechanical ambient energy are discussed. The general principles of operation for various forms of these devices are discussed and specific developmental, military, or commercial systems are described. The leading researchers and engineers, their institutions, and their locations around the globe are cited. The maturity of each type of harvester is assessed and forecasts of applications and availability are offered. An additional, overarching issue of power conditioning or control circuitry, integral energy storage, and system integration of power harvesting into likely applications is also discussed. This review concludes with a few general statements regarding the likely increasing use of power harvesting in our professional and private lives.

2. (U) Introduction

(U) The continued miniaturization of sensors, actuators, and communication modules is increasing the demand for small-scale power sources. The need for alternative power sources is most pressing for applications where energy density and mission duration exceed the capability of batteries. As a baseline for comparison, a $LiMnO_2$ battery chemistry, like that found in a typical battery, has a theoretical energy density of around 540 mW-hr/cm^3. With this energy density, a 1cc power source could only operate for 22 days at 1mW, and that is assuming that this energy density is preserved as the size is reduced from a relatively large system. However, reducing the volume of these batteries down into the milliliter range begins to seriously affect the energy density, as a proportionately larger fraction of the volume of the power source is consumed by packaging, separators, seals, and other components that do not contribute directly to the generation of power. For one of the smallest commercial batteries, a 300μA-hr system that is approximately 2cm^2 in area and 150μm thick, this system only provides 38 W-hr/L, or only slightly more than 5% of the theoretical energy density of the chemistry. For this battery, a continuous 1mW draw (roughly 350μA) would deplete the battery in slightly over 20 minutes. Since the energy stored in these systems so severely restricts the lifetime of these sensors, actuators and communication modules, an alternative means of providing power must be developed.

(U) Beginning in 1995, these energy density, lifetime, and volume demands spawned numerous efforts aimed at improving stored energy density by targeting more energy rich fuels, specifically on-board hydrocarbons. Several efforts were initiated with the goal of developing MEMS-based hydrocarbon fueled (10,000 mW-hr/cm^3) engines including gas turbine[1 2], Wankel,[3] reciprocating,[4] and resonating[5] engines. Limiting the system volume to 1cm^3 and reserving 0.6cm^3 for fuel would require a 10% efficient engine/generator occupying 0.4cm^3 to reach an energy density equal to similarly sized batteries. Unfortunately, none of the developed engines came anywhere close to this efficiency (limited primarily due to heat and bearing friction).

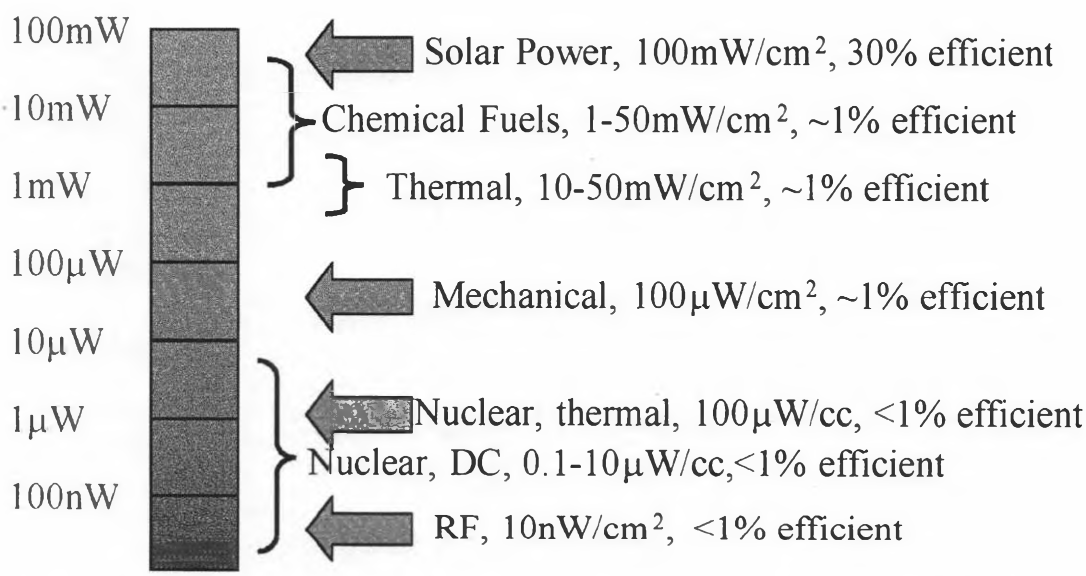
(U) If the energy needed for a mission cannot be stored by even the best commercial systems, then energy must be collected from the environment to provide the ability to recharge the power source intermittently to extend operational lifetime. The development of small, efficient power harvesting sources for long duration has been a subject of active research for the past 40 years.[6]

3. (U) Types of harvesting, energy density of sources

(U) Small power systems that have been based on harvesting of chemical[7], thermal[8], electromagnetic[9], and mechanical[10] ambient energy have all been built and tested. In their current manifestation, all of these systems are designed to be small, low power systems with limited capability to provide electrical power in the form necessary for application. Harvesting systems are dependent upon two things: the energy density or flux of energy of the harvested source (light, heat, chemicals, etc.) and on the efficiency of conversion. For all conversion systems, there seems to be an empirical rule that smaller systems are less efficient than larger systems, although the governing physics for this scaling differ for each type of conversion system.

(U) There are four basic types of conversion system, which follow each of the four types of energy available for harvesting: electromagnetic (photovoltaic or RF), chemical (or biofuel fuel cell), thermal, and mechanical harvesting. For thermal systems, the limiting physics results from the thermal resistance of smaller systems being higher than equivalent larger scale systems, resulting in a larger portion of the heat flux passing around the system. For mechanical systems, smaller systems generally have higher resonant frequencies due to lower masses and stiffer springs, resulting in a poorer mechanical match to the driving frequencies. Chemical systems are limited by the amount of system volume available as catalytic surface as the system shrinks, resulting in lower conversion efficiencies. For photovoltaic systems, the limitations are less severe, but manifest themselves as fabrication requirements both from the coverage factor for the upper electrode being smaller and for thinner systems having a thinner collection volume in the lightly doped p region resulting in lower conversion efficiencies.

(U) The density of the harvested source also varies widely. The most energetically dense source is solar power, with an incident flux of 100mW/cm2. Chemical fuels are the next most dense source, with typical harvested biological carbohydrates having approximately 4Kcal/g, or approximately 8Kcal/cc. Thermal and mechanical energies are harder to place due to the wide variety of sources. As an example, the heat flux from the human body from skin to air is roughly 20-30mW/cm^2, while the heat flux from a sun heated adsorbing surface free radiating into the air can reach 50mW/cm^2. Mechanical energies from wind can be as low as 1mW/cm^2 for light breezes, and can be as high as 100mW/cm^2 or more for vibrations from isolated tone mechanical system, such as an internal combustion engine. RF systems, a special subset of light harvesters, uses antennas instead of PV cells, and is dependent on the range from the broadcasting station, the size and geometry of the antenna, and the intensity of the source signal. A graph showing the available energy density ranges, including both source energy density as well as conversion efficiency for harvesting systems, is shown in Figure 1



(U) Figure 1: Approximate range of harvestable energies along with conversion efficiencies for current miniature systems.

4. (U) Rate capability from harvesting sources, and limitations

(U) For all harvesting systems, there is an intrinsic rate limitation that ultimately limits the power available from a direct harvesting system. For certain systems, this limitation comes from the rate at which harvestable energy can enter into the harvesting system; for others, it has to do with the rate at which the harvester can convert the energy into electrical power, expressed as current times voltage. The output voltage of a harvesting device is essentially fixed by a combination of physics and design within certain current demand limitations, so the limitation on output power depends on the output or supply current that a device produces. Of course, any power source can suffer a drop in voltage if the current demands exceed the capability of the device. This limiting supply current is usually lower than the instantaneous peak power demands of most electronics of interest for harvesting systems, and due to this fact, most harvesting systems are not envisioned to be operating any application electronics directly. Instead, some form of load leveling or power matching device must be placed between the harvester and the application to handle peak power demand.

(U) The most common load leveling system is the inclusion of a battery or supercapacitor between the application and the harvester. Under these designs, the battery or supercapacitor can be charged continuously by the harvester, and then used to provide high rate peak power with little voltage droop during high demand cycles of the application. The design of this form of load leveling system is in itself a challenge, and while load leveling is not the focus of this report, it is important to understand the basics of this system in order to understand how this portion of the device will affect the ability to implement a harvesting system.

(U) Batteries (and to a lesser extent supercapacitors) also have rate limitations, based upon their design. Batteries can be designed to be extremely high rate, but the same design choices that provide this high rate also tend to produce batteries with high leakage currents, whereas batteries with low self discharge (or leakage) rates (and therefore longer "shelf life" between charging episodes) tend to have lower rate capabilities. These load leveling systems must be designed with both the application and the harvester in mind, as the rate capability of the harvester must be matched to both the rate capability of the battery as well as to its self discharge rate. Also involved in this is the understanding of the voltage supply of the harvesting device, the charging limit of the battery, and the voltage needs of the application, as all of these must be matched in order for the load leveling component to be effective.

(U) Less prominent, but still important, are electronic load leveling systems. These systems take the variable output from a harvester device (mostly from voltage changes) and produce a steady state voltage that provides steady power for the application. These devices exact some energy overhead from the harvester, and are (at least to date) limited to higher energy harvesting systems, such as nuclear thermoelectrics and photovoltaics. In this case, providing for the power needed in high rate applications isn't as necessary, but making sure that the supply voltage to the application never dips below a certain critical value necessary for continuous operation is of paramount importance.

(U) Since these devices (of one form or another) are almost always required for a field application, ***one of the surest ways to tell if a harvesting system has left the realm of academic study and experimentation and is now being engineered for a specific application is the***

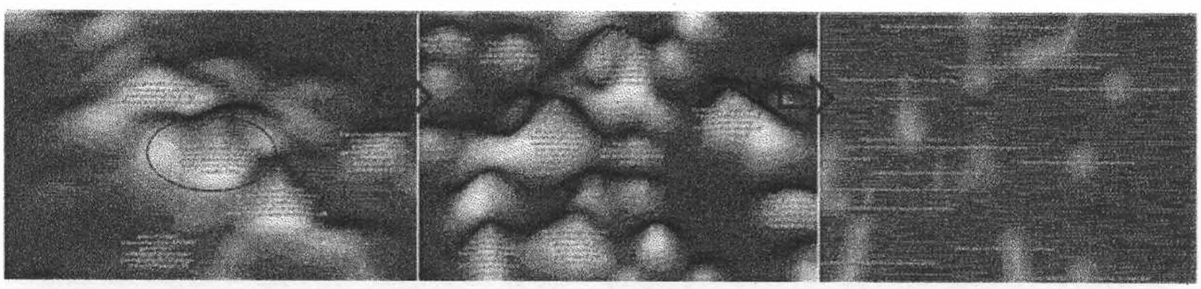
observance of a load leveling component being reported along with the performance of the harvester itself.

5. (U) Structure of the report, focus for research

(U) The methodology in accomplishing this assessment consists of three main elements which are acquisition of the data, map development and characteristics, and the analytical session. The data used to conduct this assessment was derived from Web of Science, Inspec, and ISI Proceedings. Web of Science was used in order to cover Technology Readiness Levels (TRL) one to three. Inspec was used in order to cover the higher TRL four and higher. ISI Proceedings was important to include since it covers conference proceedings, which tend to be more timely than traditional journal papers.

