Energy Harvesting

A Sagentia white paper

Contents

1. What is energy harvesting?

Energy harvesting is commonly defined as the conversion of ambient energy into electrical energy[1]. This definition is too narrow. We define energy harvesting as "the collection and storage of ambient energy for on-demand, off-grid use".

The first definition considers only the transducer technology for energy conversion, and assumes that the energy must be converted to electricity. Our definition takes a broader, application centric view, where the transducer is one component of a complete system that provides power for those niche applications where other sources of energy are unavailable or unsuitable.

Ambient energy

Energy is all around us, in many different forms – thermal, chemical, electrical, mechanical and more. To make use of energy harvesting one or more of these energy fields must be present in the environment of interest, and there must be a suitable transducer to convert the energy.

Off-grid energy

Energy harvesting is used where another supply of energy is not available. Harvesters cost money, so it only makes sense to use them when it is too expensive or physically impossible to use other energy sources such as grid electricity or batteries.

On-demand energy

An energy harvester has to supply power when it is needed, not simply when it is available, and some form of energy storage is generally required to match the demand with the supply.

[1] Steve Beeby, in "Energy Harvesting Systems", published by Springer

2. Balancing the energy supply and energy demand

2.1 How much energy is available?

There are in principle many different energy fields available from which to harvest energy:

- Radiation (light, solar, cosmic rays, electromagnetic radiation)
- Thermal
- Mechanical (potential, kinetic, elastic, fluid)
- Gravitational
- Chemical (battery, fuel cell, fossil fuels, phase change)
- Nuclear
- Magnetic (Magnetisation, currents etc)
- Electric

In practice, many have no value for energy harvesting. Sound, cosmic radiation, atmospheric pressure variation and nuclear background radiation are universally present, but have almost no associated energy. Whether the other energy fields are usable depends entirely on the location of the harvester, and the list of useful energy types usually comes down to only one or two that are suitable for a given application in a given location.

Outdoors above ground, sunlight is a good source of energy with high energy density, and good predictability. Wind can be suitable for large enough applications that are high up enough to provide clear airpaths. Suitable temperature differences and vibrations are hard to find.

Indoors, artificial lighting can provide enough power for low power applications, such as calculators, but most other fields are not present or do not provide enough energy.

For vehicles and for industrial applications, machine vibrations and thermal gradients are often practical, since there are high temperatures and strong vibrations at known frequencies.

Human motion can be usefully harvested. Commercial products include the wind up radios, torches and phone chargers produced by Freeplay and others, and bicycle powered computing in India.

Table 1: Availability of different types of energy by location

Location \ Energy Source	Radiation	Wind	Sunlight	Artificial lighting	Human	Machine vibration	Tidal	Gravitational hydroelectric	Thermal gradients
Home / Office	✓			✓	✓				
Roadside	✓	✓	✓						
Bridge	✓	✓	✓			✓		✓ River	
Vehicle	✓	✓	✓			✓			✓
Pumping Station	✓	✓	✓			✓			✓
Oil Rig	✓	✓	✓			✓	✓		✓
Battlefield	✓	✓	✓		✓	✓			
Remote sensing in Antarctica	✓	✓ Winter	✓ Summer						✓

Back of the envelope calculations are the starting point for evaluating whether a particular energy type can ever provide enough power to be useful.

Table 2: Power available from different energy types

Source	Power	Notes
Cosmic radiation	0.1µW	Neglecting conversion inefficiencies
EM radiation	0.5 µW	10 x 10cm antenna 10m below a 10kV transmission line
Blood pressure	15 µW	Estimate of Southampton University hospital device
Machine vibration	5 mW	Perpetuum PP27
Indoor lighting	20 mW	5 x 5 cm solar cell
Human power	2 W	Winding a Baygen radio

2.2 How much energy is needed?

Different kinds of devices have very different energy requirements. A pacemaker requires only around five Joules of energy to operate for a day, whereas a desktop computer requires around 5 Megajoules – a million times more.

Some devices operate continuously, and the average power requirement is the same as the instantaneous power requirement. Other devices only need to operate intermittently – something that is on for 1 second, and then off for 9 seconds has a 'duty cycle' of 10%, and the average power requirement is thus only 10% of the maximum power requirement.

