Electronics and
Computer Science

UNIVERSITY OF Southampton

Applications of Energy Harvesting

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ICT-Energy Workshop
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Overview

- Introduction to Energy Harvesting
- Energy Harvesting Types and Applications:
  - Photovoltaic
  - Thermoelectric
  - Mechanical
  - RF
  - Inductive
- Conclusions and opportunities for EH research

Energy Harvesting

External Energy Source → **Transduction Mechanism** → **Electrical Energy**

Light
Mechanical Energy
Thermal Energy

RF
Inductive

→

Solar Cell
Piezoelectric Cantilever
Thermoelectric modules

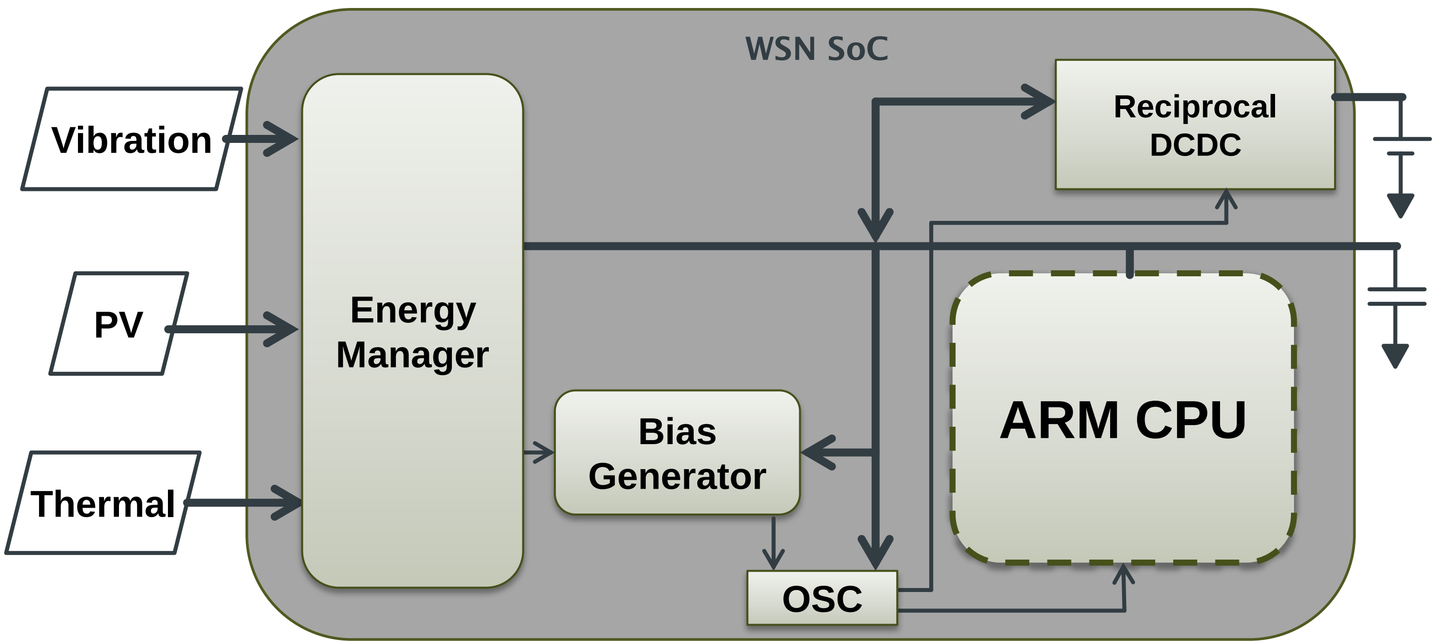
Antenna
Coil

→

Power Conditioning Electronics,
Energy Storage

Motivation

- Harvesters serve as a localised power supply for **wireless devices**
- Replace or augment batteries
- Ideal for embedded application

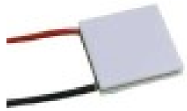


How Much Power?

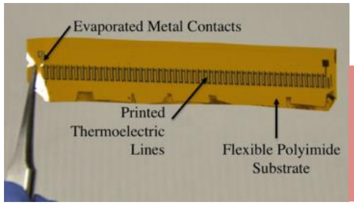
Powercast RF Harvester, 915 MHz, 6 dBi antenna, 3 W transmitter = 40 μW/cm² @ 60 cm, 0.17 μW/cm² @ 4.5 m

Inductive coupling, 7.2 W transmitter = 340 mW/cm² @ 5 mm gap

Micropelt thermoelectric generator = 155 μW/cm³, (70 °C hot side temp)



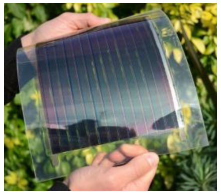
European Thermodynamics thermoelectric generator = 900 μW/cm³, (ΔT = 170°C)



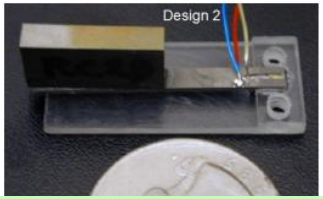
Printed thermoelectric generator = 75 μW/cm², (ΔT = 20°C)

DSSC, 500 lux fluorescent lighting = 100 μW/cm²

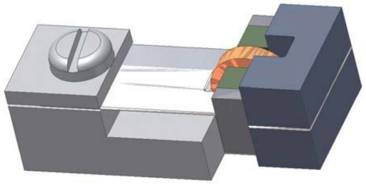
MonoSi SolarBIT (1 sun) = 18.6 mW/cm²



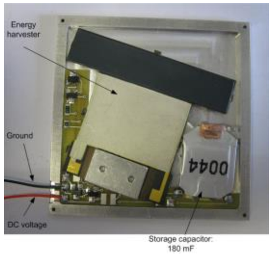
Flexible organic PV, 200 lux = 10 μW/cm²



Miniature piezoelectric VEH = 375 μW/cm³ @ 120 Hz, 2.5 m/s²



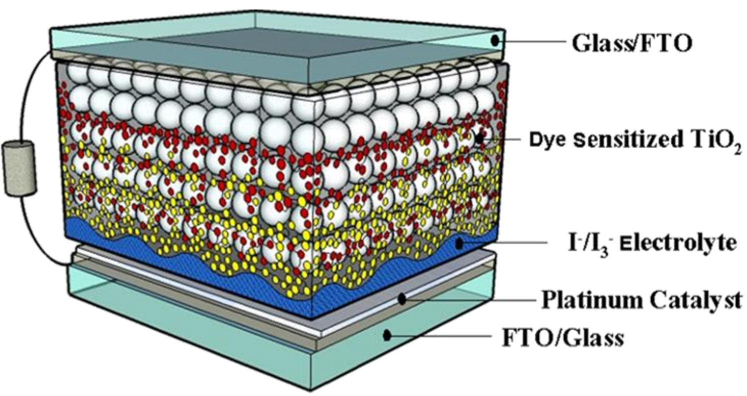
Miniature electromagnetic VEH = 300 μW/cm³ @ 52 Hz, 0.6 m/s²



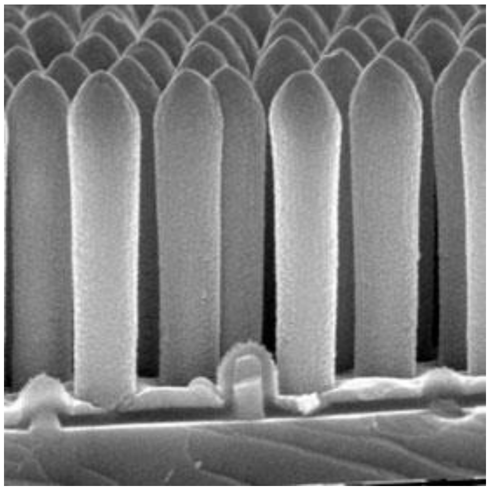
Printed piezoelectric VEH = 22 μW/cm³ @ 66 Hz, 3 m/s²