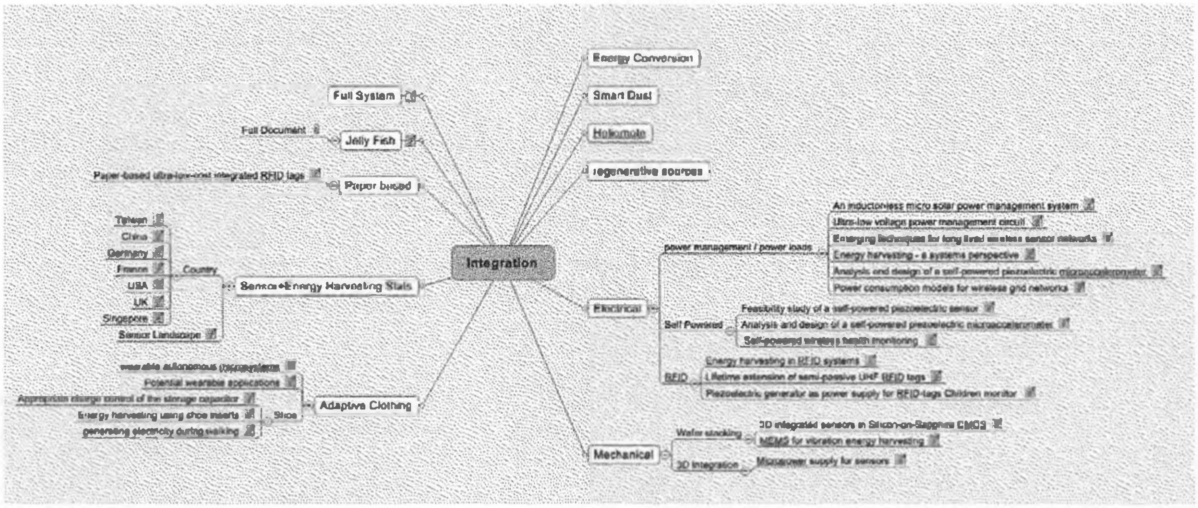
(U) The previously mentioned databases where queried by using a set of terms provided by the subject matter expert (SME). Each technology within Energy Harvesting was isolated and queried and analyzed separately. In most cases, an iterative approach to query enhancement was used in order to identify secondary enabling technologies such as materials.

(U) The second element of the assessment consisted of constructing a "landscape" visualization that enabled effective analysis of thousands of documents at a time. The "landscape" visualization is an incredibly dynamic analytical environment that resembles the interactivity of Google Earth. The visualization allows the user to get a high level view of a corpus of data and within second the user can zoom down to an individual document. As the user zooms down, cluster of related documents automatically and repeatedly break up into smaller sub-clusters. As the user zooms in, each cluster is automatically label by using the most prominent terms within the current cluster. In regards to cluster size, the density of documents are portray by the clusters height and width. (See Figure 2). For example, documents within a cluster that are very similar will tend to create a very tall and thin peak as opposed to a less similar set of documents that will result in a very wide but shallow hill.



(U) Figure 2: Zooming from a global view to each document

(U) In order to develop the landscape visualization, the similarity value between each of the documents needed to be calculated. This was accomplished by running a Latent Semantic Analysis (LSA) algorithm across each document's Title and Abstract fields. As a result, each document is given a similarity value comparing it to every document in the corpus. The LSA algorithm is completely unassisted and does not require any sort of ontology or taxonomy, as a



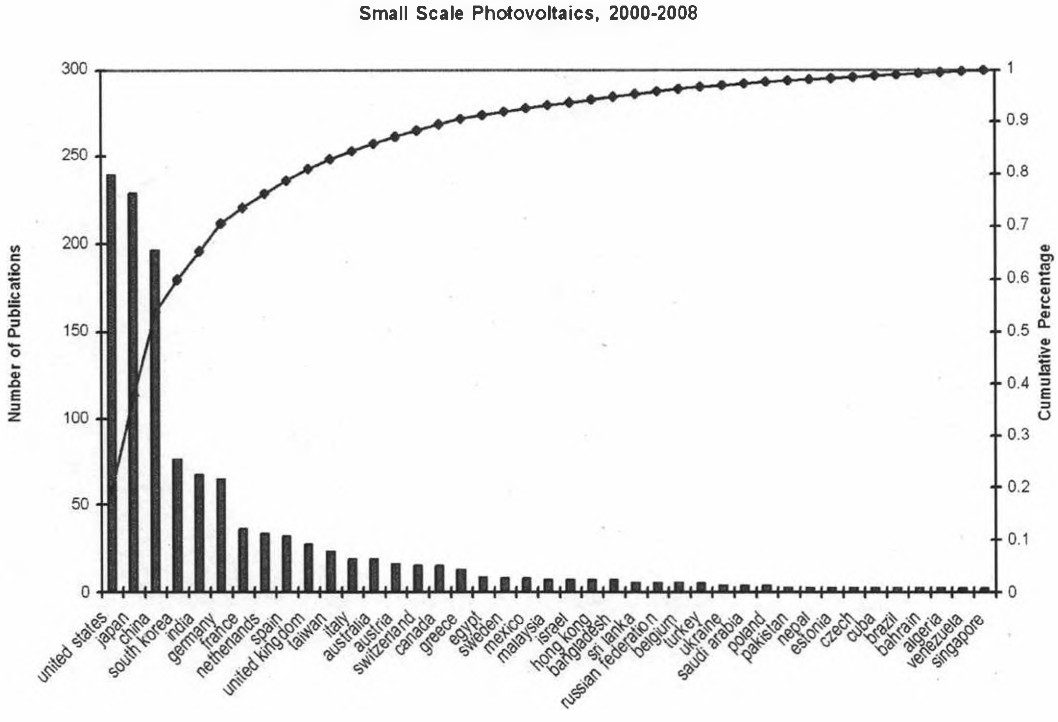
(U) Figure 3: Example of a Mindmap capturing interesting elements from a session. (This particular map was from device integration)

result there is no bias injected into the process of creating the clusters of similar documents.

(U) The third element of the assessment consisted of a three to four hour session with each of the SME's. The session comprised of interactively navigating through the landscape visualization environment with the SME's to identify interesting patterns, trends, and relationships. When an interesting element was found, it was captured using Mindmapping software. This enabled the session to be focused, organized, and effective by tracing what has been assessed and found almost instantly. A handful of sessions chose to start out with the Mindmap, such as that shown in Figure 3, in order to capture the components of a technology before assessing the landscape visualization. At the conclusion of the session, a Mindmap of the session was sent to the SME's in order to provide them with material to conduct deeper analysis of the interesting elements that were found.

6. (U) Photovoltaic Harvesting

(U) Photovoltaics as a general field of inquiry will yield millions of hits in the technical databases. However, this also includes subfields as power distribution and large scale (kW) level power generation substations for remote power applications. Since these systems are not really of interest in the current study, the searches were confined to three basic areas. The first is small scale (mW) level photovoltaics, which includes efforts to make traditional solar cells smaller, but retain the efficiency of the larger scale systems. The second is photovoltaics using a special class of generation called photochemical cells, which lend themselves well to smaller scale systems and are conformal and flexible as to substrate. The last class, due to the need to operate in interior lighting conditions or in conditions other than bright sunlight under normal 1.5AM (atmospheric mass) (http://rredc.nrel.gov/solar/spec tra/am1.5/) conditions, was regarded as low light or low intensity photovoltaic s; essentially, systems that would generate usable power under very low illumination.



(U) Figure 4: Geographic distribution of small scale (mW) photovoltaics publications from 2000-2008.

(U) The first area, that of small scale photovoltaics, is still an active research area, with almost 100,000 references pulled from the search. These systems come in various types and sizes, and are represented by most of the developed and developing countries of the world. A Pareto chart of publication by country is shown in Figure 4 for all publications in the last 8 years in this field. As has been mentioned previously, harvesting systems that have energy storage and conversion systems, as well as load stabilizing elements, reported as part of their development are significantly closer to being field ready systems than just the harvester by itself, and there are several instances of such an integrated device in this area of small PV systems. It should also be noted, that as far as small PV systems of this type are concerned, the major materials sets are silicon or gallium arsenide, and any PV systems that do not use these very well understood materials systems are not sufficiently advanced from a systems standpoint to warrant serious consideration within the next three to five years, as the long term durability concerns of new materials sets has not been sufficiently developed to warrant being placed into application.

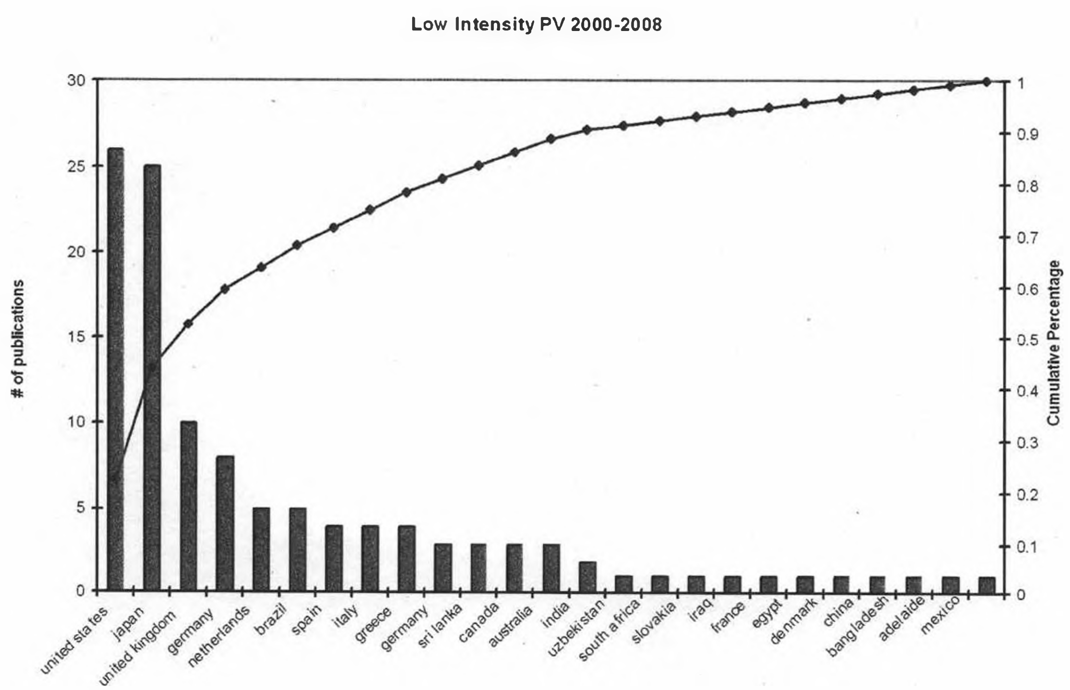
(U) A few points are significant in the landscape of foreign research in this area. A relatively recent (2002) small scale, watt level system was reported from a group working from Uzbekistan, with a very likely association from the former Soviet spaced based need for photovoltaics. The report is for a photovoltaic recharging system for up to 8 "AA" type secondary batteries, including it being ruggedized for resistance to shock, indicating that the system is fully capable of field application. Although the stated application is for battery recharging, the majority of the volume of the system is for holding the batteries themselves, and a relatively small portion of the volume (perhaps less than 10%) is reserved for the solar system and associated electronics. This system outputs a constant (i.e., voltage regulated) 2.5V, more than sufficient to directly drive many important electronic applications directly, but insufficient to recharge any modern lithium chemistries.

(U) Another very well developed small system comes from contributors from the European Union, with principle authors from Spain. This work focused on single square centimeter PV systems (0.78cm^2) with a one sun, AM1.5 generation rate of 5.4mW, with a ~7% total system conversion efficiency under these conditions. These systems were single crystal Si cells that were thinned to be 100mg/cm^2, which is very low for terrestrial applications. Manufacturing cost and weight figure prominently into their discussion, which indicates that the application target is likely to be space based, but the testing with AM1.5 fluence indicates that they expect at least some terrestrial applications for the system. Power output from their device is 5V regulated with a peak current of 1.3mA, which is again, more than sufficient to power many different terrestrial sensing applications.