Whether or not a particular application can make use of energy harvesting depends on understanding its energy usage profile, and matching it with the energy available from harvesting. The table below gives figures for the energy and power requirements of a range of common devices.

Table 3: Energy usage requirements for a range of devices

Device	Power usage	Energy usage over 24 hours	Assumptions
Pacemaker	50 µW	5 J	70 beats per minute
Wired sensor	100 µW	10 J	1 Hz strain sensor
Wireless sensor	1 mW	10 J	Humidity sensor 10% duty cycle Zigbee radio protocol
Hearing aid	0.4 mW	70 J	Continuous
Mobile phone	15 mW standby 1.5 W transmit	5 kJ	23¼ hours standby 45 minutes talk time
GPS receiver	100 mW	8 kJ	Continuous
Low power computer	2W	60 kJ	8 hours on, 16 hours off
Laptop computer	15 – 25 W	500 kJ	8 hours on, 16 hours off
Desktop computer	50 – 150 W	5 MJ	8 hours on, 16 ours standby

3. When is energy harvesting appropriate?

3.1 Energy harvesting – a great solution

Energy harvesting is useful when:

- There is a match between the available energy and the energy needed
- Energy harvesting provides a benefit that is not achievable using batteries or grid electricity

Industrial condition monitoring

At a large oil pumping station, there are thousands of pieces of vibrating machinery. Knowing the operating conditions prevents failures and downtime, increases performance, and reduces costs. Wired sensor networks with miles of cabling can be expensive to install, and regular battery replacement for thousands of sensors is possibly even more expensive. A network of autonomous vibration powered, wireless sensors provides a “fit and forget” solution to the problem of data collection.

Powering remote infrastructure

A bus stop becomes more useful with an electronic bus information display. In remote areas, the information is even more useful, but grid electricity is expensive to install because of the distance, and single use batteries wouldn’t last very long. A generator would be noisy and need to be maintained. The most economical way to power the display and associated electronics is a solar panel and / or small wind turbine, together with a rechargeable battery and power management electronics.

Wireless sensor networks

Sensors rarely need much energy, so that readings of flow rate, temperature, humidity and pressure can be taken with small amounts of harvested energy. Transmitting those readings with newly developed efficient wireless communication protocols then allows that information to be used to save money by early diagnosis of problems and planned maintenance.

Wireless tyre pressure sensors

Monitoring tyre pressure allows for reduced fuel consumption and safer driving, but there’s no route for power cables from the battery to the tyres. Battery powered sensors with wireless data transmission don’t last long enough, so introduce a maintenance overhead for battery changing. Vibration energy harvesting from the regular impacts as the wheel rotates provides the best solution for powering the sensors.

Pipeline actuators

In an industrial gas pipeline, or a steam pipe distribution system, plenty of energy is available. Thermal energy can be harvested using maintenance free solid state thermoelectric transducers. The energy can be used to open and close valves without the need to run cabling to the actuators.

Other suitable applications

- Road / rail side traffic signs and monitoring using solar panels and wind turbines

- Remote environmental sensing
- Wind scoop on a lorry to provide autonomous container tracking
- Self powered wireless light switch for retrofit dimming without rewiring or battery replacement
- Solar powered mobile phone base station in Africa
- Keeping batteries topped up on small boats

3.2 Energy harvesting – not a great solution

Free energy often comes at a cost, and thinking through the complete system is key to determining whether energy harvesting is going to solve your power needs.

Green energy

A myth that keeps cropping up is that energy harvesting is a small scale demonstration of how we can collect freely available energy in the environment, and that in the future these same technologies will be scaled up and used to power our homes and businesses. This is false. With the exception of photovoltaic cells for collecting sunlight, the technologies are completely different.

	Energy harvesting	Green energy
Scale	Small	Large
Typical power	Microwatts to Watts	Kilowatts to Megawatts
Where is the power used?	Power is used by the same device that collects the energy.	Power is connected to a grid for use by many different devices.
Key drivers	Reduced total cost Safety Autonomous power	Reduced carbon emissions Energy independence
Most suitable energy fields	Sunlight Temperature differences Vibration	Sunlight Wind Tides Waves Gravity (hydroelectricity)

Collecting wasted energy

It's easy to do calculations showing how much energy is 'wasted' by the footsteps of a thousand people, but there's no business sense in powering ticket machines from the footsteps of commuters at underground stations. The harvesters will be expensive, and the amount of energy that can be collected is trivial in comparison to the energy used in lighting, heating, and ventilation. If cost savings are the goal, then optimising the operation of the existing building infrastructure and replacing old plant will pay back much sooner.

