

Can Energy Harvesters Drive Coin-Cells Obsolete?

Abstract

The EU reports 225,000 tonnes or eleven billion small batteries are disposed of every year in Europe or about 21 batteries per head of population. Their report states 24% are coin-cells which translates into five coin-cells per person per year to buy then "recycle". They also report that only about 5% of these batteries are disposed of in an environmentally friendly manner.

What if we could remove a whole class of batteries from the consumer market world-wide?

Well, we can and in this note we briefly show how. We compare the ubiquitous CR2032 coin-cell in your kitchen scales and most of your children's toys with an Energy Harvesting prototype which replicates their use-case behaviour. We show that we have a viable alternative to coin-cells then discuss how we might capitalise on this opportunity.

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Why Electromagnetic Energy Harvesting?

Traditionally environmental energy harvesters¹ have been sidelined when designing small consumer products due to the erratic nature of their energy availability whereas chemistry based cells have a probability of power being available during their operational life that approaches unity. However, after this period the probability of power being available drops off to zero. For light based Energy Harvesters the probability of energy being available (particularly when harvesting solar) approaches 0.5 over eternity, world-wide.

To explain: consider that every point on the earth's surface receives 6 month's insolation per year. Inconveniently, this comes in one six-month long "day" at the poles. However, since we are considering consumer applications here we can say that most consumers live between 50 degrees north and 50 degrees south, we can reduce the problem to an 8-hour day and 16-hour night in most places for most use-cases.

Therefore, if we can harvest sufficient excess energy to run our application through the dark we can smooth out the erratic nature of energy availability typically seen in solar energy harvesting.

What are the implications of the probability of power being available for 50% of all-time? With the "right" components we might have a product that works well beyond our own lifetime, which is quite a game-changer for product specification and new product introductions. It would open a new market where it becomes possible to create products that are available over the whole of a human lifetime, or more.

Added to which there would be no need to dispose of any environmentally threatening chemistry and conveniently the solution to end-of-life disposal issue for small batteries comes for free!

The above observations have been self-evident for some time - particularly for kW solar installations, however for micro-power applications such as small battery operated consumer products there have been two significant blockers to wide adoption of such electromagnetic energy harvesters: most existing components suffer from zero-power self-start "hysteresis" since all but a few technologies need a certain level of input energy to operate. This energy-gap effect might be described as being normally off at rest.

The second reason is that whilst energy can be stored to overcome that energy-gap when at rest, most secondary storage solutions tend to consume more energy due to internal self-leakage than can easily be generated by compact electromagnetic sources such as those suited to small handheld consumer products. At best, compact energy harvesters can only be considered as part of a battery augmentation strategy and the battery chemistry remains present in the product in some form.

¹ See "[Appendix 1: Energy Source Technologies](#)"

The first of the above reasons may be addressed through use of zero-bias devices - these are on at rest (that is, not consuming power). Applying an energy source to them progressively turns them off (the age-old Gunn-diodes as used in hand-held radar units are a good example). Once these devices are configured as an oscillator, their potential energy can be multiplied up to useful levels for standard electronic systems through resonance and impedance multiplication. We have demonstrated start-up levels in the single mV range which is well below the 300mV levels demonstrated by currently available solutions. At low light levels such as a cloudy winter's morning (at 300lux) we regularly generate 6uW for an active area of one square-centimetre. A level which (once the second issue is solved) is sufficient to run a state-of-the-art microprocessor in its low power mode, once that energy has been accumulated over a 3:1 accumulation-to-run period.

The storage issue may be illustrated by the above mentioned CR2032 coin-cell at its extremes of operation: at one extreme it might be called on to dump all 1800 joules in a single one-watt thirty-minute splurge (which equates to a "shorted" cell) and is a valid use case since this does happen and cell must survive such abuse in a benign fashion. At the other extreme the cell may be left to power a 57uW application continuously over one year of operation. We might even extend the perceived operational time to ten years by keeping the load dormant for 90% of the time (ie: the application runs for 10ms then sleep for 90ms) - then we can create an apparently "always-on" application that seemingly runs non-stop for 10 years. At that point the battery needs replacing or if in a sealed product, the whole unit must be discarded - hopefully in an environmentally friendly manner.