Photovoltaics

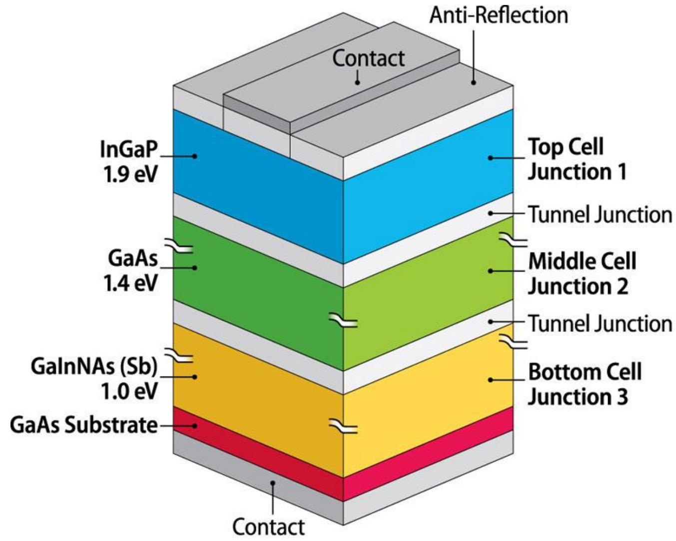
Generation of electricity from incident photons, 1st generation used silicon, 2nd generation used thin films e.g. cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). 3rd generation research include printed devices and nanotechnology to improve bandwidth and reduce cost.



Dye-sensitised solar cell (e.g. G24 Power)

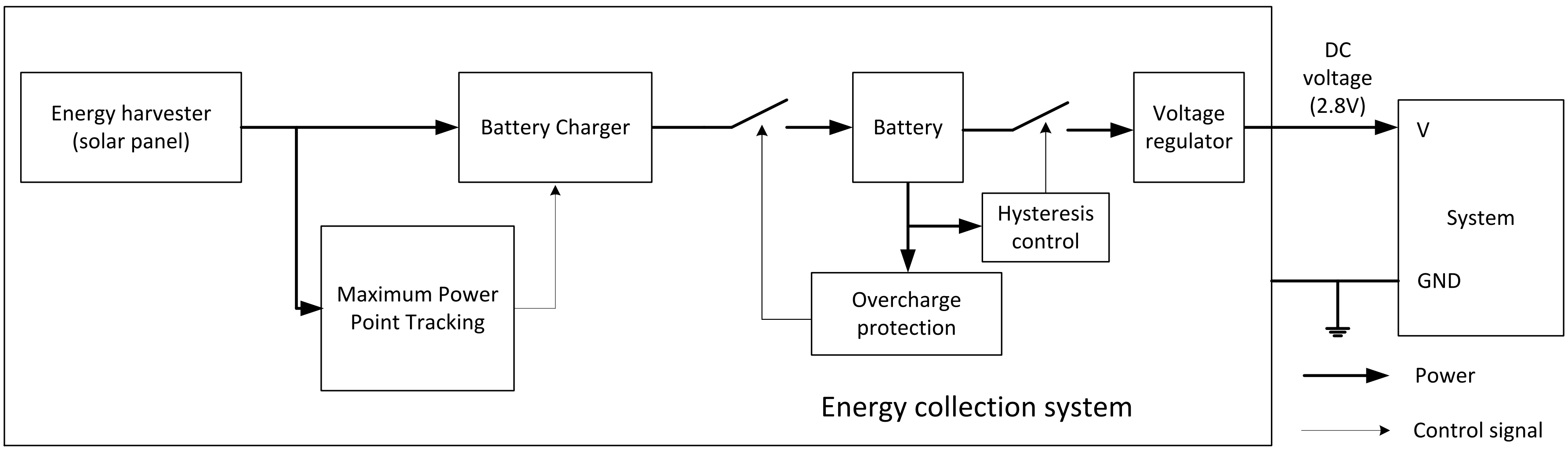


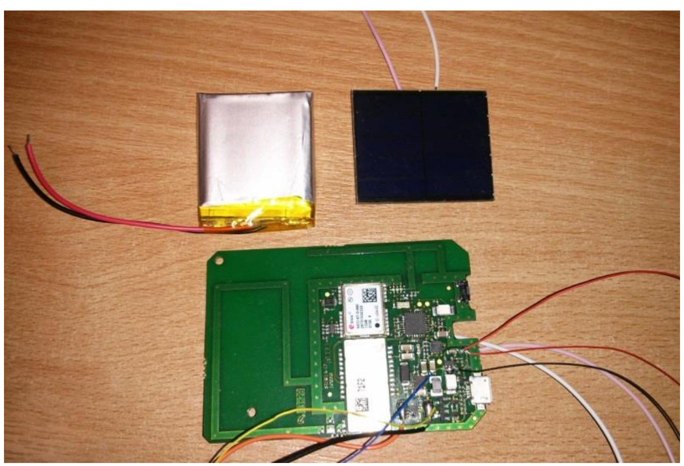
InP nanowires demonstrate 13.8% efficiency



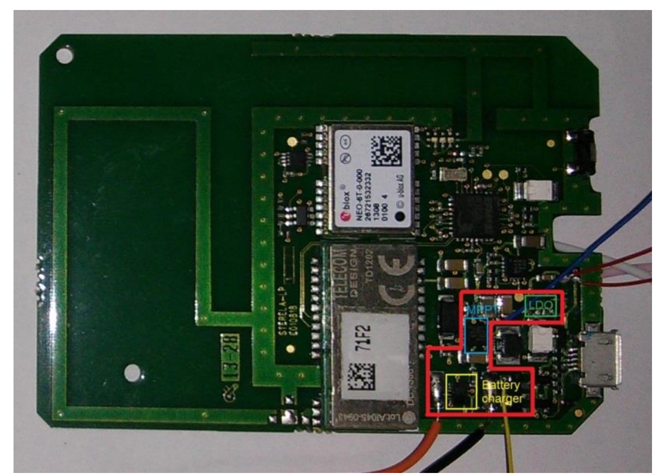
Multi-junction devices, different band gaps for different wavelengths, 46% max efficiency demonstrated.