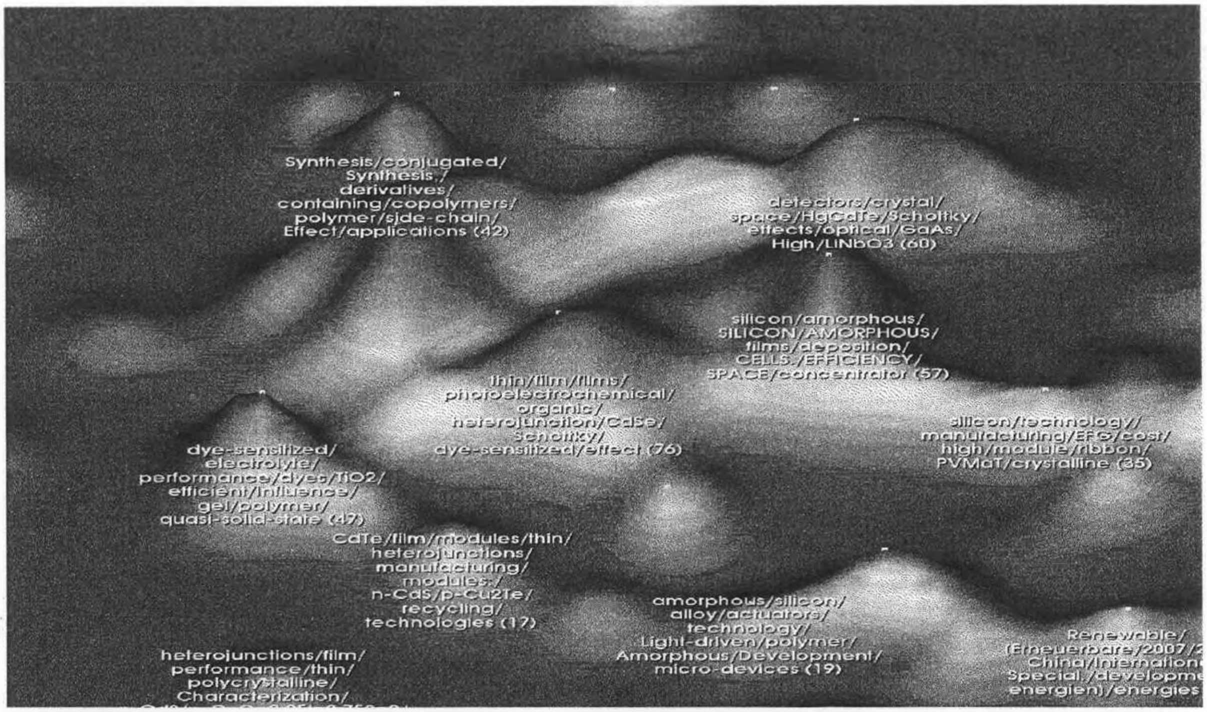
(U) There are a number of less well developed systems under development as well, but bear mention because they are being reduced to practice in a way that the previous examples have been. The Center for Applied Energy Research in Germany has a relatively efficient (10.6%) porous silicon PV cell that has been monolithically integrated with other components on the same piece of silicon, which has dramatically reduced the size of the integrated system. While not ruggedized against environment, this system is at least an order of magnitude smaller than any other integrated (PV plus application) system, and does not use any expensive processing to achieve this system. As a comparison to US related activities, a 2004 report from Brown University shows a similar system generating roughly the same energy conversion efficiency in a 1cm^2 PV system integrated with a small sensor. As a final, perhaps anecdotal, point, a single paper on photovoltaic conversion of H_2S gas appeared in the search (1987) originating from S. A. Naman from the Solar Energy Resarch Center in Baghdad, Iraq. In all, these types of PV systems are likely to be the most readily converted to a field application, as the power output, low light performance, and electrical performance are well characterized and can be integrated most readily into a field device. Based on the state of the art being reported, harvesting devices such as these systems are likely already developed to the point of field use.

(U) Less well developed are photochemical cells, which are often called "Grätzel" cells in honor of one of the original workers in the field who demonstrated operation of such a cell. Rather than generating electron-hole separation in a semiconductor, these devices generate electron hole pairs at the surface of a nanoparticle, and then conduct the hole through a polymer or liquid electrolyte, while the electron is conducted through electron tunneling from nanoparticle to nanoparticle. Electronic field separation comes from surface treatments of the nanoparticles, as well as appropriate choices for the electrolyte and polymers. While these systems are much less well developed, and have significant technological challenges to being implemented (such as loss of electrolyte and low electron/hole mobilities), they hold forth the promise of being, perhaps, a very thin, coatable PV cell that could be realized as a thin, flexible polymer that has commercial applications as a power generating roofing material and as a very inexpensive alternative to traditional Si based photocells, which require high temperature and lithography to realize.

(U) The two most common nanoparticle materials in use in photochemical cells are titanium dioxide (TiO_2) and zinc oxide (ZnO). The majority of the recent research in this field is not involving the nanoparticles themselves, but rather the polymer and electrolytes surrounding the nanoparticles. Pacific Rim countries dominate this field currently (Japan and China being front runners), and based upon the number of publications issuing from these countries, are dedicating significant resources to the development of these types of photovoltaic devices. Phthalocyanine and thiophene derivatives are current hot topics of considerable technological study, due to their ability to generate reasonable voltages from these types of cells. A number of review articles in this field also exist, including reviews from China ("Development of Photovoltaic in China: Status and Future", Qiang Cui Rong, et. al.) and Russia ("Development of Solar Power Engineering in Russia", D. Strebkov). One interesting sidenote on these "organic" solar cells; there is one (2003) study from Israel studying the photovoltaic effects of the Oriental hornet, using the cuticle of the pupa stage has significant (mW) power capability even in low light intensities of a few mW/cm^2 (0.01sun). Since biological systems are known to have better dynamic range than any equivalent human systems (human eyes have dynamic range of 16 orders of magnitude in fluence, whereas the best PV systems are less than 3 orders of magnitude), it may be an interesting development if biologically photoactive materials are studied and used to enhance the low light performance of these organic systems in the relatively near future (5 years). As a rule, however, Grätzel type cells are unlikely to see field use in the next 3 years, and only marginally likely to see real application in the next 5 years, [due to the difficulties in long term operation of these types of cells, combined with significant performance losses when compared to more traditional photocells (and more traditional photocell processing).



(U) Figure 5: Distribution of publications in the area of low light intensity photovoltaics, 2000-2008



(U) Figure 6: Topographical map of relations between different topics within the photovoltaic community. The largest efforts are focused around Gratzel cells, thin film photovoltaics, and lower cost manufacturing

(U) Low light operation is a unique subcategory of photovoltaics. In this field, it is relatively assured that grid type power generation is not under consideration for the people working in this field. Instead, operation in indoor light or in shaded regions is often the target application. Because of this specialty application space, there is an understandably more meager offering of information in this field, both within the United States as well as in foreign work. A Pareto of the publications by country of origin in this field for the past 8 years is shown in Figure 5.

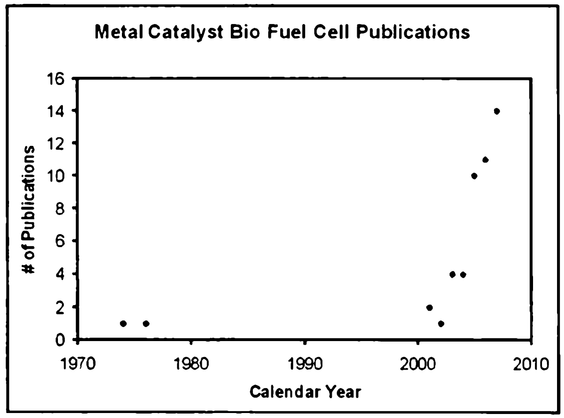
(U) Despite this, it is also likely that these workers are focused on generating power for applications that are smaller, almost certainly portable, and are in the milliwatt to microwatt range. Although the number of publications between the Japanese and US authors is similar, the general trend from the literature is that the Japanese efforts are much more closely focused on delivering functioning hardware, while the US efforts are more on basic physics associated with generation at low light levels. One paper in a collaborative effort from last year (2007) between Danish Risoe National Laboratory and a Japanese corporation (Kyosemi) showed excellent field quality generation of a spherical PV system that was still functioning well even at 25mSun (about 4 times indoor light intensity). The use of the spherical collectors allowed function of the cells even under glancing angle illumination, however.

(U) Lawrence Berkeley Lab has also shown good performance for Grätzel cells under low illumination by changing the basic chemistry of the electrolyte. The principle is to assure during the solution phase that the nanocrystalline material in the polymer matrix is well dispersed and free of any surface contaminant in the resulting polymer sheet. These workers report a 59% quantum efficiency (note: this is NOT solar cell efficiency, but just the efficiency of conversion of photons to electron hole pairs) at 1milliSun, which is indoor lighting intensity.

(U) The majority of the work in new photovoltaics is being dominated by a drive for cheaper manufacturing methods. Gratzel cells, thin film photovoltaics, and CIGS (Copper Indium Gallium Diselenide alloys) are dominant in the field, and represent the vanguard of a push to lower cost per watt of generation in the thin film markets. To give the reader a feeling for where most of the current work is concentrated, a texture map showing some of the local points of interest in the field is shown in Figure 6. From this image, the largest fields are in what has been identified here: Gratzel (or heterojunction) cells, thin film photovoltaics using traditional semiconductors, and cost reductions realized at the manufacturing level. Thin film photocells capable of generating 1 to 10 microwatts per square centimeter in indoor lighting are already in existence, and the cost of these system and the ubiquity of such devices capable of generating at the high end of that spectrum will likely grow in the near future, given the growing demand for alternative energy generation.

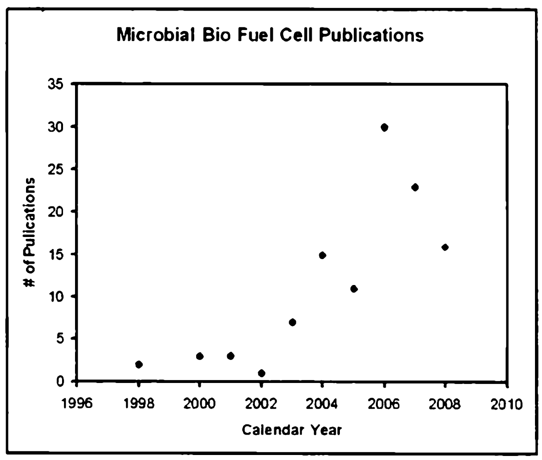
7. (U) Chemical

(U) Research activity in bio fuel cells started approximately 30 years ago with a few publications on precious metal based fuel cells working on glucose in blood, but then lay dormant until about the year 2000. Within the last 10 years, activities in all types of bio fuel cell research have picked up dramatically. A sampling of the types of biological chemical harvesting publications by type are shown in Figure 7, Figure 8, and Figure 9.



(U) Figure 7: Publications on bio fuel cells utilizing metal catalysts, such at Pt and various alloys, plus other metal. Although there were a few papers 30 years ago, the field lay dormant until activity started to pick up around the year 2000.

(U) Figure 10 and Figure 11 indicate that a majority of the publications involve US authors, but work is going on world wide, and network of interconnections between researchers is extensive. Much of this network is established naturally through the training of graduate students and post-doctoral students who move on to establish their own programs at other locations, often returning to their home country after study abroad.



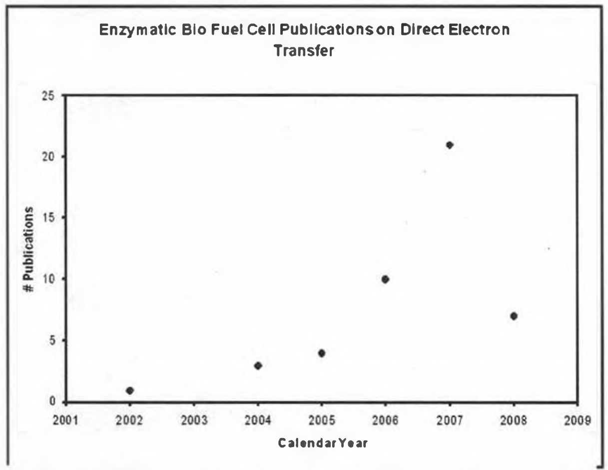
(U) Figure 8: Publications related to microbial bio fuel cells also picked up within the last decade. Note, 2008 is a year-to-date number.