For light-based electromagnetic harvesting, we have two "aces up our sleeve": most consumer applications are co-located with humans who generally augment their daily quota of light with artificial sources such that we might expect 16 hours of light availability per day, 365 days per year. The second "ace" is that light levels can vary by as much as 400:1 through summer days down to 10:1 through winter days. So, if our storage mechanism can handle a minimum of eight hours of storage and can accumulate all of the minimum available daily energy, we then have a very high probability of making a seemingly "always-on" application using an energy harvester.

Thus, our challenge has moved from "... can we harvest enough energy?" out to "... can we store enough energy?".

If we figure on a minimum of 4 hours at 3000lux and we can accumulate 0.864 Joules of energy and figure the other 12 hours being at 300lux, we might then be able to accumulate a further 0.259 Joules of energy making a total of 1.123 Joules. Compare this to the CR2032 cell's daily budget (as in the one year on use-case) of 4.932 Joules. Whilst this seems that we have one quarter of what is needed for continuous operation, we can borrow from the technique of extending the CR2032's usable life from one to ten years outlined above. This means that on a typical winter's day we can accumulate approximately two and a half day's worth of apparently continuous operation.

We could then run our "always available" application until the next most vulnerable component in the system fails and this might be twenty to fifty years (or more) later? We shift the end-products' aging vulnerability away from the battery chemistry and manufacturing process.

Rather we have changed useable life to be dependent on that nemesis of Energy Harvesting: internal leakage. But before we leap into that subject, remember that even though leakage will deplete the energy store that storage will always recover autonomously once the energy-harvesting activity recovers.

Whilst we can accumulate enough energy for two and a half day's operation, once the energy-harvester falls into darkness any practical storage element will self-deplete due to leakage inherent in the storage components' manufacturing processes - which we have already noted are substantial in chemical cells. One alternative is to use dielectric storage in the form of low-leakage high-voltage film capacitors. Their leakage specification is generally wrapped up in a time constant between the bulk capacitance value and the leakage of that capacitance. Generally, the best film capacitors are rated at about 5000 seconds at 100 degrees Celsius. By derating the temperature, we can improve this by approximately one order of magnitude per 25 degrees. Unfortunately, these capacitors tend to be physically large and can be expensive. Through judicious selection of manufacturer, it is possible to get reasonable performance from ceramic capacitors. By noticing that if the current through a ceramic capacitor is de-rated, we can actually put about 2.5x the rated voltage onto the capacitor so we can use smaller capacitors however, the leakage also goes up. By noticing that most ceramic capacitors are specified at up to 125 degrees Celsius, we can de-rate them to achieve lower maximum expected leakage. Put together we can use 50V capacitors to store 125V then run them below 75 degrees Celsius.

By dropping the unit's operating temperature to 50 degrees Celsius or less, we might reasonably expect the rated time-constant for the best ceramic capacitors at 500 seconds to increase up 50,000 seconds (13.9 hours) or so.

Notice that this depletion curve describes an R-C type exponential decay. Therefore, at one time-constant, 13.6% of the original energy remains. After two time-constants only 0.2% of the initial energy remains. Even so, this is still 21mjoules or 343 seconds (or 5.7 minutes) of continuous operation left.

Enough time to sound an alarm to attract the attention of a nearby human who might then place the unit in a well lit area and it would only take about 40 seconds to completely replenish the above one joule of energy when placed in direct sunlight - something the button cells cannot achieve.

To store 1.123 joules, we would need a 160uF capacitor charged to 120V then figure on an end-of-discharge voltage of 20V to allow some over-head for the following circuitry. As the charge and discharge processes must be powered from the energy harvested, the design of the boost- and buck-converters need are exacting - particularly in achieving the very low leakage performance needed to preserve the leakage performance of the storage capacitors. Surprisingly, it is the boost converter that presents the most difficult challenge as this must be a resonant converter to achieve the very low losses needed to achieve reasonable (ie 60% or better) efficiency in storing our hard-won energy. To efficiently recover this stored energy, we have conceived a novel ("pat-pending") buck converter capable of independent single pulse operation.

What if we could create an energy store that does not age and where the probability of its availability converges to unity instead of zero and is free from end-of-life disposal issues?