Self-charging consumer electronics

A mobile phone that does not need charging would be wonderful, but we're unlikely to see one any time soon, despite increasingly common press releases to the contrary. Existing pocket sized solar chargers will take a day to charge a standard phone, and you can't keep your phone in your pocket while it's charging. Vibration energy harvesters that exploit energy from walking can provide enough power for charging, but only while walking, and are not small enough to be integrated within the phone. Couple these limitations with the increased power consumption of smartphones compared to older phones, and the gap between the energy needed and the energy available is only increasing.

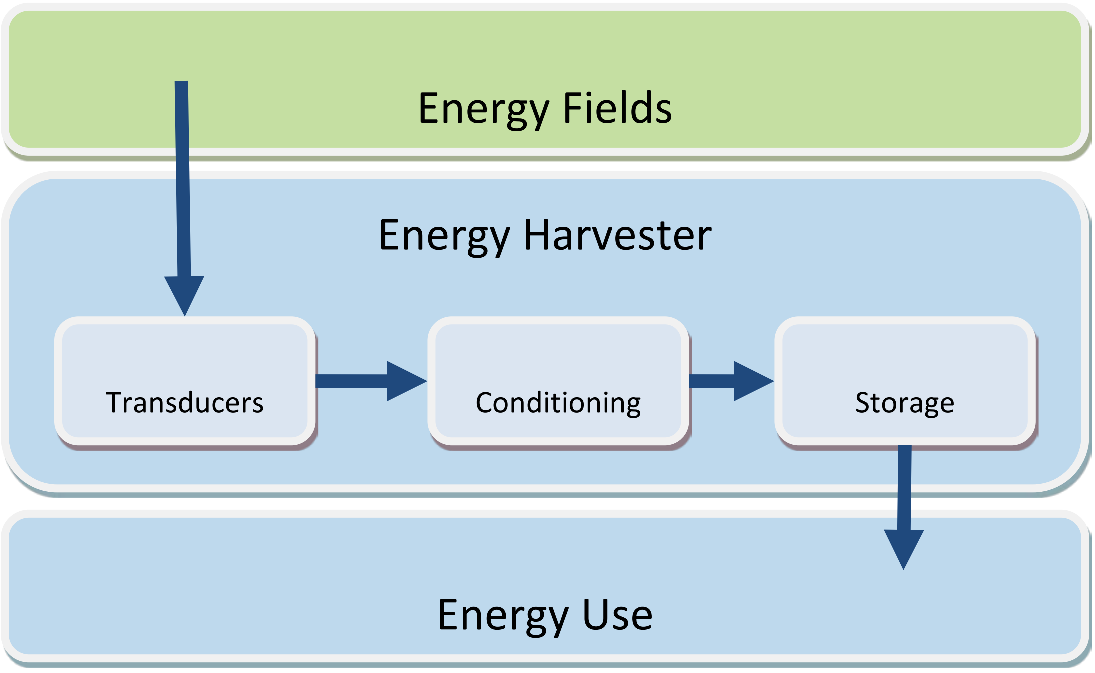
Extending device operating time

Our batteries don't last long enough. How about using energy harvesting to keep them topped up when the power runs out? In our experience this rarely works out. For an application where you can harvest energy faster than you use it, you don't need the battery in the first place and can rely entirely on energy harvesting. For an application where you use energy faster than you can harvest it, adding a harvester will only increase the lifetime of your device by a small fraction, e.g. 10% rather than the factor of two or more that you're looking for.

Drop in battery replacement

A battery powered device works wherever it is. Harvesters can only provide power when there's an appropriate energy field. Batteries are mature, low cost commodity items available from a large number of suppliers. Energy harvesters currently are immature, high cost, often bespoke, power solutions available from a small number of suppliers.

4. How does energy harvesting work?



An energy harvester comprises one or more transducers, power conditioning, and energy storage. These technologies work together to collect energy and deliver power to the device.