(U) For the purposes of this study "bio fuel cell" is defined to include fuel cells that can utilize readily available or harvestable fuels. These fuels could be found in plant or animal fluids, readily available foodstuffs, or even waste stream materials. These types of fuel cells can be categorized into:

- those incorporating catalysts to directly oxidize a complex fuel substrate (any of a variety of carbohydrate and other compounds) to produce useable electrical power
- those that utilize catalysts to convert or reform a complex fuel into a more conventional fuel, such at hydrogen, methanol, etc. to be used in a more conventional fuel cell

- those that utilize microbial organisms to digest a fuel; in this case the catalysts are a natural part of the microbe, and the challenge is to access the electrons released in the natural process.

(U) In principle, the first two types mentioned above can be miniaturized, made portable, and can produce tens to hundreds of milliwatts electric per square centimeter of active area. On the other hand, microbial fuel cells tend to require square meters of area to produce milliwatts, and are not portable. Catalysts for the first two types can be based on Pt and its alloys, other metal compounds, or they can be fuel specific enzymes found in nature. Enzymes found in nature can also be engineered to function better in a fuel cell application. Someday in the future, it should also be possible to build bio-inspired or biomimetic catalysts that mimic the key functions of enzymes, but in a completely man-made structure.

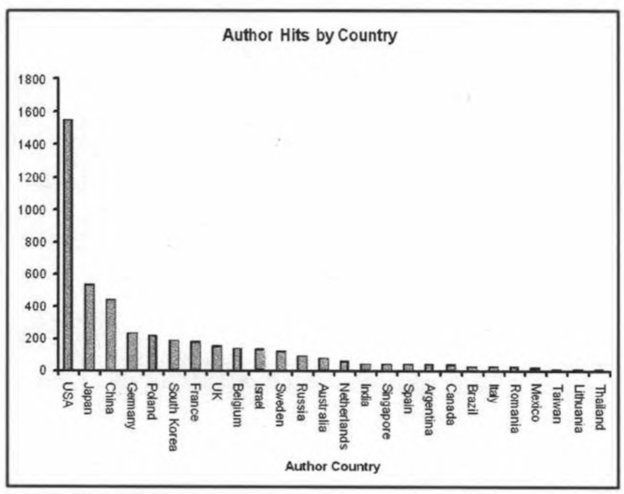


(U) Figure 9: Publications by year dealing with direct electron transfer in enzymatic bio fuel cells. Note, 2008 is a year-to-date number. Again, activity has picked up in the last decade or less. Activity in other enzymatic fuel cell topics displays similar trends.

(U) All three types of bio fuel cells mentioned above share key technological challenges. A high level look at the research and development activities described in the publications represented in the graphs shown above indicates the vast majority of the work in bio fuel cells is still at the level of understanding fundamentals, and establishing proof-of-concept. Most of the electrochemistry work is done in half cell measurements, addressing either the anode or cathode processes separately. Full fuel cell measurements, when reported, are usually done in "beaker type" quiescent cells, rather than a flow-through arrangements needed for a deployable power source.

(U) Major topics being addressed include:

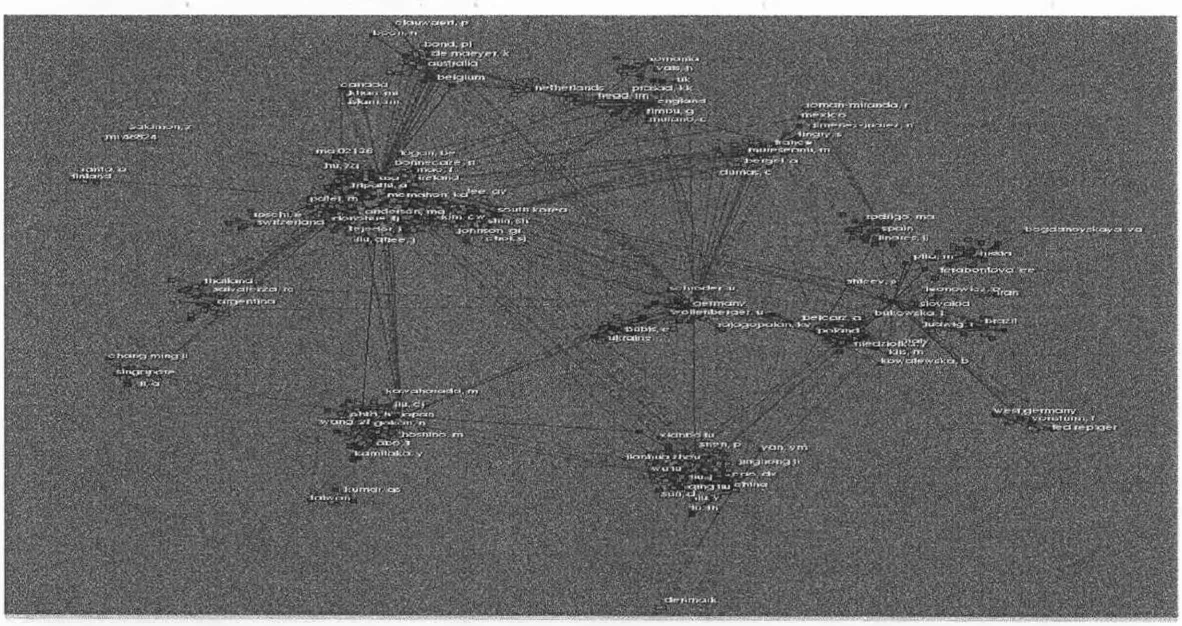
- (U) understanding fundamental electrochemical mechanisms for a variety of fuel substrates and catalysts
- (U) how to increase the power output per unit area
    - o (U) increased catalyst activity or turnover rate (true for all types of catalysts)



(U) Figure 10: This graph indicates the number of times authors from the various countries show up in author lists for publications. Clearly the bulk of the work is happening in the U.S., but it extends worldwide.

 - (U) more efficient electron transfer (direct or mediated – critical with enzymatic catalysts and in microbial fuel cells)
- (U) lifetime issues
  - (U) poisoning of catalysts by impurities and oxidation by-products
  - (U) degradation of catalyst/fuel/electr olyte environment and/or interface
  - (U) immobilization of enzymes and mediators while maintaining or even (U) enhancing activity and extending lifetime
  - (U) degradation of the electron transfer mechanism whether direct or mediated

(U) Some of the primary capabilitie s/techniques being utilized include:
- (U) combinatorial electrochemistry for development of metal-based catalysts
- (U) polymer and membrane science to create a favorable environment for enzymatic catalysts
- (U) protein or enzyme engineering to modify the performance characteristics of native enzymes (greater turnover rate or wider stability ranges for pH, temperature, etc.), to enable direct electron transfer, or to assist in immobilizing the enzyme or an electron mediator
- (U) use of carbon nanotubes, attachment of pendant groups, or other methods to enable electron transfer from the active site to the electrode surface
- (U) implementation of enzyme cascades for reformation or more complete direct utilization of complex fuel substrates



(U) Figure 11: Lines between dots on the graph indicate collaborations between authors in various countries indicated. The vast number of interconnected lines indicates the extensive web of interactions

(U) It is not apparent that anyone is seriously addressing the challenging system integration issues at this time. For example, no one reports a deployable prototype that has addressed continuous fuel and oxidant supply, ability to operate at variable fuel concentrations, operation over variable ambient temperatures, start up under ambient conditions, water management, power management (to produce power that is useful to drive electronics), etc. Some of these aspects have begun to be addressed in bench top demonstrations, but this sort of engineering work is currently taking a backseat to the more fundamental science issues mentioned above.

Certainly learning from prior work on more conventional fuel cell systems can be leveraged, but many of the system challenges will be exacerbated by the use of bio fuels and biocatalysts.

(U) One attractive scenario for bio fuel cells is to tap into a continuous fuel source, thus eliminating the "fuel tank" from the system. In this case an animal or plant host replaces the fuel tank. This possibility has been pointed out by multiple research groups, but there is no evidence than anyone is addressing the special issues that arise from that sort of application. For example, biocompatibility will be a critical concern – the fuel cell cannot kill the host. Furthermore, one must overcome the natural defense mechanisms of the animal or plant host, which will try to seal off and/or expel the foreign object.

(U) In summary, the field of bio fuel cell research and development has ramped up significantly in the past decade, the effort is world wide, and the collaboration network is extensive. Most of the work is still at the proof-of-concept and fundamental science end of the spectrum utilizing specialized laboratory techniques to investigate the use of complex fuels, to enable the discovery of suitable catalysts, to increase the power output and longevity of the electrochemical system. Progress is being made in all fronts, but performance characteristics are still not close to competitive with battery technology, even under ideal laboratory demonstration conditions. Researchers acknowledge the daunting system engineering challenges for bio fuel cells, but the required engineering work awaits better fundamental understanding of the underlying science.

8. (U) Thermal

(U) This section deals with thermoelectric (TE) energy harvesting from low-grade heat sources. Our assessment is restricted to this thermal range to enable concentration on devices utilizing heat sources available in 1) nature or from 2) low-level waste heat.

(U) A particular area of interest involves harvesting the heat flux through soil strata caused by diurnal variations in ambient temperature. This concept has been pursued within the US and in the Ukraine. Research within the US was initially focused on theory[11] and modeling[12] of systems. Attempts were later made, with very little success, to develop functional power sources. One device[13], never fully realized, had a predicted average power output of 50μW and was the size of a football. Another device[14] generated an average load voltage and power output of 50mV and 50μW respectively and was the size of a large popsicle. Neither design was successful because the TE modules they used were commercially fabricated for cooling applications and were not optimized for power generation from low-grade heat. The key is the TE module.

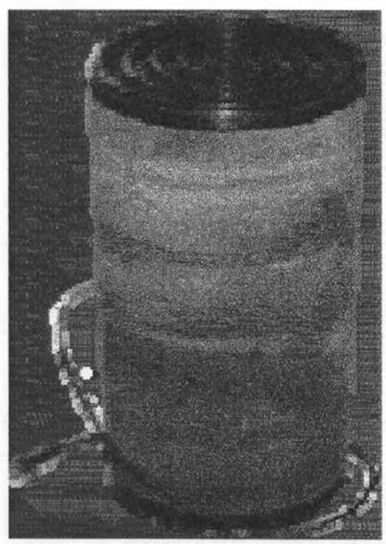
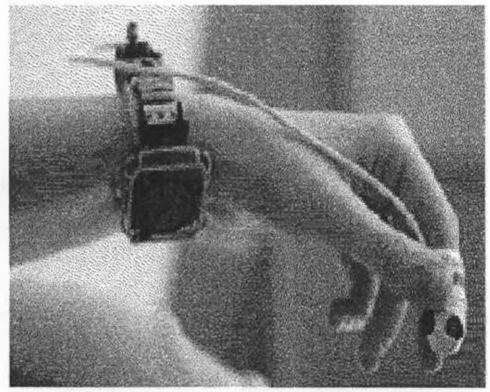


Figure 12: TE Soil Harvester.

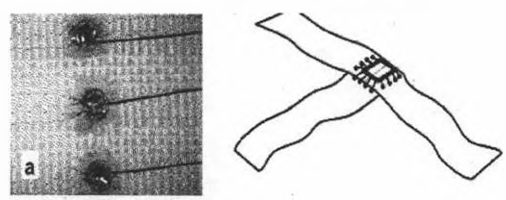
(U) Efficient harvesting from low-grade heat requires modules having thousands of high aspect ratio, series connected elements. Specialized and complicated manufacturing processes are required to produce such modules. This capability does not exist in the US, but it does reside at the Institute of Thermoelectricity (ITE) in Chernivsti, Ukraine. ITE has successfully developed harvesters using optimized TE modules that operate efficiently off the diurnal heat flux in the soil. Researchers at ITE have recently published a large body of work on theory[15,16], design[17], and prototype devices[18]. In fact, ITE has a family of TE soil energy harvesters that are available for purchase though their website[19]. Figure 12 shows a picture of a typical unit. These devices generate single digit milliwatts, can be regulated to 3, 6, or 12V, and come in various sizes. Such performance is entirely enabled by the ability of ITE to specially manufacture TE modules optimized for conversion of low-grade heat.