We can and it is a game-changer: such a disruptive enabling technology allows us to design completely new products like always available monitoring systems that can run well beyond the life of any commercially available battery technology. The idea that an electronic system may still be completely functional well beyond one's own lifetime is quite a sobering thought.

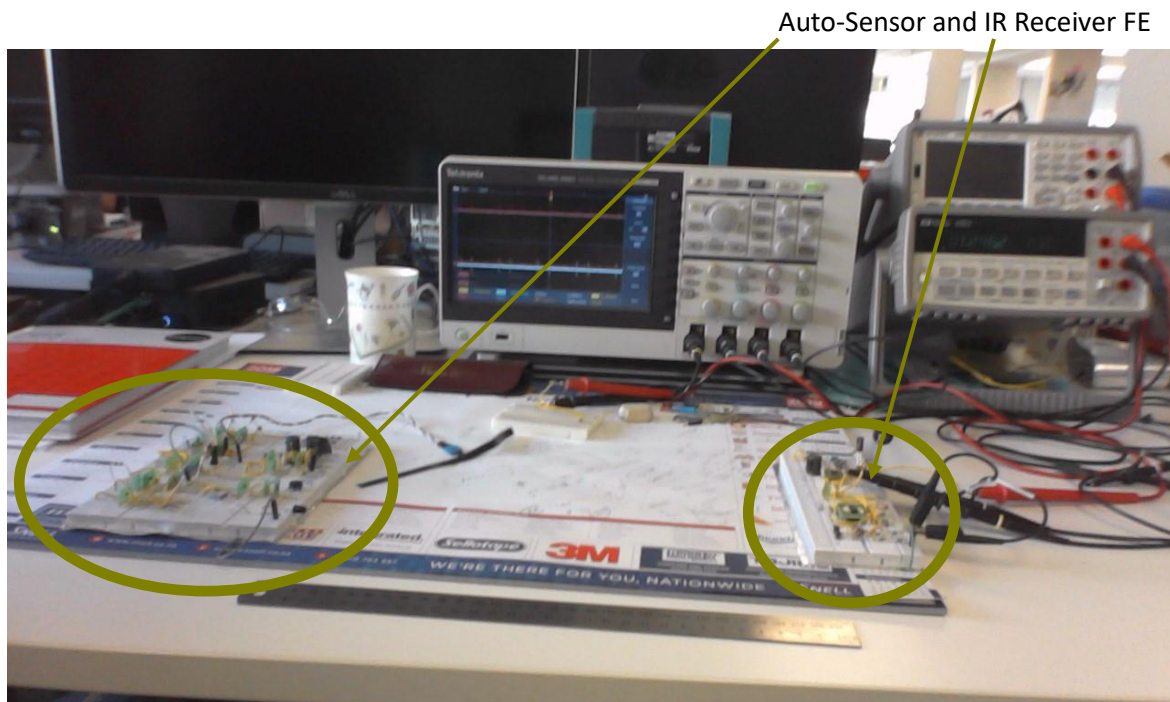
Similarly, once we have a system that is completely self-powering for greater than the planned life of the product, we can seal the supply permanently. This allows us to create yet another class of new products such as those containing a system that can be integrated into wearable products and clothing that can be machine washed - particularly important for sports-wear where it is exposed to sweat and other contaminants.

Our Technology

We already have an Autonomous Sensor Prototype on-the-bench that has been shown to be self-powering from ambient light down to 60lux in a poorly light lab in the morning. We can demonstrate data transfer via an Infra-Red over-air Data-link to a self-powering Receiver up to 1 metre during sunny afternoons at 300lux in that same lab. The sensor measurement front-end for this Autonomous Sensor has been migrated into a customer's product and has been put to fabrication. These two units can readily be migrated into a form-fit end-product prototype into a sales demonstrator capable of measuring and displaying the output from any capacitance based sensor.