The transducer converts energy from one energy type to a second energy type, usually electricity.

Energy Field	Transducer	Notes
Light	Photovoltaic cells	Efficiency is typically 5 to 15%. It's not always best to have the highest efficiency, as a larger lower efficiency device may provide the power at lower cost.
Vibration	Linear electromagnetic generator	Harvesters can only harvest at a single frequency, and vibrations must be high amplitude. Power harvested is proportional to the vibrating mass in the harvester, so bigger is better.
Heat / Temperature	Peltier thermoelectric module	Power produced is proportional to the square of the temperature difference across the Peltier module, so big temperature differences (50C) are much more useful than small ones (5C).

Power conditioning is necessary because the natural output of the transducer can be intermittent, and at the wrong frequency, voltage and current to directly drive the device. A specialised DC-DC converter microchip takes in power from the transducer and outputs typically 3 to 5V, which can then be stored or used. The converter is an integral part of the system and requires careful electronic design to minimise power losses.

Energy storage is needed to balance the energy supply and energy demand. For applications where energy is used as soon it is collected (e.g. RFID and wireless light switches), no storage is needed. Usually however a rechargeable battery, capacitor, or supercapacitor is used. Batteries degrade over time, and so the lifetime of the storage device can often be the limiting factor in the overall lifetime of the harvester.

The device which uses the energy needs to be designed to work with energy harvesting as the power source. This entails reducing the power requirement to the absolute minimum necessary.

5. What is the future for energy harvesting?

Much of the effort in energy harvesting has focused on the transducer, to determine how to obtain as much energy as possible from a given energy field. As the technology matures the focus will shift to the new applications enabled by energy harvesters.

System integration

Plug and play energy harvesting will become the norm. In place of buying each component of the harvester and having to integrate them for each application, we are beginning to see manufacturers and consortia such the EnOcean group designing complete systems which allow a range of different harvesters (solar, vibration, heat) to be connected to common energy conditioning and storage units.

Low power electronics

New low power electronics will enable applications that were previously out of bounds. Large microelectronics companies such as Texas Instruments are developing specialised power conditioning chips that minimise power losses and make it easier for energy harvesting to be used as a source of power.

Low power wireless communications

Communications protocols that are explicitly designed to minimise the energy required to transmit data are being developed. Their deployment is hindered by the understandable nervousness in committing to technologies which may fall by the wayside in the competition for the best protocols. In time a consensus will emerge.