(U) Another area of interest involves harvesting heat from the human body. This approach actually resulted in commercially successful ventures by both Seiko[20] and Citizen[21] to power wristwatches. These devices produced tens of microwatts at roughly 1.5V and contained boost circuitry to bring the voltage to a useful level. The Seiko Thermic® and Citizen Eco-Drive® watches were discontinued due to high cost. The largest and most successful body of work on wearable thermoelectric devices comes from IMEC, a large commercial semiconductor company in the Netherlands[22]. IMEC has developed a wrist-worn device with an integrated voltage booster that generates 100μW, powers a sensor, and charges a NiMH battery[23]. IMEC has also developed a wireless pulse oximeter, shown in Figure 13, that utilizes a watch-sized TE device as the power source.[24] This device integrates a supercapacitor to store charge for burst mode and generates similar power and voltage to the aforementioned device. IMEC has also developed an electroencepha logram (EEG) that is powered by a TE module strapped to a patient's forhead.[25] This device generates roughly 2mW.



(U) Figure 13: IMEC Pulse Oximeter.

(U) Researchers at the University of Pisa in Italy are developing flexible polymeric "Smart Skins" that would improve the performance of wearable TE devices by enhancing thermal contact at the TE/human interface.[26] Reasearchers at Infineon Technologies in Germany are developing a thermoelectric module woven into the fabric of clothing to power an RFID.[27] The technology, shown in Figure 14, is very immature and currently not workable but the concept is nevertheless provocative. Maintaining good thermal contact between the TE and skin is a major system level challenge. Researchers at the Center for Thermoelectrics Research at RTI International (USA) are exploring implantation of TE modules that harvest thermal gradients within the human body near the surface of the skin.[28] This work is very early but shows feasibility based on other successes from this group.

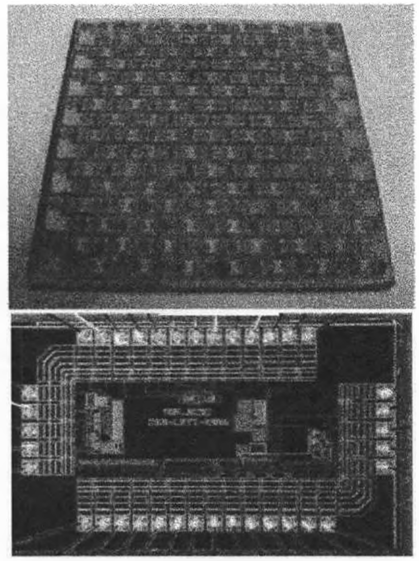


(U) Figure 14: Unworkable Smart Skin prototype

(U) Since miniature TE generators are an enabling technology regardless of heat source type, it is instructive to document who is active in the area. The best commercially available miniature TE generators are manufactured by ITE (Ukraine), ThermoLife (US), Thermix (Ukraine), MicroPelt (Germany), Nextreme (US), and Hi-Z (US). These are listed in rank order with our opinion of the most useful devices for harvesting low-grade heat listed first. Other promising TE generators are being developed at the R&D level. French researchers have developed a device, shown in Figure 15, which fully integrates a TE generator, charge storage, voltage booster, and

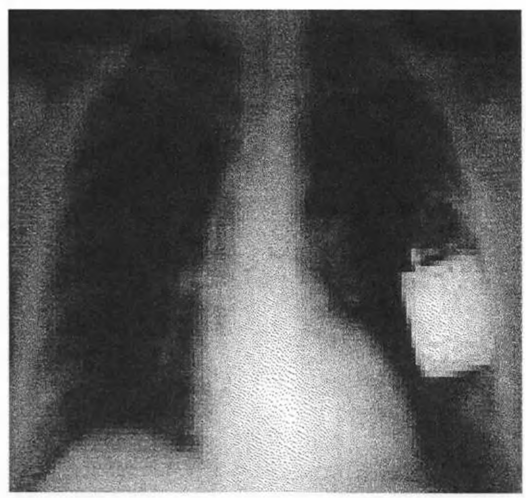
RF technology on a single chip.[29] The TE module utilizes thick-film processing to generate 50-100μm tall TE elements. The device is quite impressive and demonstrates a high level of systems level competence. One unique approach to generating the required high aspect ratio elements is the use of ink printing technology. Researchers in Poland have implemented this approach at the R&D level.[30]

(U) There have been numerous micromachined TE modules reported in the literature, however, these research efforts are typically one-off efforts with no follow on work. This is most likely due to the fact that these devices produce power in the nanowatts range and are not suitable for harvesting low-grade heat. Thin film devices suffer from very low aspect ratio TE elements and very high electrical impedance. We do not believe that TE modules made from thin film processing are viable for harvesting low-grade heat.



(U) Figure 15: TE generator and DC boost circuitry.

(U) During the late 1960's and early 1970's, miniature radioisotopic TE generators were developed worldwide for use as power sources for pacemakers in biomedical applications.[31] Between 1970 and 1984, over 3000 radioisotopic TE generators using ^{238}Pu as the heat source were implanted in human patients. This practice was discontinued in the late 1980's with the advent of Lithium battery technology. There is currently no technical or medical reason to revert to a nuclear powered pacemaker. This makes a recent press release from Iran of particular interest. On February 18th, 2008 researchers from Amir-Kabir Industrial University in Tehran announced the successful development of a long-lasting nuclear battery for use as a cardiac pacemaker.[32] Neither the nuclear fuel type nor the heat-to-electric conversion scheme is disclosed but the image in Figure 16 is given. This indicates that Iran claims to be proficient in converting low-grade heat into electricity.



(U) Figure 14: Iranian nuclear pacemaker.

(U) The largest advances will come from improving the efficiency of bulk thermoelectric materials. It is bulk material, not thin-films, which can be incorporated into useful low ΔT harvesters. Two recent discoveries have opened new possibilities for improving thermoelectric conversion efficiency in bulk materials. Heremans (USA) has increased by 50% the efficiency of bulk lead-telluride at 500°C via thallium doping.[33] Poudel (USA) has increased by 40% the efficiency of bulk p-type bismuth-telluride at 100°C by adding nanopowders.[34] We expect these discoveries to spawn a widespread research effort aimed at nanostructuring of bulk materials. It is likely that such efforts will results in continued improvement in the efficiency of bulk thermoelectric materials. Engineering these materials into useful harvesting devices will soon follow.

9. (U) Mechanical

(U) This section provides a review of mechanical energy harvesting research activities based upon English-language science and engineering journal publications from 1960 through July of 2008. The objective is to delineate the field of research, and identify active areas of investigation as well as the researcher's country of origin and their networks. Projections on the direction of mechanical energy harvesting technology are provided based on this survey and the author's experience.

(U) Mechanical energy harvesting dates back to at least the 1880's where hydroelectric plants first generated DC electrical power for carbon-arc lighting. For the modern-day purposes of providing a long-duration (albeit, often intermittent), portable power source to supplement or even replace batteries for micro electronics applications, mechanical energy harvesting has been adapted to a multitude of environmental sources. Examples include vibration, wind and pressure fluctuations among others. Mechanical energy harvesting has also been implemented through a variety of manufacturing technologies from conventional miniature machining to wafer-scale silicon processing methods. These factors control device effectiveness, size, cost and ultimately the ubiquity of use.

(U) A breakdown of the major components of a mechanical energy harvesting system, shown in Figure 17, provides a framework for discussing research activities:

(U) The mechanical energy input, or source, falls into five primary categories and are often the anchor of a research focus in order to take advantage of an area of expertise and/or device fabrication capability. Since the mechanical source defines the energy availability, it is a primary driver for device size and the application space.

- (U) Vibration – has received intense study and some actual use in industrial settings given its pervasiveness and the opportunity for tactical exploitation where an energy harvester may be simply attached to the source.
- (U) Stress/strain – has been generally of interest for strategic applications such as structural health monitoring or generating power for anticipated needs since the harvester must usually be built into a structure to be effective.
- (U) Pressure – has been examined and utilized on a limited basis as there are fewer application spaces.
- (U) Acoustic – has been examined out of academic interest, but regarded as a feeble energy source in most environments.
- (U) Shock – has been studied and utilized generally for fusing applications and starting gas grills.

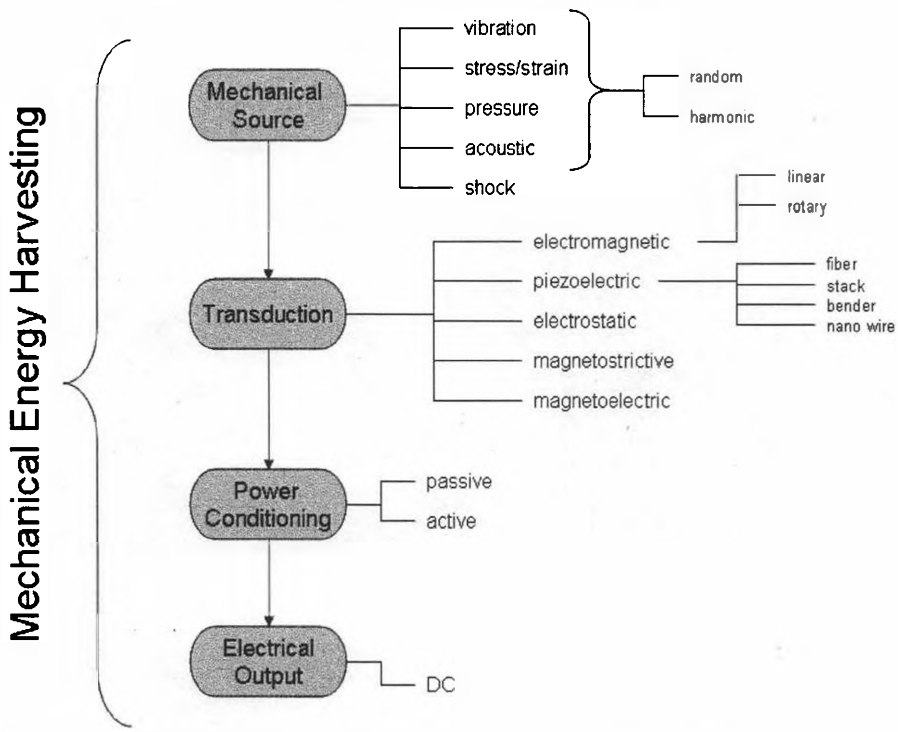
(U) Transduction mechanisms bridge the mechanical to electrical conversion process and may be divided into five categories. Their use is dictated by the researcher's device-size goals, fabrication approach and means for effective impedance matching to the environmental source.

- (U) Electromagnetic – the first practical approach employing permanent magnets magnet wire to create the typical generator. Best suited for meso (mm^3) to macro-scale (cm^3) devices due to physical scaling laws. Matches well to low-impedance mechanical sources.
- (U) Piezoelectric – the most widely used energy conversion mechanism to date given its superior power density at small size scales.

- (U) Electrostatic – generally employed in surface micro-machined devices or micro electrical mechanical systems (MEMS) due to scaling laws and compatibility with fabrication methods.
- (U) Magnetostrictive – (manifested by a magnetic response where a ferromagnetic material responds to stress with a magnetization change) has high power densities, but employed on a limited basis due to material integration challenges.
- (U) Magnetoelectric – an indirect transduction mechanism where piezoelectric and magnetostrictive materials are coupled mechanically.

(U) Power conditioning mechanisms provide the final link in producing a useful DC electrical output. This aspect of an energy harvester system is often tightly integrated with transduction mechanism for the sake impedance matching to the load, and is an important consideration in the overall mechanical energy harvester design. Two predominant categories of power conditioning include:

- (U) Passive – represented by the standard bridge rectifier and storage capacitor
- (U)Active – utilized to improve harvester effectiveness in particular mechanical environments.