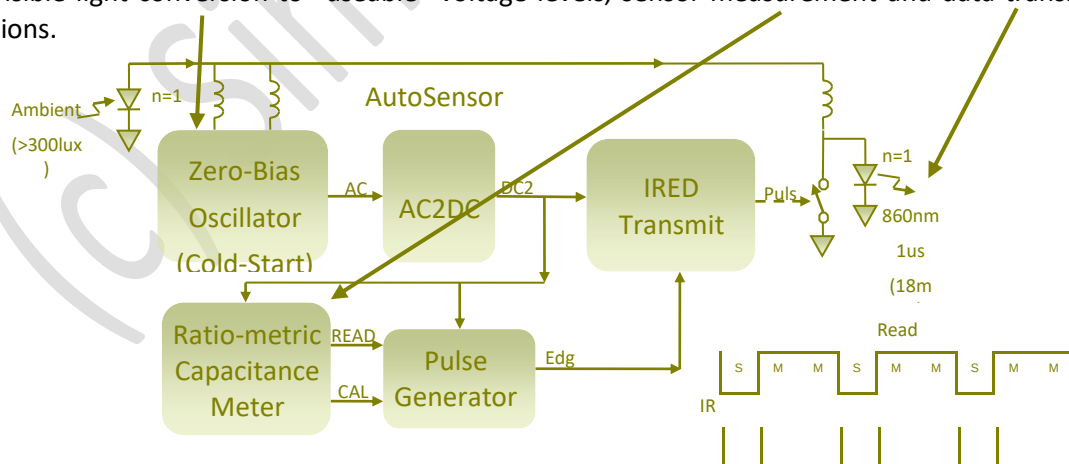
The above front-end design has been exhaustively simulated over a wide range of use cases and is expected to go into production with a minimum of issues and will be the first product of a "Right-by-Design" strategy that we have developed.

Presently we are migrating the IR-data receiver onto PCB and concurrently developing a minimal embedded software to present the capacitance of the above sensor on an E-paper LCD display, so creating a stand-alone autonomous sensor with a remote hand-held display unit. To avoid historic problems with batteries and power supplies, both of these instruments have been designed to harvest sufficient power in typical Lab ambient light levels. As such they form the enabling core of a revolutionary new smart-sensor concept being a truly wire-less and battery-less system. The Autonomous front-end capacitance measurement system may be used with any capacitive sensor and forms a significant piece of core Intellectual Property. Both of these circuits exist and form our bench proof-of-concept prototype:

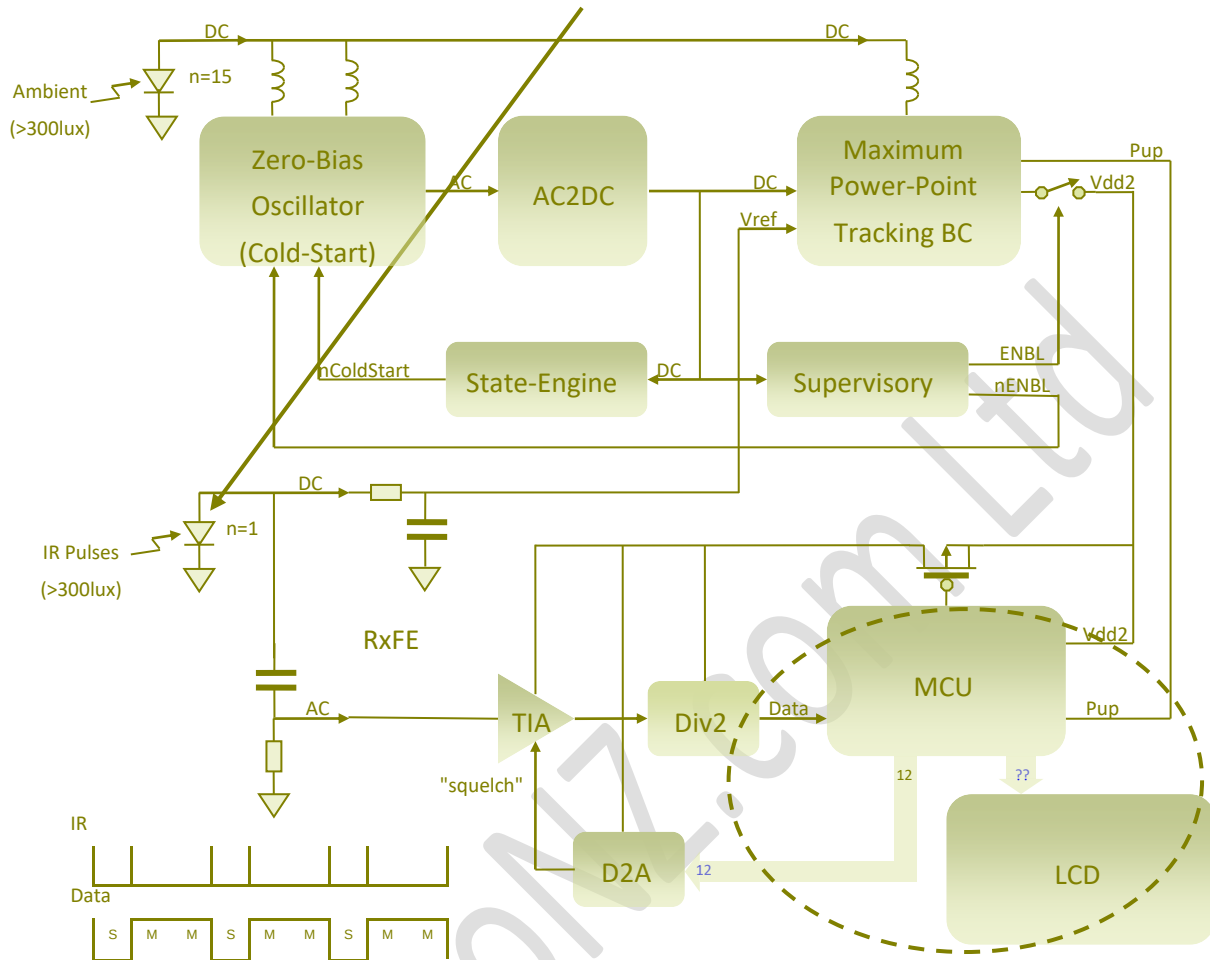


Autonomous Sensors

Autonomous Sensors free people and things we wish to be mobile. Sometimes these are remote so need to be maintenance free. Our proposed Auto-Sensor consist of three parts: Ambient Infra-Red or Visible light conversion to “useable” voltage levels, sensor measurement and data transmission sections.



Necessarily the IR pulses transmitted must be received and may be done as follows:



The Auto-Sensors implement a simple point-to-point protocol which favours an un-encoded broad area physically mobile link (between the two circles on the photograph above) which can operate up to 3 meters in high ambient light levels (>3klux) using IR-LEDs or up to 500m with IR-VCSELs. This type of link enables stand-alone simple single channel products such as wrist-band measurement systems where the photo-diode array can be embedded into the wrist band and the supporting electronics may be encapsulated in an optic much as wrist-watches are presently manufactured.

680nm Infra-red over Polymer Optical-Fibre

Multi-point to multi-point operation might be done through use of a fibre-optic Personal Area Network merged into a host garment which might targeting use as a Virtual-Reality Suit. This would demonstrate how the Auto-Sensors and their Energy Harvesting ability are key to enabling an on-suit PAN and is key to concentrating sensor data into a low-latency high-data-rate bit-stream which might then be fed into a 4th or 5th generation mobile phone to enable high-speed low-latency cloud processing applications. These in turn may earn royalties from data-mining applications such as medical studies on the effect of prolonged use of VR kit on game players. The key to enabling such

an application is to "go-on-chip" to reduce the footprint of the interconnecting nodes within the PAN and would form the second phase of development within this project.

To affect a rapid time to market and to reduce the complexity (and cost) of a bespoke suit of sensors we can avoid the "Bluetooth data bottle-neck" typically seen in most offerings, by going directly to the host mobile phone via the recently released USB-C protocol as interface between the multiplexer hub and that phone and so establish a low latency link to the Internet. Importantly this connection also allows us to power the hub from the phone (rather than relying on the somewhat limited capacity of on-suit batteries) and will future-proof the end product(s) through use of 4G and soon to be released 5G mobile phones. More importantly it removes the data-pipe bandwidth limitation we have seen elsewhere through using the Bluetooth link to the mobile phone.

Similarly, if we were to sew a fibre-optic network into the suit this reduces the energy constraints imposed on the Autonomous Sensors and may possibly enable sensors powered by body heat alone. We have already seen this ability in the aforementioned bench proof-of-concept prototype.

Unfortunately, we may not be able to generate any strong stand-alone patents from the fibre-optic network (as it is old technology) however, applying it to "wearables" may give us some weak conditional patents by virtue of its application to a new market segment and possibly for derivative attachment methods evolved.