PV System Block Diagram





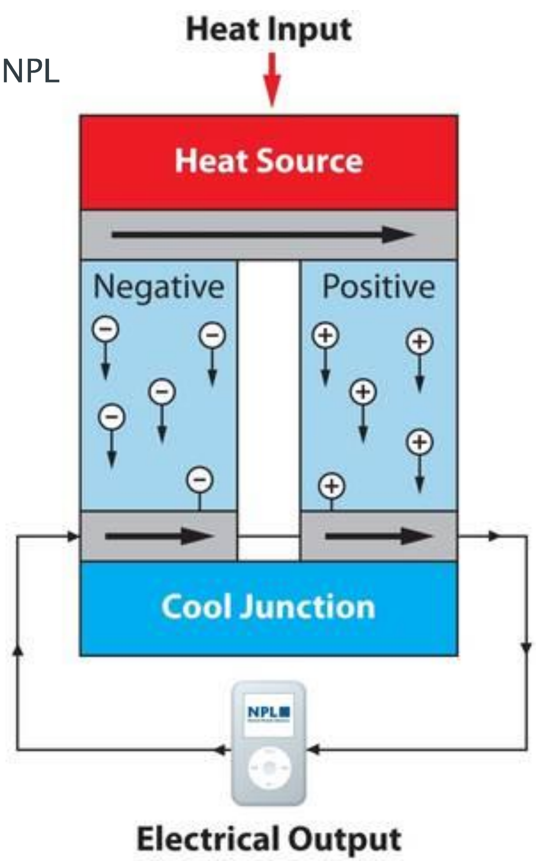
LDO
MPPT
Battery charger



System efficiency ~73%

Thermoelectric Energy Harvesting

NPL

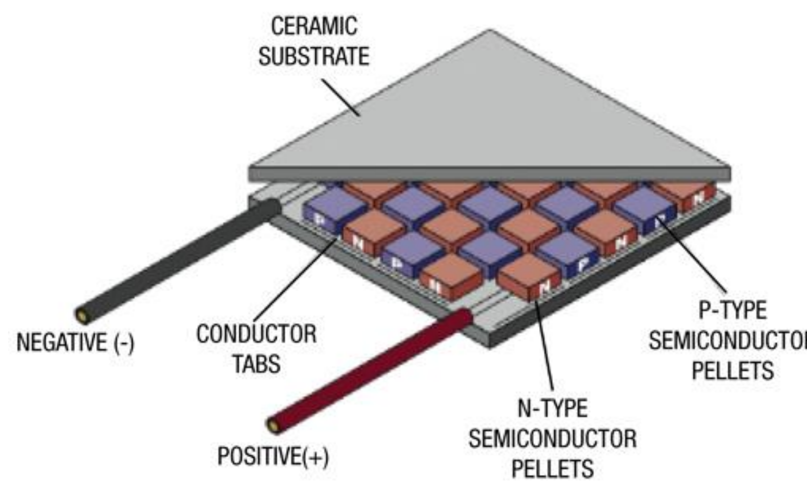


Generation of electric energy from a temperature gradient across two different materials (n and p-type). Commonly fabricated from Bismuth Telluride and Antimony Telluride bulk semiconductors sandwiched between ceramic substrates.

$V = S\Delta T$

$ZT = \sigma S^2 T/\lambda$

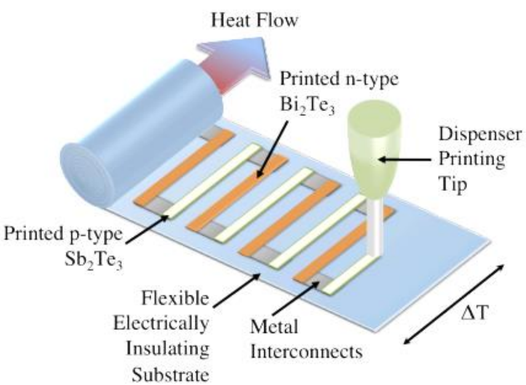
S = Seebeck coeff., λ = thermal cond, σ = electrical cond., T = absolute temperature

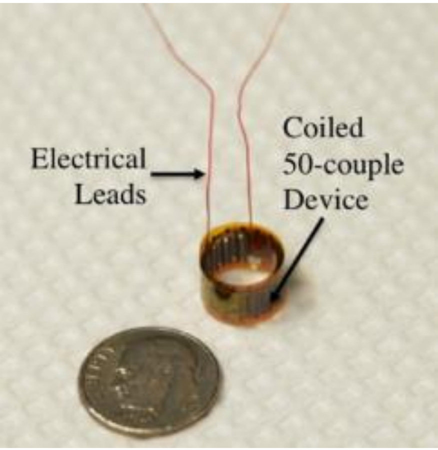


Linear Technology

Thermoelectrics - Research

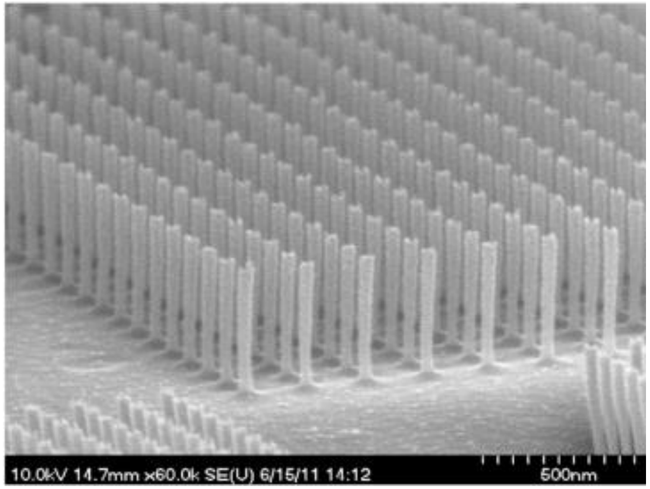
Printed thermocouples have been demonstrated (e.g. Berkeley and Southampton). Bi_2Te_3/Sb_2Te_3 powders mixed with epoxy binders to form a printable paste. Cured at temperatures up to 350°C.





Seebeck coefficients approaching bulk material values but ZT values quite low ~0.2 due to poor electrical conductivity. Coiled module gave 10.5 μW at 171.6 mV for ΔT = 20°C (75 μW/cm²).

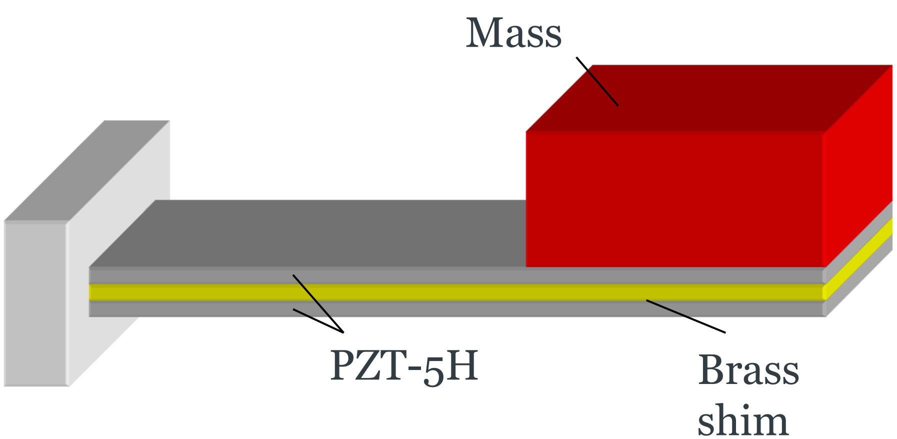
Nanoscale engineering can enhance thermoelectric properties by reducing thermal conduction without affecting conductivity. This approach can enable alternative materials to be used in place of toxic and rare materials currently used in bulk devices



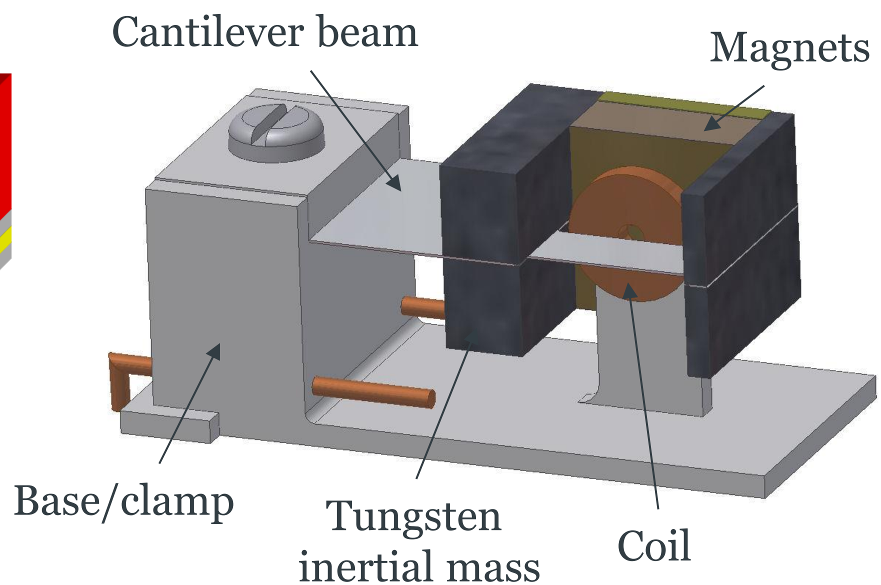
50 nm wide etched Si/SiGe nanowires
(FP7 GREEN Silicon project)

Mechanical Energy Harvesting

Generation of electric energy from a mechanical energy present in the environment. Normally used where vibrations (e.g. machinery) or periodic large forces (e.g. shoe insole). In vibration case, the harvester is typically a spring-mass-damper system tuned to a characteristic frequency of the application.