Smart cities

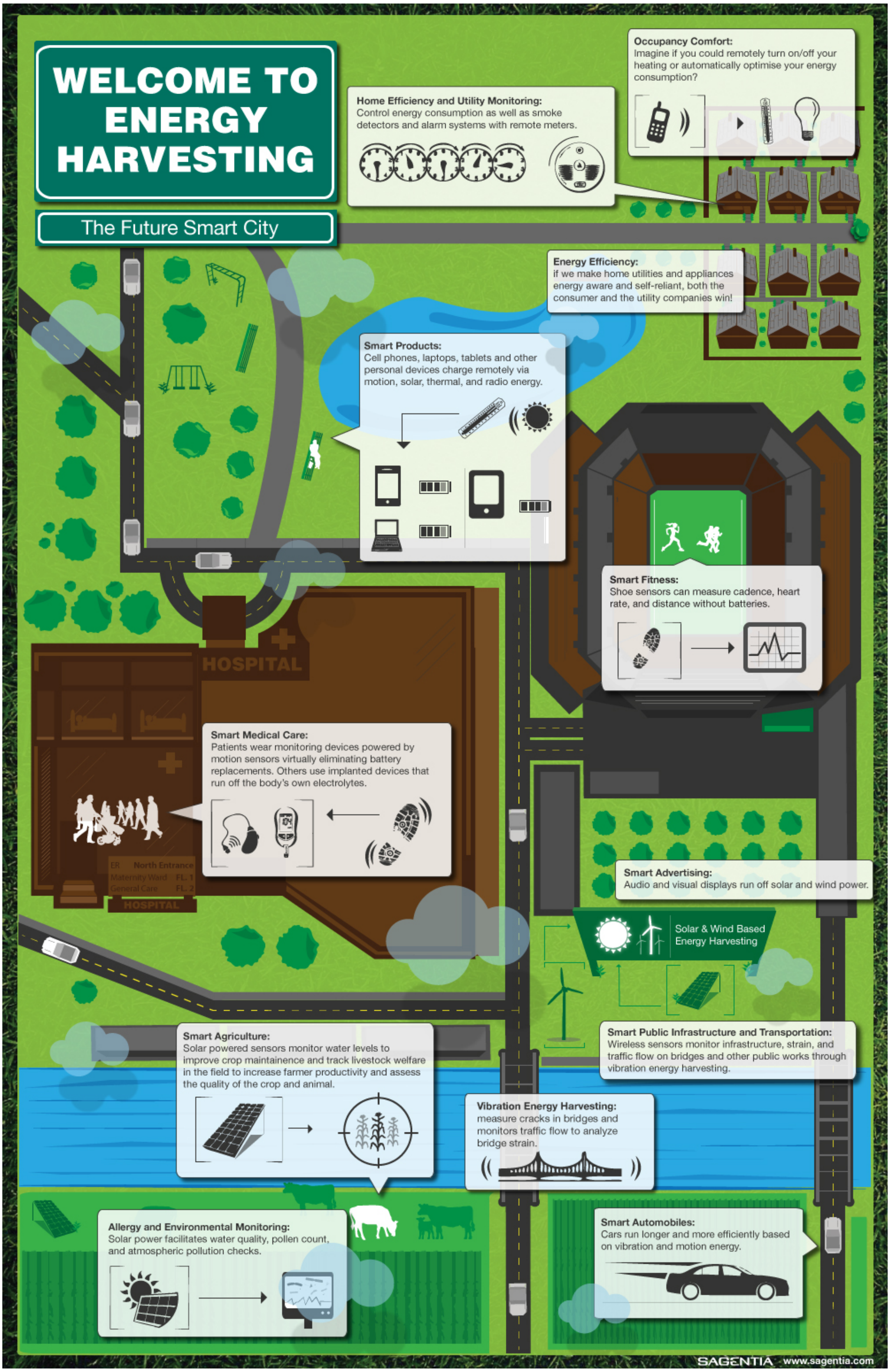
Energy harvesting powered wireless sensors will become ubiquitous, providing ever more valuable information that is used to enable improvements to transport, health, and infrastructure.

Biological systems

Power from breathing or blood pressure could power ultra low power medical implants. Researchers at Southampton University hospital have developed an experimental pace maker that is able to draw 1/3 of the power it requires from blood flow.

Falling costs

The cost of energy harvesting will fall dramatically if it makes its way into mass market consumer applications. Then it will be possible for industry applications to make wider use of energy harvesting enabled devices by piggy backing on the development work of others.


WELCOME TO ENERGY HARVESTING
The Future Smart City
Home Efficiency and Utility Monitoring: Control energy consumption as well as smoke detectors and alarm systems with remote meters.
Occupancy Comfort: Imagine if you could remotely turn on/off your heating or automatically optimise your energy consumption?
Energy Efficiency: if we make home utilities and appliances energy aware and self-reliant, both the consumer and the utility companies win!
Smart Products: Cell phones, laptops, tablets and other personal devices charge remotely via motion, solar, thermal, and radio energy.
Smart Fitness: Shoe sensors can measure cadence, heart rate, and distance without batteries.
HOSPITAL
Smart Medical Care: Patients wear monitoring devices powered by motion sensors virtually eliminating battery replacements. Others use implanted devices that run off the body's own electrolytes.
Smart Advertising: Audio and visual displays run off solar and wind power.
Solar & Wind Based Energy Harvesting
Smart Public Infrastructure and Transportation: Wireless sensors monitor infrastructure, strain, and traffic flow on bridges and other public works through vibration energy harvesting.
Smart Agriculture: Solar powered sensors monitor water levels to improve crop maintainance and track livestock welfare in the field to increase farmer productivity and assess the quality of the crop and animal.
Vibration Energy Harvesting: measure cracks in bridges and monitors traffic flow to analyze bridge strain.
Allergy and Environmental Monitoring: Solar power facilitates water quality, pollen count, and atmospheric pollution checks.
Smart Automobiles: Cars run longer and more efficiently based on vibration and motion energy.
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