The use of fibre-optics is low risk as it is a well-established technology. The recent development of Polymer Optical Fibres such as Mitsubishi Rayon's CK-20 (available in 6km spools at NZ\$870) means that the cost increment for using this communication method is minimal and fibre solves many of the Electromagnetic Interference issues that frequently hamper pre-production ramp-ups. Some development will need to be done for mechanically terminating the fibres onto the PCBs and on its attachment to the suit - particularly if we wish to make these suits machine washable. Notice that these fibres might be stitched in a serpentine fashion since they can be as thin as 250um in diameter and can traverse a 10-15mm radius curve comfortably. Serpentine stitching may allow the fibres to concertina within the host suit's weave as that host moves. The method would be fully patentable once determined. Use of this fibre allows us to vastly reduce the energy needs of the Auto-Sensors (so making them physically smaller) as the path-loss for these fibres is around 0.25dB per metre (compared to -40dB/m for the free space loss for a typical broad-beam IR LED²) meaning that the link requires much less energy to communicate effectively, so can operate in lower light levels.

Importantly, fibre optical coupling (and the use of an IR-link) removes the galvanic connection that causes so many of the noise issues we encountered when testing a PAN - entirely. Through use of one fibre per sensor the need to code each channel's output is also removed - so the need for a microprocessor per node to code the transmission and its incumbent power consumption are removed too. Encoding of the signal before sending off the suit may be dealt with at the data multiplexing stage in the central hub, pre-mobile-phone.

² The Auto-Sensors' LEDs transmit 18mW in a typical lab ambient. We can upgrade to 100mW VCSELS (a type of Laser which over a few tens of metres would allow us to power the sensors through a Polymer Optical Fibre which in turn when sewn into the suit seams might also form a Personal Area Network within that suit.

Potentially we might develop reverse powering of the sensor electronics when there is no ambient IR available to the Auto-Sensors by driving IR back down the fibres from the multiplexer hub. This versatility might in the future be further developed to allow us to do a bidirectional hand-shake and possibly (in future re-developments) place a microprocessor at the sensor end of the fibre and power it through that same fibre for some as yet unknown application.

Conclusion

We have proposed a path to enabling battery-chemistry free long-life Autonomous and Smart-Sensor products targeting the enabling a wireless and battery-less Internet-of-Things. We can now answer the “last metre” challenge whilst maintaining full consumer mobility independent of the product constraints created by batteries and cables. Here we have under-take to migrate our existing bench solutions into a market ready ASIC suited to powering wearable Personal Area Networks.

We have also proposed a simple solution for creating Autonomous Sensors by tapping into the use of ambient light levels around humans – we need light and if we can see clearly then ambient light levels are sufficient to provide enough energy to quantify then transfer sensor data the critical few metres to a mobile phone which can then transport that data to the “cloud” for further processing, data-mining and the sale of derivative analytical data to Internet entities.

In this note we have outlined the challenges in creating an always-ready energy harvesting source capable of replacing button-cells in portable and handheld consumer-products then briefly looked at solutions for those challenges. Interestingly it is the storage of the harvested energy that presents the greater technological challenge where the management of leakage in that system dominates efficiency in the Energy Harvesters and their sources. We see that perhaps the greatest benefit from light based energy harvesting is in the probability of power availability approaching 0.5 over eternity - whereas other energy source approach then hit zero in a few tens of years at most.

We see our solution as a game changer since it opens the door to multi-decade fully autonomous applications with the added benefit of removing a whole class of environmental pollutants for free.

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Appendix 1: Energy Source Technologies

In the following table we see that Electromagnetic Energy Harvesting and in particular Photoelectric Energy Harvesting compare well as an "off-grid" energy source against other presently available technologies:

Class	Type	Maturity	Robustness	Complexity	Cost	Reusable	Bulk	Autonomous	Sealed	Noise	IR signature	Energy Density			Note
												Whr/ltr	MJ/kg	W/ltr	
electrochemical	battery	maturing	excellent	low	low	yes/no	low	yes	yes	none	low	600	1.0	459	Li2S specific gravimetric energy density = 2.6kW/kg
thermoelectric	Seebeck (TEG)	poor	excellent	low	moderate	yes	heatsinks	yes	yes	none	high	670	---	340	includes wind cooling
	fuel cell (methanol, hydrogen)	poor	moderate	moderate		yes		no	no	some	high		18.8E-3		30 sec startup, vibration vulnerability
nuclear	betavoltaic	infancy	excellent	low	high	no	low	yes	yes	none	none	876	31.5E-3	0.004	Tritium - Silicon Carbide, > 25 years, ~1uA
dielectric	ultracap	young	excellent	low	low	yes	low	yes	yes	none	none	9.6	18.0E-3	68	NB: not supercaps (which are electrochemical)
photovoltaic	solar cells	reasonable	moderate	low	high	yes	moderate	yes	yes	none	high	---	---	3.0	$\eta=30\%$ at 500suns, 17.5W at 2.5V (die: 1cm x1cm x1mm) lense (22cm x22cm, focal length 12cm)
mechanical	heat engine (diesel, petrol, gas)	mature	moderate	high	moderate	yes	moderate	yes	no	high	high		2.16		petrol engine at 20% efficiency
	mems turboelectric	infancy	poor	moderate	unknown	yes	low	yes	no	moderate	very high		43	680	2kWhr/kg, 600degC, audible (8kHz) bearing issues
	gyroscopic		good	high	moderate	yes	moderate	yes	yes	some	low		11.4E-3		Automotive: KERS (braking) safety/weight issues
	gravitational (hydro, pendulum)	mature	good	high	high	yes	high	yes	no	yes	none		1.0E-3	8.8	for h=92m from 9 bar osmotic pressure (see below)
	pneumatic storage (via turbine)	young	good	moderate	moderate	yes	high	yes	no	yes	low		180.0E-3		1m^3 air into 5l Kevlar bottle at 200bar 60% eff.
	kinetic (spinning pendulum)	mature	excellent	moderate	moderate	yes	low	yes	yes	low	none	---	---	1.0	Personnel: wrist-watch (x10 at ankle)
	wind (rotor, turbine, turbosail)	maturing	good	high	high	dependent	high	yes	no	yes	low	---	---	0.60	Magnus Effect (turbosail)
	clockwork	mature	good	moderate	moderate	yes	moderate	yes	yes	low	none	318.0E-3	240.0E-6	0.47	Patent no WO 2005115091 A2
	vibration (magneto-Inductive)	young	moderate	moderate	moderate	yes	moderate	no	yes	yes	none			0.23	100mW at 0.25g(rms) and 65Hz, 100uF storage
piezoelectric	vibration (electro-Inductive)	young	moderate	high	moderate	yes	moderate	no	yes	yes	none	416.7E-6	---	0.36	30mW at 3.2Vdc and 1kHz, supercap storage (1.5J)
chemical	osmosis(fresh/salt water)	infancy	good	low	moderate	yes	high	no	no	yes	none	0.81		8.8	Statkraft - depends on hydroelectric conversion
biological	methane (via thermoelectric)	maturing	moderate	high	moderate	dependent		no	no	some	none			68	via fermentation
	sandwich	mature	poor	low	low	no	moderate	yes	no	some	none		5.42		Why we have evolved to eat sandwiches

PE-EM harvesting has an "Achilles' heel" in the need for storage overnight, during bad weather and through winter. If we consider that every region of the earth receives 6 months of insolation per year (even if it is during a "6-moth-day" at the poles) we see that if we limit our energy consumption to less than the average energy per day for the darkest day, we might then store sufficient energy for the local worst-case night too.

By regarding a solar array as a collector of nanometre wavelength electromagnetic energy we see that photovoltaic sources are a special class of Electromagnetic Energy Harvesters that includes RF Energy Harvesters which are cm to metre wavelength EM harvesters. RF-EH based on WLAN technologies have typical Energy Densities between 30nW to 100nW/cm² at 1 to 3m from a PC or WLAN router. Typical ambient light levels in an "average" room are in the 40nW/cm² (50lux) to 400nW/cm² (500lux) range. Direct sunlight varies from 1mW/cm² (1.23klux) for weak winter's sun at a latitude of $\pm 50^\circ$ through to 140mW/cm² (1.7Mlux) for mid-summer tropical sun. Low light levels may be increased through judicious use of simple passive reflectors. For wide-range adoption systems must cope with extremes of the sun's range.