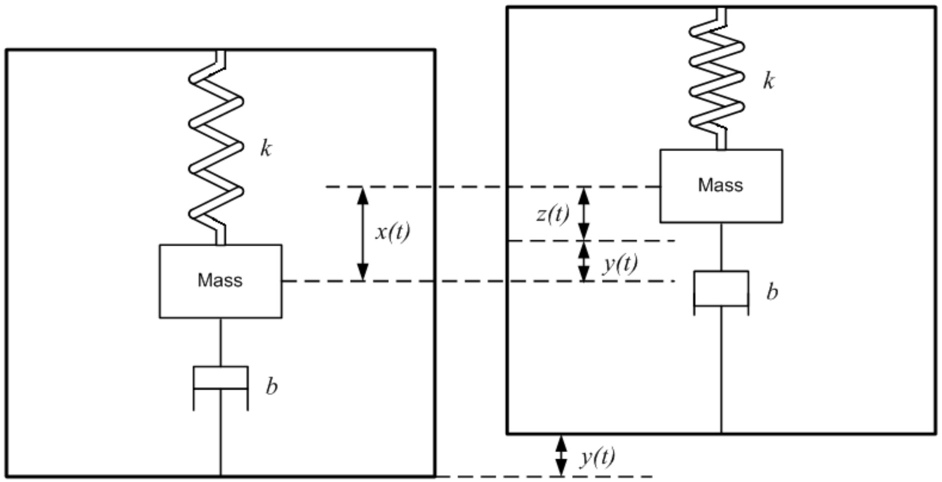


Piezoelectric cantilever generator. Uses bulk piezoelectric material bonded to the cantilever surfaces



Electromagnetic cantilever generator. Exploits relative motion between coil and magnets.

Capturing Mechanical Energy



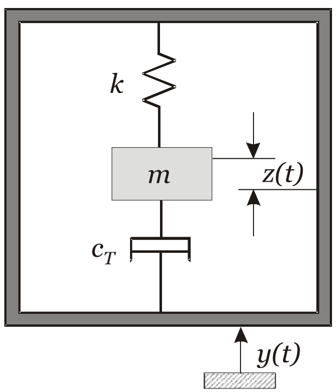
Inertial generator – Mass m, stiffness k, mass displacement $z(t)$, damping coefficient b and input amplitude $y(t)$.

$$\omega_{res} = \sqrt{\frac{k}{m}}$$

- Majority of generators are inertial devices (not all)
- Mechanical structure resonates at characteristic application frequency
- Design depends upon the nature of the mechanical energy i.e. ***APPLICATION SPECIFIC***

Power in the Generator

P_{av} = mechanical energy stored in the generator



Mass → m; Frequency → ω_{res}^3; External vibration amplitude → Y; Inertial mass amplitude → z_{max}

$$P_{av} = \frac{m\omega_{res}^3 Y z_{max}}{2}$$

ω_{res} and Y determined by excitation characteristics in the application, m and z_{max} governed by size and form constraints.

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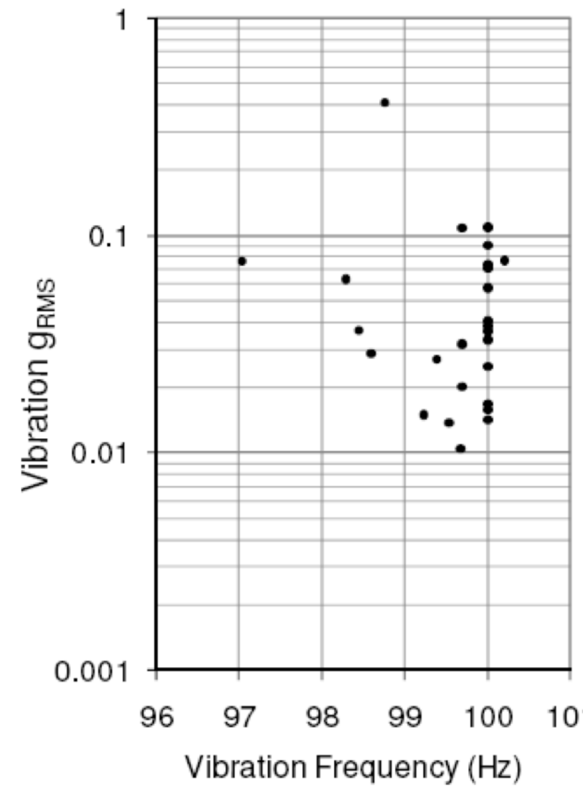
Industrial Applications

Many industrial applications operate at fixed frequencies (50/60 or 100/120 Hz). Most straightforward case for EH – statistically the 100/120 Hz provide more power. However:

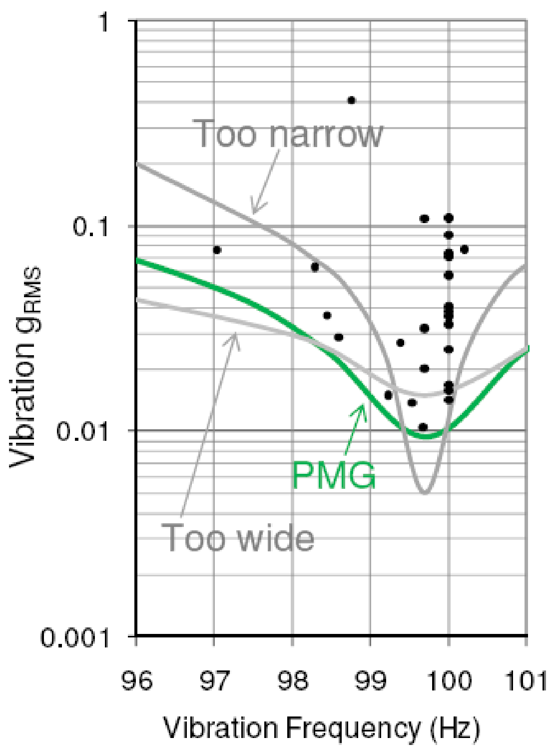
- Range of frequencies
- Vibration levels can be very low (<25 mg, 1g = 9.81 m/s^2)
- Reliable operation is required over many years
- Operate across wide temperature ranges.



Vibration data from AC motors at UK Waterworks

Industrial Applications

Many industrial applications are not space constrained. Perpetuum's harvesters are considerably larger, deliver greater power and provide earlier warning of failure.



Harvester bandwidth optimized to deliver 0.3mW from 95% of industrial AC motors with no adjustment. Maximum power output 50 mW.

All points above the green line will result in at least 0.3mW using the PMG17.