(U) Figure 17: Mechanical energy harvesting components delineate areas of research activity.

(U) A survey of peer-reviewed journal literature from 1960 to present reveals the who, what, where and when of mechanical energy harvesting research. The first modern-day concept of a

(U) Table I: Number of journal publications, relating to mechanical energy harvesting, by country and year from 1995 through July 2008.

Year	Malaysia	Nether-lands	Norway	Russia	Singapore	South Korea	Spain	Sweden	Switzerland	Taiwan	Thailand	Tunisia	Turkey	USA	unkown	Sum
1995																1
1996																3
1997															1	4
1998														1	1	2
1999																1
2000														1		2
2001														5		11
2002				1										5		7
2003									1					10	2	15
2004														2		4
2005						1	2		1					26	4	61
2006	1				1	1	2		2	6				36	5	99
2007		2	1		1	3	4		2	6	1	1	4	38	7	134
2008						1	3	1		2			1	15	5	47
Sum	1	2	1	1	2	6	11	1	6	14	1	1	5	139	25	391

Year	Australia	Belgium	Canada	China	Czech Reb.	Egypt	England	France	Germany	Greece	Iran	Ireland	Israel	Italy	Japan
1995															1
1996							1								2
1997							1						1		1
1998															
1999															1
2000				1											
2001							5		1						
2002				1											
2003		1													1
2004	1						1								
2005	3	1		3			3	14				1	1	1	
2006	1	2		7	2	1	11	7	6		1	2		2	3
2007	2	3	1	16	1		14	12	8	1		3		2	1
2008	2		3	4			5	4	1						
Sum	9	7	4	32	3	1	41	37	16	1	1	6	2	5	10

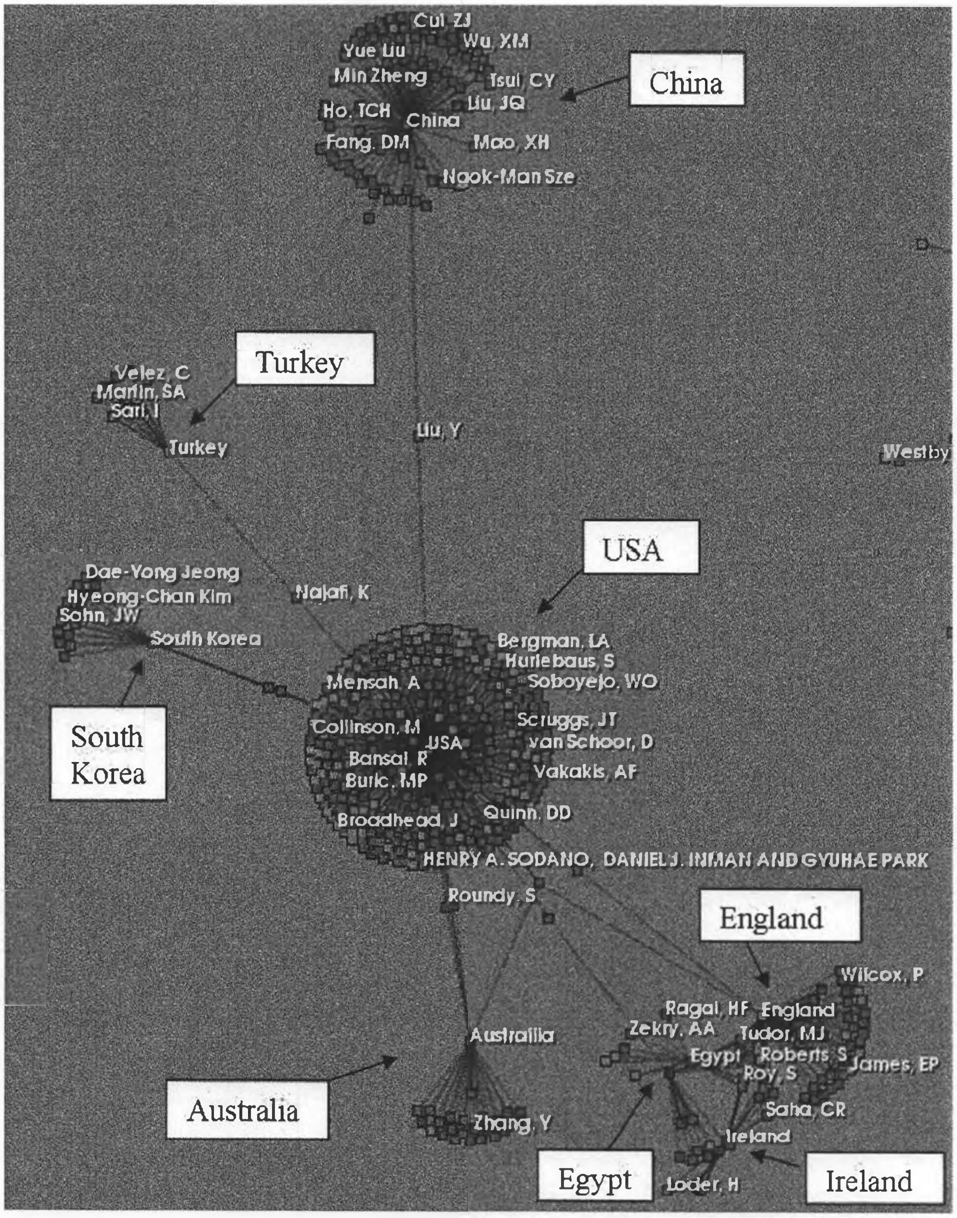
mechanical harvester was developed as early as 1963 where C.C. Enger and J.H. Kennedy implanted the lead-containing piezoelectric material, lead zirconate titanate (PZT), onto a dog's heart to power a pace maker. The next reported mechanical harvester is a wrist watch based AC electric generator in 1986 by P. Goemans from the Netherlands. Little research activity occurred until 1995 after which it was probably recognized that microelectronic power requirements could be made low enough to begin to capitalize on harvested mechanical energy sources. A tally of publications (Table I) indicates the effort of research by country over time from 1995 though present day. One can see that England and Japan showed early interest, beginning in the late 1990's and that the USA has been the most active with research accelerating from 2000 on. Other significant players from 2005 onward include Australia, China, France, Germany, Spain and Taiwan. For 2008, through July, only 47 articles have been published world wide.

(U) The contributing authors and country of the research institution from which each journal publication originated were extracted from the survey data (29 countries and 391 papers in Table I) and used to construct network maps. Figure 18, for example, shows that of all the journal articles originating from the Chinese and US institutions, one individual (Liu, Y) was a common author. One can also see a handful of ties between the US and Turkey, South Korea, Australia, Egypt and England.

(U) This author-and-country comparison was conducted on the entire publication data base and only a few additional collaborations were evident:

- (U) Czech Republic and Iran
- (U) Egypt, Ireland and England
- (U) Belgium and the Netherlands

(U) The absence of collaboration may also be of interest: Despite France's high publication rate, they appear to be working in isolation. Also, China and Taiwan do not appear to be interacting.



(U) Figure 15: Contributing authors and country of the research institution originating each journal publication.

(U) An overview of the trends in mechanical energy harvesting research may provide an indication of the technology's future direction. Note that it has become evident from this journal survey that no particular institution or country appears to have cornered a specific area of research as there is a broad spectrum of institutions addressing mechanical sources, transduction and power conditioning topics.

(U) Beginning from 1995, mechanical energy harvesting research initially addressed manufacturing techniques, such as winding miniature coils for electromagnetic transduction mechanisms. Research emphasis on the fabrication of meso-scale electromagnetic and piezoelectric devices continued into the late 1990's along with forays into different harvesting approaches and theory. Over the time period from 2000-2004, MEMS-scale harvesting research emerged as well as interest in optimization, power conditioning, systems integration and packaging. As the potential of mechanical energy harvesting became more popularized, with wider availability of lower power micro electronics, the published research effort expended dramatically from 2005-2007. Over this time period, the research effort intensified into MEMS, fiber composites, functional textiles, advanced configuration, active power conditioning, advanced power management and adaptive capabilities. From 2007 onwards one sees the research efforts somewhat more focused upon model refinement, performance tweaking, overall system operation and finally an emerging discussion of commercial devices for unique applications.

(U) Given the maturation of research topics, from discovery-type articles to those on system integration and optimization, and the decreased publication rate so far in 2008, mechanical energy harvester research may be seeing a peak in activity. There are indications, however, that the commercial sector has already begun their own development efforts to mature the technology for widespread consumption.

(U) Over the next 2-3 years we can expect to see the deployment of macro and meso-scale mechanical energy harvesting technologies for specific government and industrial applications by commercial entities. In this time frame, there should be rapid improvements in manufacturing and packaging. Only modest gains in maximum power density, however, are anticipated over advanced research devices, as the energy content of mechanical sources (such as acoustics or vibrations for example) remains constrained by the same physical principles which the research community has already attempted to exploit. With regard to MEMS-scale technologies, we can anticipate continued research toward their integration into microelectronic systems and the beginning their adaptation by the commercial sector.

(U) Over the next 5-10 years expect that mechanical energy harvesting will develop to the state of being pervasive in our everyday lives. By then, MEMS-scale technologies will have caught up in maturity to macro (cm^3) and meso-scale (mm^3) devices. Ultra-low-power microelectronics (sub microwatt) will be able to make use of even feeble energy harvesting power sources. By this time, also expect that advanced transduction materials with enhanced durability will be combined with flexible circuitry to produce smart clothing and other everyday products. The development of these advanced transduction materials may involve nanotechnology, however, they would need still need to be implemented over larger size scales to effectively couple into mechanical environments to produce useful power. By the end of the 10-year period, I would anticipate that almost any item larger than a few cubic millimeters could have a combined sensor array, computational capability and storage capacity and function indefinitely from harvested mechanical energy. Although not ready for prime time, I anticipate that mechanical energy harvesting at the nano scale, for powering nano-scale devices, will be an active area of research over this time period.

(U) Speculating out to 25 years, I would finally expect nano-scale mechanical energy harvesters to see use in the consumer market.

10. (U) Radio Frequency (RF) Harvesting

(U) RF power harvesting from ambient signals presents key challenges in RF electronics, low-power electronics, and antenna design. The key challenge is collecting sufficient energy for efficient rectification and conversion to a useful voltage. Many of the enabling technologies are either commercially available due to consumer market demand, or can be obtained or fabricated through commercial sources. Current technology will allow for ambient RF power harvesting in locations with predictable high RF emissions, but further technology advances in antenna and rectification technology are required to allow use of the approach in a wide range of locations.

- (U) RF energy harvesting can generally be broken into two categories: power remoting and ambient power harvesting. While the technologies, concepts, and challenges are similar between the two technologies, it is important to draw a distinction between the two in order to define the limits of practicality. Because the output voltage of zero-bias rectifier diodes scales linearly with frequency, the available DC output power generally scales as the square of the RF input power up to the saturation or destruction limit of the diode. This suggests relatively large RF powers for efficient RF-DC rectification, which is best obtained with a cooperative source.
- (U) **Power remoting** uses a compliant transmitter of known energy and frequency with the intention of providing energy to a receiver elsewhere (usually within close proximity). Most of the reported work falls into this category, which includes the majority of RFID tag work, "wireless battery charging", and microwave power transmission (such as microwave power beaming from space).
- (U) Power remoting can be further broken down into resonant systems and directive systems. Resonant systems use two electrically small resonant antennas that reside near each other, often in each other's near-field region, where they couple strongly to one another. The resonant frequency of the two antennas is closely matched, to allow efficient power transfer between the two. This can be used to transfer mW of power with ranges of a few meters, but generally requires several watts of transmitted power.
- (U) Directive power transmission systems use a high-gain transmit antenna to achieve a high RF power density in a specified area. Because of the high RF power density, high rectification and conversion efficiencies can be obtained. This approach can be used over long ranges, but beam divergence and path loss generally cause the power to drop as the square of the distance from the source.
- (U) **Ambient power harvesting** attempts to obtain useful energy from an existing RF power source. Potential sources include broadcast sources such as radio or television, communication sources such as paging systems, mobile telephony, wireless internet, or two-way radio, and other ambient signals such as radars, microwave ovens, and noise. The energy, polarization, and frequency of these signals will vary depending on proximity to broadcasters, terrain, and other factors, but will generally be much lower than that obtained in a designed power transmission system, resulting in the challenge of collecting enough energy to drive a detector diode efficiently. Received power on the order of 10-100 μW is required to approach 10% rectification efficiency, with most RFID tags requiring DC powers in the range of ~50 μW to function. The challenge of obtaining sufficient power is apparent when compared to the energy density of a typical AM or FM broadcast station of ~10 $\mu W/cm^2$ at a range of 1 km and typical receiver sensitivities in the pW to nW range.
- (U) While the power levels and other requirements differ, the enabling technologies for each approach are similar, and will be discussed jointly here.