Perpetuum PMG17 - 100

Water Utility - Outdoor Pump

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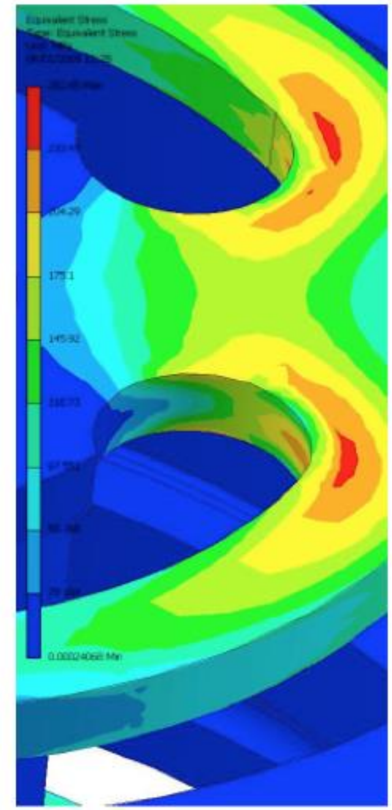
Reliability

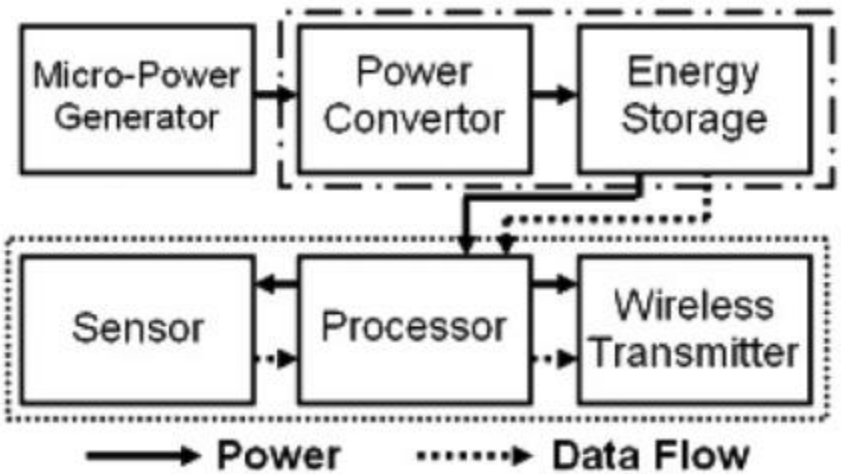


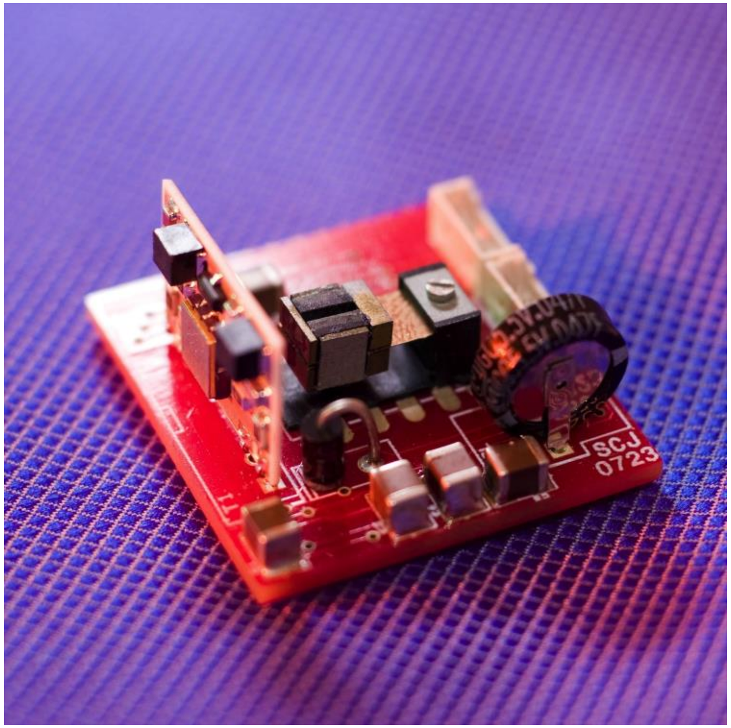
Energy harvesters are only a viable power supply option if they are reliable. If a harvester survives 10^8 cycles, at 120Hz that only 96 days. The PMG17 spring design has been extensively modeled and tested. Mean time to failure is estimated to be 440 years (2% failure in 10 years)

However, system reliability and component performance over time should be considered. For example, the lifetime of the energy storage components.

Note: MTTF of 10yrs implies 37% fail in this time.

Mechanical Energy Harvesting System





Example self powered wireless sensor system, 30 x 28 x 14 mm. Operated on a variable duty cycle that monitors energy stored on the supercapacitor. Cold start circuit included. Generator delivers >50% of mechanical energy to the power converter. Power converter efficiency 65%.

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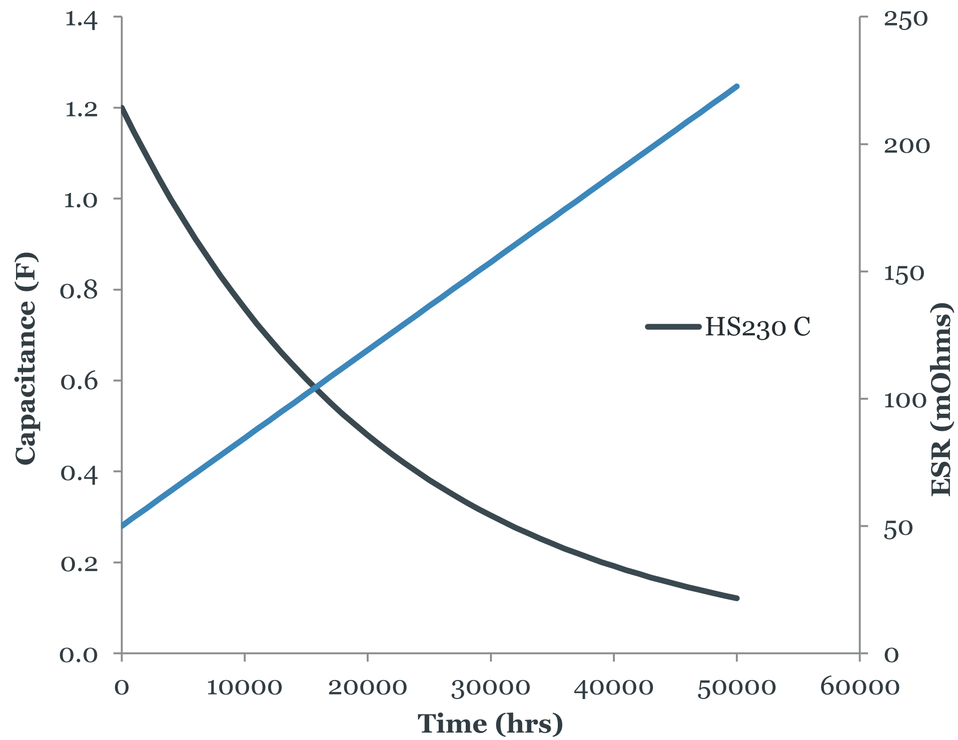
EnergyMan Project

Perpetuum and Southampton have a joint project to investigate the practical lifetime of supercapacitors in practical applications.

Power management circuits designed that precisely control the charge and discharge rates. Supercapacitors operated at low voltages. Current minimized - charged in parallel and discharged in series. Total capacitance overspecified.



Rail Applications

- Large Potential market.
- High vibration levels but NOT fixed frequency.
- Applications on passenger trains:
    - Wheel Bearing monitoring
    - Wheel Health monitoring
- Freight wagons:
    - Many opportunities (no power available)

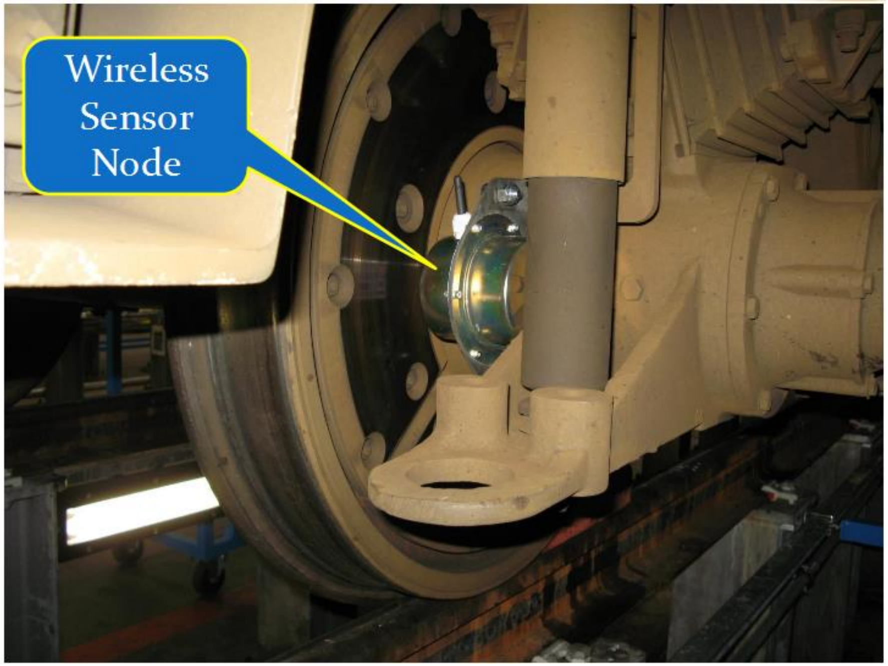
Motivation

100 car, 13,000 ton freight train, 1 faulty bearing, >$2 million damage.