10.1 (U) Enabling Technologies

10.1.1 (U) Efficient power collecting antennas

(U) **Challenges:** Obtaining broad bandwidth, high efficiency, large electrical size, and polarization insensitivity in a physically small antenna.

(U) **Current Status:** Large body of work on antenna miniaturization for consumer wireless applications can be applied to the problem. Most rectenna research is focusing on narrowband designs to operate with specific known sources, but with relatively large areas. Metamaterials may have application to reducing the physical size of the antenna, but the potential is not clear.

10.1.2 (U) High efficiency voltage conversion and power management

(U) **Challenges:** Efficient conversion of low power signals to useful levels, converting from high source impedance to meaningful power delivery impedance, power management with low overhead power consumption.

(U) **Current Status:** Numerous efforts in efficient step-up power conversion reported, generally utilizing commercial CMOS foundries. The clock required for typical boost converters remains a large power drain, but voltage multiplying rectifiers offer passive step-up capability. Many monolithic solutions are integrating rectifying RF electronics with low-power CMOS.

10.1.3 (U) High efficiency low power rectifiers

(U) **Challenges:** The diode RF-DC conversion efficiency is limited by the I-V characteristics of the diode.

(U) **Current Status:** Zero-bias Schottky diodes in both Si and GaAs have been pushed to the limits of practicality by low-power receiver requirements and represent the best performance available in these material systems. Other material systems such as InAs and InGaAs have been investigated at higher frequencies (primarily to reduce parasitic elements), but it is not clear if these materials will have improved rectification efficiency at relevant frequencies when compared to commercially available alternatives. Direct integration of the diode with CMOS power conditioning and mixed-signal electronics is common but the diode performance suffers.

10.2 (U) Key Efforts

- (U) University of Colorado at Boulder (USA) has an active research program involving both rectenna research, power conditioning research, and wireless sensor nodes. Sponsors are the NSF, DARPA, and others. Some specific reports include:
  - (U) A 162 cm^2 broadband 64-element rectenna array designed for low power energy collection from 2-18 GHz[35]. Incident RF power densities ranged from 0.01 to 100 $\mu W/cm^2$. RF-DC conversion efficiency ranged from 0.1% at incident powers of 0.01 $\mu W/cm^2$ to 20% at 100 $\mu W/cm^2$.
  - (U) An 81 cm^2 rectenna and power conditioning system[36] that delivers DC power ranging from 8-430 μW with input power densities of 30-70 $\mu W/cm^2$ at 2.4 GHz. The system was built using COTS parts and consumes about 50 μW of power.
  - (U) A wirelessly powered sensor including an accelerometer, thermometer, and skin conductivity sensor operating from a 100 $\mu W/cm^2$ 2.4 GHz field.[37] The antenna size is unclear but appears to be >10 cm^2. The sensor operated 3-4 meters away from a 1 W RF source.

- (U) Texas A&M University (USA) has been investigating rectennas for receiving energy from a cooperative source, apparently for microwave power transmission [38,39]. DC powers of >100mW with efficiencies as high as 80% have been reported at power densities of $>10^4$ μW/cm^2 at 5.8 GHz with 10% bandwidth.
- (U) University of Pittsburgh (USA) has an RFID "Center of Excellence" that is exploring various aspects of low-power RFID. Of specific interest to this discussion, this team published an analysis of RF remote powering [40] and has investigated multiple antennas for improving the amount of energy collected in a given space specifically for power harvesting. They obtained a 300% increase in energy collected with an 83% increase in area.[41] A 180 cm^2 antenna delivered approximately 20 mW of power at a range of 50 cm from a 6 dB antenna with a 5.5 W source power at 900 MHz. The actual RF transmitted power or power density at the rectenna is not separately specified but is approximately 500 μW/cm^2 at 50 cm range.
- (U) Visvesvaraya Natl Inst Tech (India) has an effort on "ubiquitous sensing" targeting tags that harvest energy from wireless communications [42]. This team describes an antenna and diode detector system operating at 2.4 GHz, with the intention of harvesting energy from wireless communication devices [43]. The authors predict input RF power levels on the order of 0.1 – 100 μW within a few meters of a 1-100 mW RF source, with projected output power levels of 1.4 to 373 μW (this is >100% efficiency, calling the whole paper into question). It is not clear if they have actually built anything.
- (U) McGill University (Canada) reports a monolithic RF power scavenging system (fabricated at TSMC in 0.18 μm CMOS) for powering a tag with a 1 W signal at 900 MHz and a range of 2 meters, resulting in a received RF power of -5 dBm (316 μW) and a converted DC power of 30 μW at 1.5V.[44] This group appears to specialize in low-voltage, low-power electronics for wireless network tags.
- (U) The National Changhua University (Taiwan) recently presented wireless battery charging.[45] They claim to have transformed radiated power from a base station to 1.7 V with no details in the one-page abstract.
- (U) Oregon State (USA) reported far-field RF harvesting for passive networks.[46] A 0.25 μm CMOS power conversion circuit was developed using floating-gate transistors as rectifier diodes. The rectifier was able to operate at RF (915 MHz) input powers as low as 5.5 μW with 10% efficiency. Approximately 1 μW of output power and 20% efficiency was realized at 10 m from a 4W EIRP transmitter (power density ~0.5 μW/cm^2). The antenna was a 15 cm x 2 cm meandered dipole on circuit board material.
- (U) Korea Advanced Institute of Science and Technology (Korea) reports an 8 μW temperature sensor powered by a 900 MHz tag interrogation signal of unspecified intensity.[47] The chip is realized in 0.25 μm CMOS and operates at 1 V. The authors separately report a 5 μW backscatter RFID tag with integrated sensors.[48]
- (U) Powercast (USA) is commercializing a wireless power delivery system that operates in the 902-928 MHz ISM band [49]. The receiver circuits can pick up "70% of the theoretical maximum", meaning a few mW when placed within 1 meter of a 1W isotropic radiator (where the field intensity is ~8 mW/cm^2).
- (U) Several companies, including Splashpower (USA), Visteon (USA), Fulton Innovations (USA), and the University of Tokyo (Japan) are working on commercializing inductive power transfer [49]. This approach can achieve very high coupling efficiency, but requires close proximity and good alignment between two coupled coils.

- (U) MIT (USA) has demonstrated powering a 60 W light bulb with two 10 MHz inductively coupled coils sharing their near-field region.[50] The resonant coils were 30 cm in diameter spaced 2 meters apart and demonstrated 40% power transfer efficiency. It is not clear if this is substantially different from previous inductive coupling work.
- (U) The Hong Kong Institute of Technology (Hong Kong, China) is developing power conversion circuitry specifically for low-voltage energy harvesting, which may include RF harvesting[51]. The circuit, realized in 0.35 μm CMOS, converts a 0.2 V input signal to 2 V, but the efficiency is not clear from the publications. The same group reported simulations from an integrated boost converter more recently.[52] The City University of Hong Kong is investigating 5.8 GHz rectennas.[53]
- (U) Kanazawa Univ. (Japan) reported an energy harvesting system-on-chip with total power consumption of 2.2 mW for the microcontroller and RF transmitter[54]
- (U) Intel and Univ. Washington (USA) published a paper on "energy harvesting for RFID" that focuses on multi-stage voltage multipliers for energy harvesting RFID tags.
- (U) University of Maryland (USA) reported simulations of a 25% efficient harvesting circuit designed in 0.13 μm CMOS intended to operate with 66 μW RF input power.[55] The group also has interest in low-power receivers, small antennas, and 3D chip-stacking, and CMOS-foundry compatible Schottky detector diodes.
- (U) Toyohashi Univ (Japan) reported an RF-to-DC power converter with surface mount components integrated into deep etched holes on a chip.[56] The system included a silicon carrier chip, power supply CMOS circuits, a rectifier diode, and a few passive components in an 8.64 x 8.64 x 0.625 mm^3 volume. The antenna was a quarter-wave monopole approximately 8 cm in length. The system delivered 4V and 1mA harvested from a mobile telephone in close (but undefined) proximity. The authors also report a 15 x 15 mm^2 sensor node operating off of 100 mW of RF input power at 1.45 GHz.[57]
- (U) The Chinese Academy of Science (China) has been working on rectennas for wireless power transmission since at least 2004, with efficiencies on the order of 60% for input powers of 15 mW at 5.8 GHz and work at 35 GHz[58,59].
- (U) Chongqing Univ (China) has a novel concept for collecting an compressing electromagnetic energy using an interdigital transducer and inhomogeneous piezoelectric material to compress the incoming energy into higher power bursts[60]. Experimental results were measured, but the improvement was not quantified.
- (U) Univ. Erlangen (Germany) reported an ultra-low-power multistage rectifier that converted 10 μW of input power to a 2 V_{DC} with 13% efficiency.[61] This group is active in a variety of RFID topics.
- (U) Berkeley University (USA) has previous efforts in "Smart Dust" and "picocubes" but it appears that they are targeting other methods of power harvesting[62]. They have explored low power management circuits for these other methods of power harvesting.[63]

11. (U) Capability Forecast

11.1 (U) Short-term Capabilities (<5 years)

(U) Based on the existing reported capabilities, harvesting RF energy from ambient signals is possible using today's commercially available technologies using a combination of short range (~1-100 meters), high transmitter power (Watts), and relatively large receiving antenna (10-100's of cm^2). These factors must be balanced to provide a minimum of 10 μW of DC power at a useful voltage, suggesting power densities of >1 $\mu W/cm^2$ (assuming a 100 cm^2 effective area antenna and 20% RF-DC efficiency) which is about 3m from a 1W isotropic radiator or 300m from a 10 kW radiator. The short-term opportunities are in areas with predictable high RF emissions such as electronics sites, airports, and broadcast towers, where narrowband antennas and rectifier circuits can be used.

11.2 (U) Medium-term Capabilities (5-10 years)

(U) Extending RF power harvesting to regions of lower power densities will result from advances in ultra-low power conditioning electronics, physically small antennas (possibly including metamaterial antennas), low-power rectifier diodes, and the ability to collect energy from multiple signals. All of these areas are of interest for both commercial and military applications, primarily for RFID and connectivity. Assuming a 2X improvement in each of these areas, it may be possible to cover large portions of urban areas with reasonably sized (10-100 cm^2) antennas, especially if low leakage, all-passive battery charging approaches can be developed. Similarly, areas of predictable high RF emission properties may be covered with smaller antennas with these types of improvements. Adaptive antenna tuning technologies and approaches will also serve to maximize the RF power delivered to the rectifier circuit, provided it can be done with sufficiently low overhead.

11.3 (U) Long-term forcast (10+ years)

(U) Over the long term, additional RF services in previously unutilized bands will increase the opportunities for power scavenging, and it is anticipated that open access and cognitive radios will increase the utilization of existing bands. Ultra-wideband services will raise the overall RF spectrum noise floor, presenting opportunities for broadband collection. Local data communication appears to be pushing towards higher frequencies such as 60 GHz, presenting additional collection opportunities with smaller antennas but likely smaller power densities.