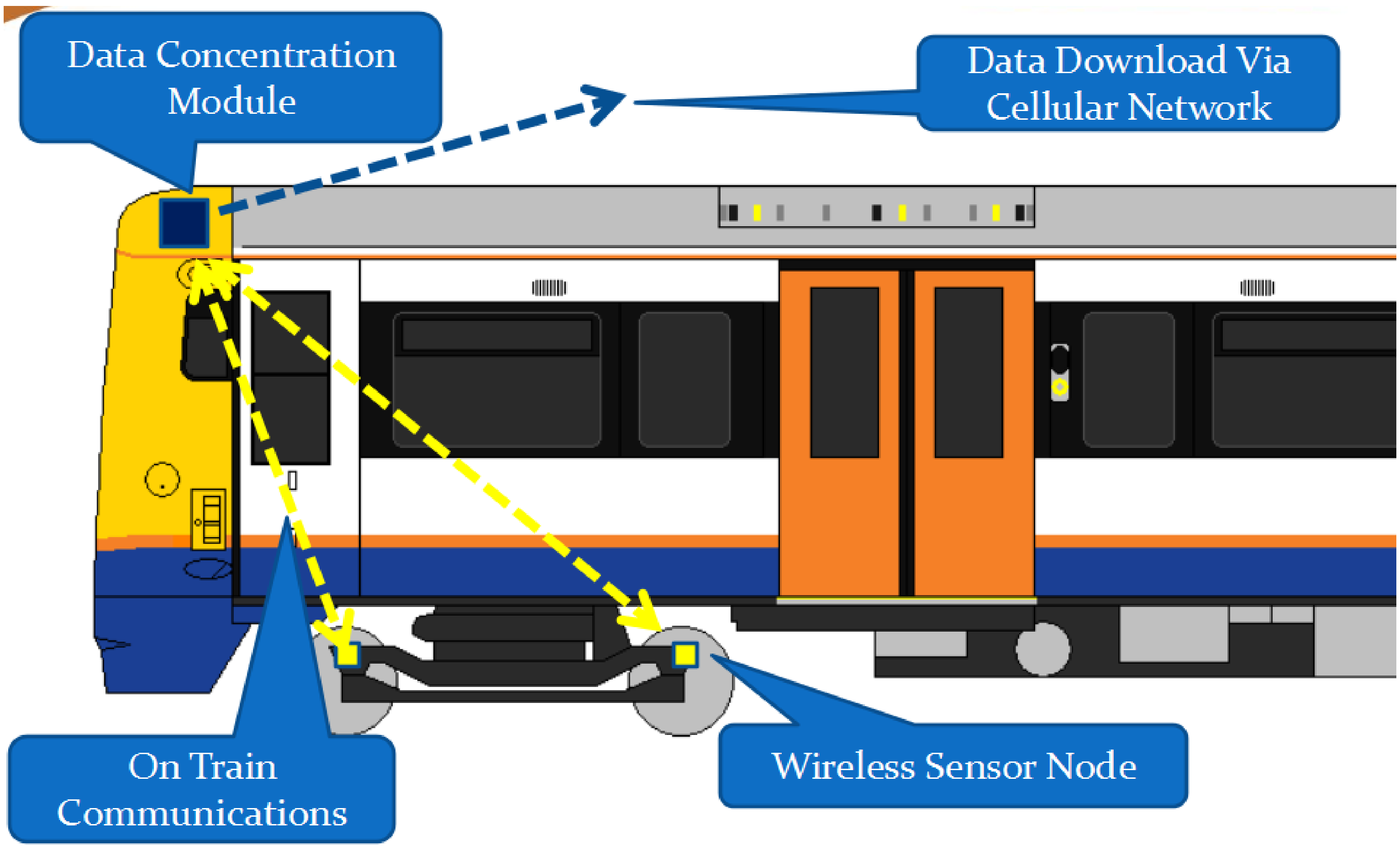
http://www.arizonarails.com/bad_day.html

Perpetuum Sensor System

- Perpetuum marketing a complete sensor system enabled by energy harvesting - predicts failure of bearings.
- Reduced operational and maintenance costs.
- Improved asset utilization
- Operate over wide temperature range (-40 to +85^{o}C).
- Suitable for use in high vibration environments.



Communications



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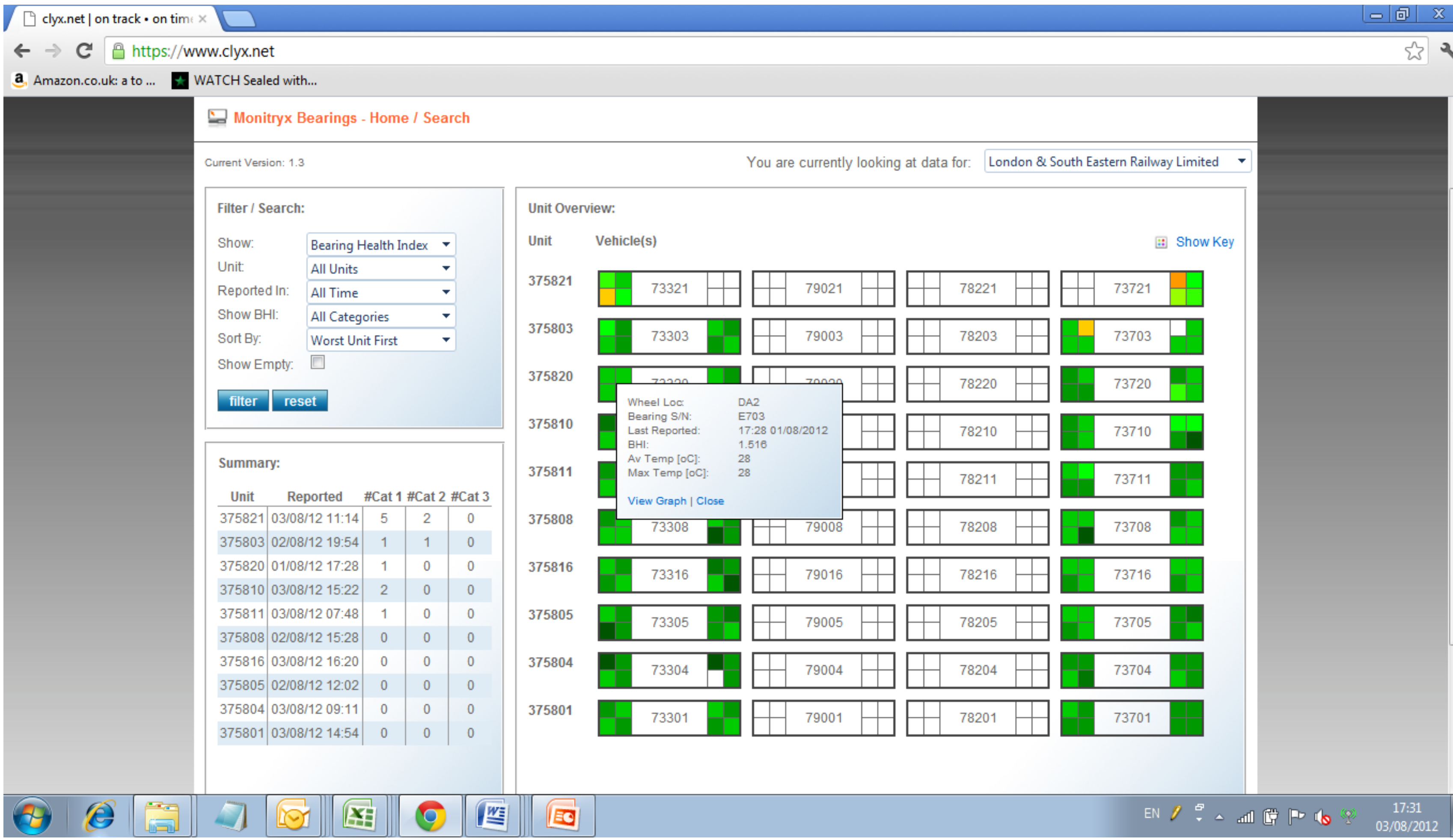
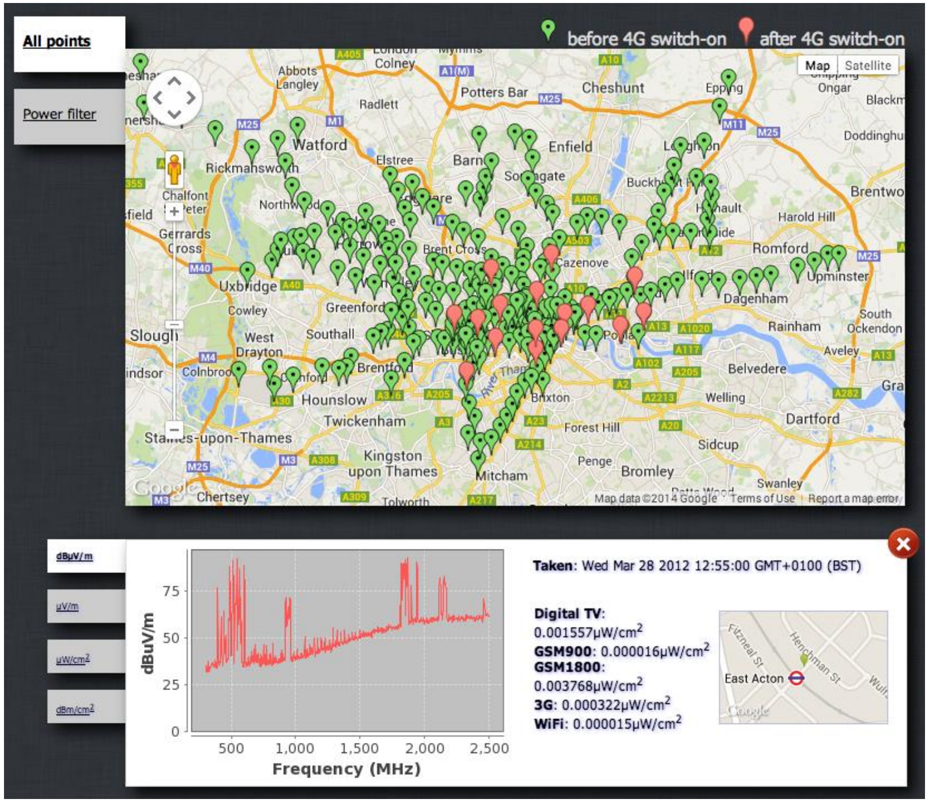
User Display

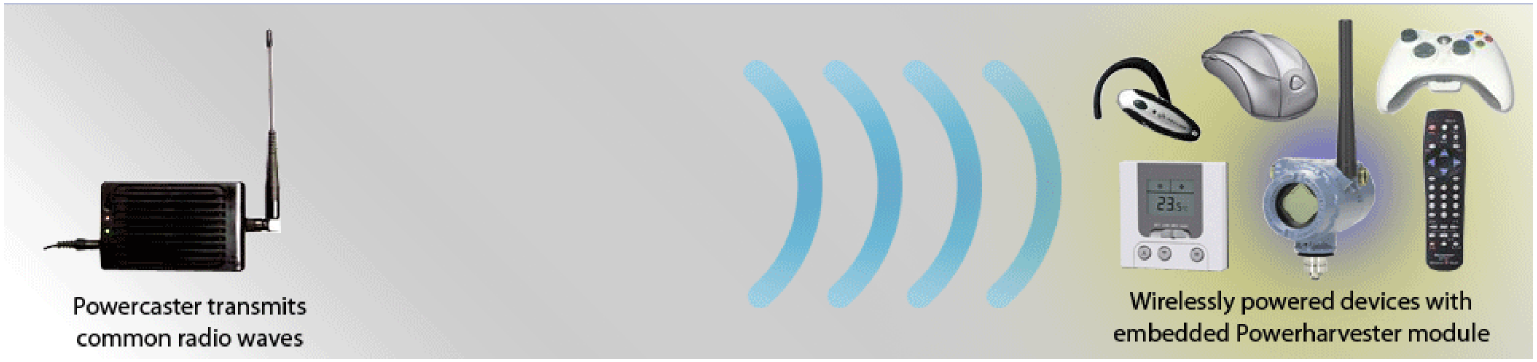


RF Power Transfer

Generation of electric energy from a radio waves either ambient waves typically present in the environment or deliberately broadcast for wireless power transfer. Ambient RF energy typically very low. Powercast system transmits up to 3 W at 915 MHz, receiver chips enable battery charging or duty cycled system operation from standard 50 Ohm antenna.

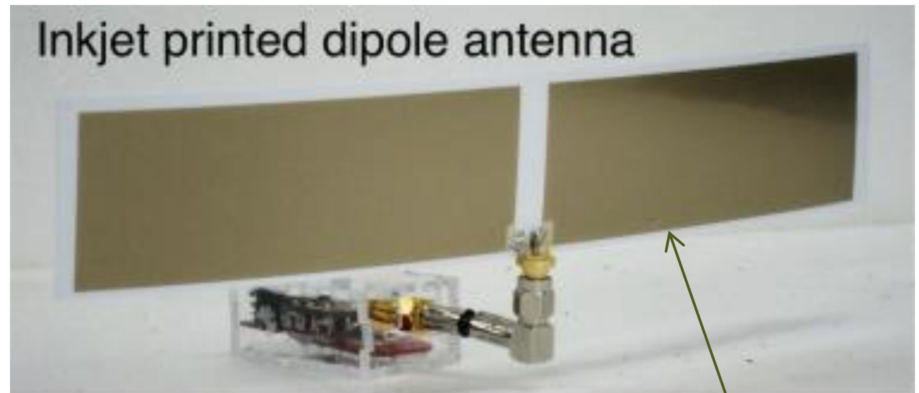


(www.londonrfsurvey.org)

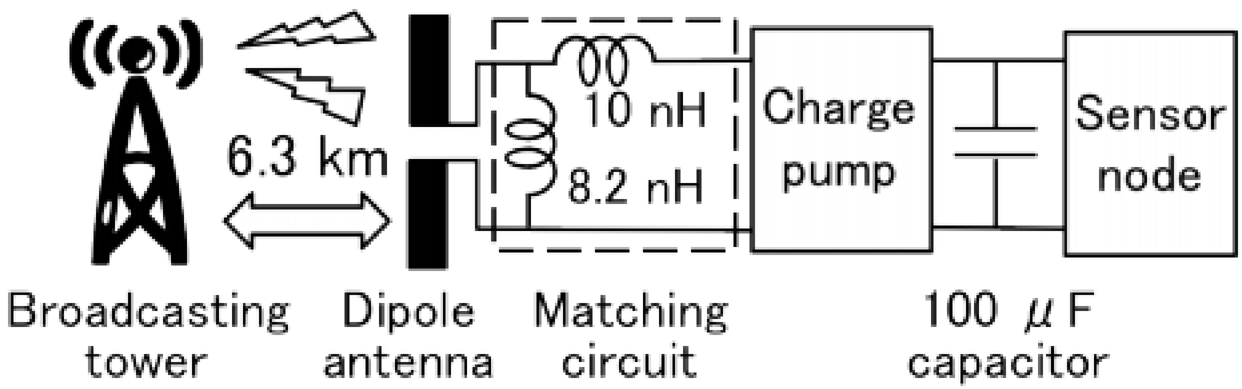


Printed RF Antennas and System Design

Printed antennas straightforward. Example shows a 540 MHz dipole antenna on paper. Harvest 30 - 100 µW from a TV transmitter 6 km away. System uses a 5 stage Dixon voltage multiplier/rectifier the incoming RF signal. Energy stored on a capacitor.