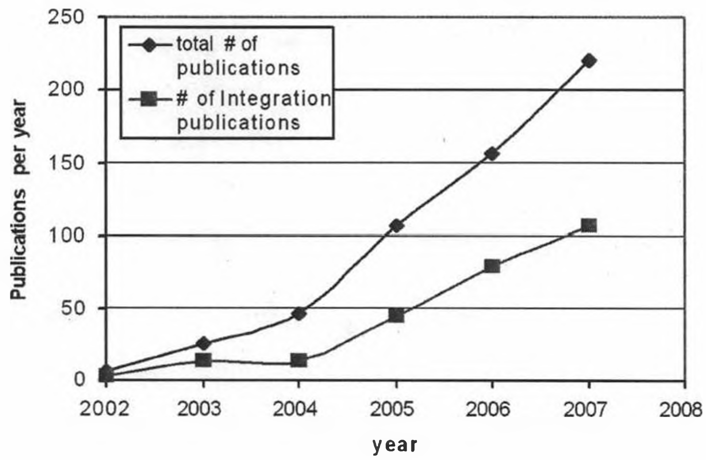
- (U) Assuming these and other unanticipated technical advances in rectifier, power management, antenna, nanoscale electronics, and adaptive radio technologies, it may be possible to perform RF energy harvesting in a large percentage of urban areas with antenna areas <1 cm^2.

12. (U) Integrated power management

(U) Active autonomous platforms are of utility only when integrated with components that provide energy. Most current technologies rely on batteries alone to provide power, however often it is desirable to increase the lifetime of the system through the integration of an energy harvester. This requires two main challenges be addresses independent of the harvester technology implemented: (1) electrical compatibility, and (2) physical integration. The electrical compatibility of the energy harvester with other components requires that the supply and demand voltages and power budget match, which can severely limit the technologies that can be paired. Additionally, the complexity is often compounded by mission needs for short duration, high current draw situations, e.g. RF communication, and / or the dynamic power output of most energy harvesting systems. To address these issues research efforts are currently focusing on integration of harvesters with energy storage, batteries and super capacitors, and on power control circuitry. Physical integration of individual components with energy harvesters has the same challenges associated with any fielded system, e.g. vibration, moisture, and temperature survivability. However, for systems where size and / or weight are critical parameters, such as motes, standard fabrication techniques are not feasible and new techniques must be developed to integrate and package sub-millimeter systems.

(U) Energy harvesters in watches have been commercially available for over a hundred years with Abraham-Louis Perrelet being credited with inventing the first self-winding mechanism in 1770 for a pocket watch. These early watches used a pivoting eccentric weight that winds a spring where the mechanical energy is stored, a technology still in use by Rolex and a few other high-end watch manufacturers. However, modern watch efforts have focused on energy harvesters that produce electrical energy. Two systems in recent production are Citizen's eco-drive, and the Seiko Thermic. The Citizen eco-drive uses an amorphous silicon solar cell to charge a lithium-ion battery; where as the Seiko Thermic uses a thermoelectric converter to provide electrical power. It is worth noting that the Seiko watch only had a very limited run due to the high production cost, whereas the Citizen photo-voltaic technology is still in production.

(U) The use of energy harvesters integrated into clothing is also an area of significant research in both the public and private sectors. The practical power limit for these types of devices is typically a few watts driven by the desire prevent these systems from being an encumbrance to the wearer rather than a person's power production limit. One commercialized integrated systems is Nike's Nike+ product line, where an RF transmitter, primarily powered by battery, send signals from a piezoelectric accelerometer to an IPOD. The next step in the evolution of a product such as this is to have the harvester provide the majority of the energy, which is being actively researched by groups such as MIT's Media Laboratory.



(U) Figure 19: Plot of the total number of energy harvesting publications (blue) compared to the number of publications where sensors were integrated with energy harvesters (red).

(U) The integration of energy harvesting components is the single larges component of the energy harvester publication portfolio examined in this study. Figure 19 is a plot of the total number of energy harvesting publications per year (blue curve) overlaid with the total number of publications addressing integration of sensors and energy harvesters (red curve). As the plot shows, the number of integration publications has grown consistently with the total number of publications, with the percentage remaining nominally 50% over the years of interest. The remainder of this section is a breakdown by geographic region of these research efforts.

(U) 12.1. Integrated energy harvesters and sensors

(U) In exploring the current state of the art in integration of energy harvesters we focused on the integration of sensors with an energy harvester. This pairing was chosen because energy harvesters in active autonomous platforms are typically, though not exclusively, used in applications where monitoring of the local environment is key. Also, as shown in Figure 1, approximately half of the publication since 2002 in the area of energy harvesters addresses integration with sensors indicating that the research community views this as a critical pairing. These works include systems where the energy harvester also acted as the sensor, e.g. vibration sensors, and systems where the harvester and sensor were discrete systems, e.g. glucose fuel cells for medical implants. As an important aside, it is apparent that integration research in the US has not seriously focused on the integration with energy storage in microsystems. This is likely the result of the inability to fabricate energy storage systems with current technologies that meet the power and energy density needs of these systems in the desired size scales.

(U) Table II is a break down of the number of publications by region. There is little

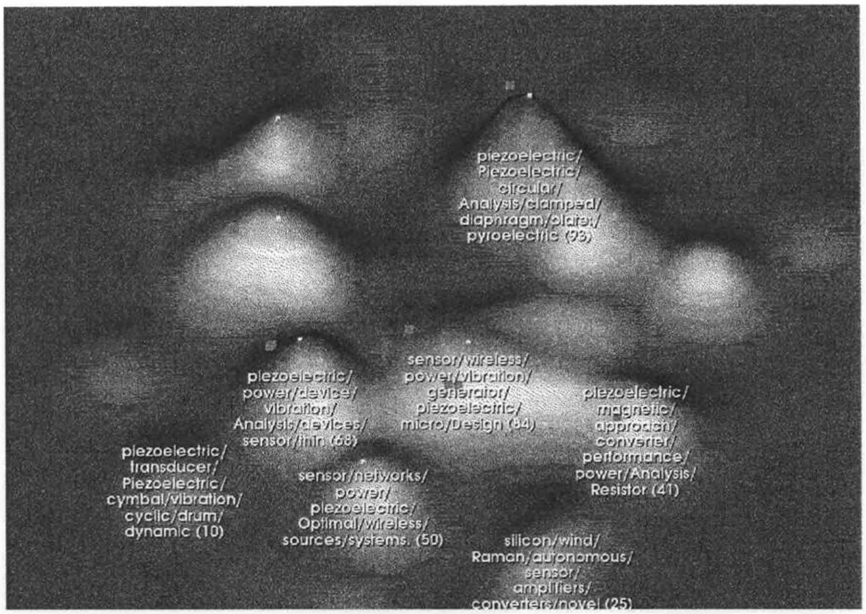
(U) Table II: Number of publications in the open literature where sensors were integrated with energy harvesters. Note in the Asia regions, the PRC was the single largest country publishing in this area.

Region	Publications since 2002	% of integration publications
Europe	76	28
USA	72	27
Asia	39	14

difference between the Europe and the USA in terms of the number of publications, with Asia being only half of the number of publications of Europe or the USA. Of the Asian publications, the People's Republic of China represented the single largest contributor.

(U) Over the time period examined, 23 of the US publications were by M. Srivastava's group from the University of Californi a Los Angeles's electrical engineering department. This group, partially funded by DARPA, has published numerous papers on the design of energy management in wireless systems stressing adaptive power management techniques, which form the bases of the Heliomote technology. The Heliomote technology used COTS parts hand assembled into stand alone unit. This technology should be considered mature and is also readily available in the open literature. Another notable technology is one sold by Microstrain, Inc. This product uses an imbedded wireless strain sensing node with a vibration energy harvester for energy production. Both the Heliomote and the Microstrain products are the size of the proverbial breadbox and represent immediately available solution. However, it is not clear that either of these technologies are scalable. Current US efforts in smaller scale systems have not been commercialize in any meaningful fashion and remain lab curiosities, e.g. U.C. Berkley's Smart Dust and Yale's Smart Sand. It should also be pointed out that the Center for Energy Harvesting and Materials (CEHMS), a collaboration between Virginia Tech, Clemson University, and UT Dallas, mission statement includes the study of integration of energy harvesting systems. However, CEHMS's publications did not represent a notable contribution to the area of sensors combined with energy harvesters efforts to date appear to be primarily on energy harvesting components rather than integrated systems.

(U) The published European research efforts are not clearly focused on a single issue. Rather their efforts span from wearable energy harvesters to semi-passive RFID's. There does not appear to be a single research effort that stands far ahead of the others in terms of the publication activity. However, wearable electronics / energy harvesters appear to have the most active community publishing.



(U) Figure 20: Technical landscape of the People's Republic of China investment in power integration research.

(U) The research efforts on integrated energy harvesters in Asia appear highly advanced based on the publication records. Two universities efforts, both based in Hong Kong, stood out and are discussed here. The first group is from the Chinese University of Hong Kong, which was very active in 2004 with a series of publications where they demonstrated a piezoelectric that acted as both the sensor and energy harvester for the system. This group measured the trade-off between optimizing their system for the two different functions and proposed an optimum compromise system. The other notable group is from Hong Kong University of Science and Technology and has been actively publishing since 2006 in the area of micro-solar power management systems. In this work, they fabricate an integrated test chip using 0.351 micron technology that provided experimental verification of power management methodology for ultra-low power harvesting.

(U) 12.2. Anticipated Research Direction and Comments

(U) A substantial trend in the integration of energy harvesters with other devices has been the push to reduce the power needs of the powered systems. For example, in the summer of 2008 the University of Michigan demonstrated the Phoenix micro-processer that operates on 30 pico-watts and has a foot print of 1 mm^2. In 2006, Hewlett-Packard unveiled a 1 mm^2 RFID system, called the Tomato seed, which has 4 megabits of storage. The key to the future success of these systems will be the physical integration with energy harvesters and energy storage systems. Based on the current published literature, it is unlikely that within the next 2 to 3 years there will be any delivered commercialized systems of this type. A more realistic time frame is 5 to 10 years. The main technical challenges center on the integration of the energy storage device. These challenges are the effective packaging of ultra-small (cubic mm) sized batteries and the lack of a consensus over best energy storage technique to use at this size scale.

(U) Based on the publications and commercialized products that are currently available, the two countries leading the research in integration of energy harvesters with sensors and microprocessors are the US and the PRC. In larges scale systems it appears that the US has the lead in the electrical integration and networking, whereas in small scale systems the PRC appears to lead in integrated harvesters and microprocessors / energy management. This leads to the observation of two different strategies; the US desire to demonstrate fully functional systems and then use that learning to shrink to smaller systems, whereas the PRC's focus on limited functionality but with the desired final size scale. An overview of the landscape of the PRC's focus in terms of research areas shows this to be the case, and is shown graphically in Figure 20.

13. (U) General statements for commercial utility and rise of harvesting in the near future

(U) There are, of course, some synergies between these technologies and the commercial world, so that development of a systemized energy harvester does not necessarily mean that the system has only military applications. Several excellent review articles on human source harvesting[64,65] as well as overall reviews by Thad Starner and Joseph Paradiso provide excellent insight into power sources for medical and wearable applications. A similar review to the Starner/Paradiso review (Appendix A of this report) can be found from the Netherlands (Appendix B). Photovoltaic applications and investigation will almost assuredly continue to have worldwide investment that will increase as domestic and foreign sources of traditional (coal, oil, natural gas) energy resources go into decline in the next decade. Biological harvesting systems, both for medical and for portable applications, will also likely continue to grow, funded mostly through academic research for implantable applications. The other methods, being mechanical, thermal, RF, and nuclear thermoelectric, will likely continue to stay at an academic level for the next decade, as the energy density and the applicability of these systems is, at current, relegated to mostly niche applications for long duration power away from direct access to fuels and grid based power.

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