104 x 36 mm 1.3 dBi gain



Inductive Power Transfer

Wireless power transfer of electrical energy using coupled coils. At close range and good alignment the coils are tightly coupled and the system is operated off resonance. To increase range the coils can be operated in a resonant mode.

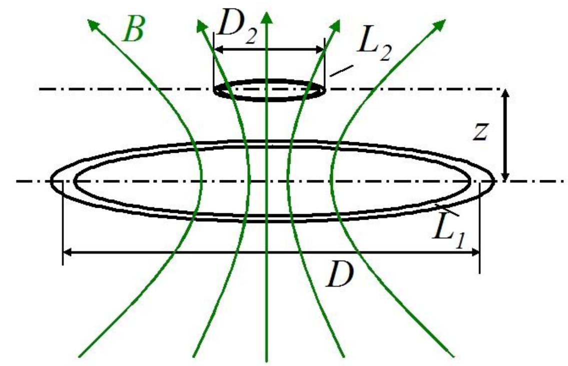


Figure 1 Typical arrangement of an inductively coupled power transfer system

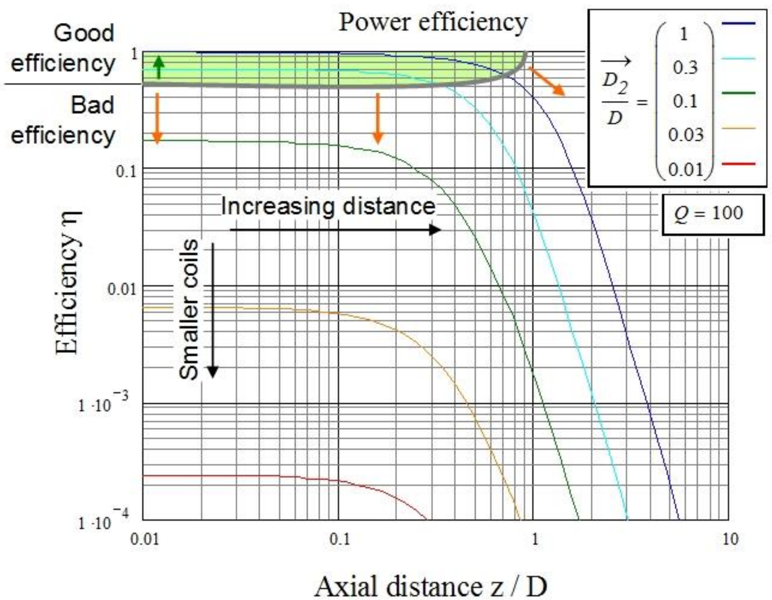
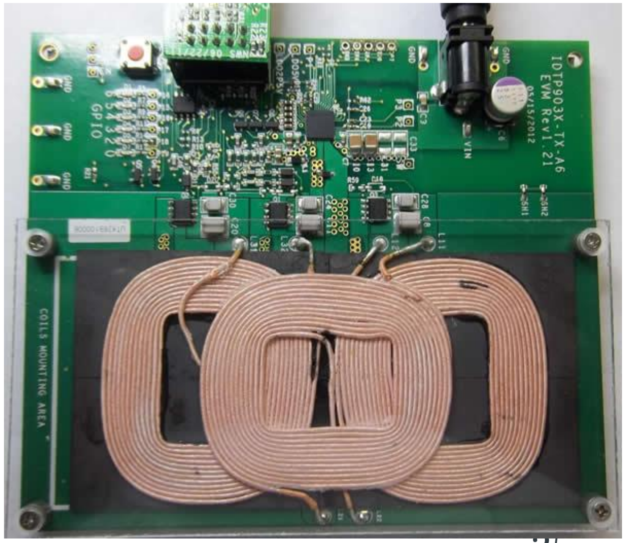


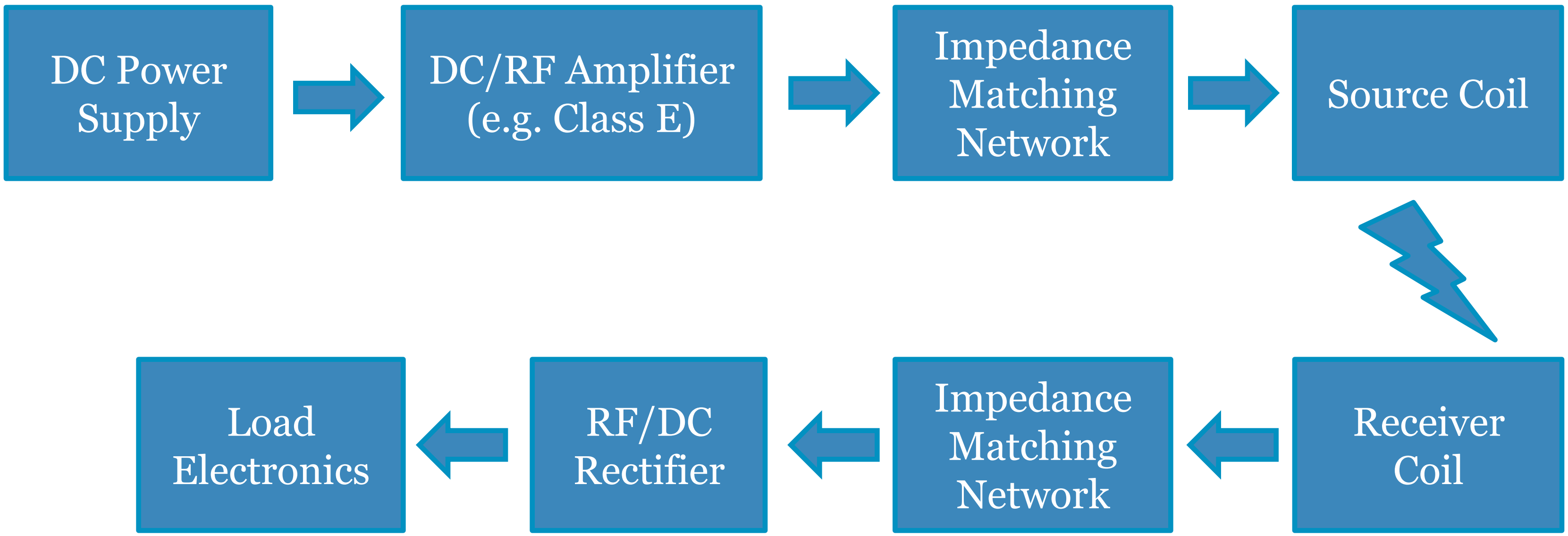
Figure 2 Power efficiency for an inductive power transfer system consisting of loop inductors in dependence on their axial distance z with size ratio as parameter. Calculated for a quality factor of Q = 100

$$Q = \frac{\omega L}{R}$$

For mass produced conventional coils a Q of 100 is typical. A quality factor below 10 is not very useful.



Inductive System Block Diagram



Chipsets available (e.g. from TI) based on WPC and PMA standards (largely based on non-resonant – resonant being added to standards). Non resonant technology already built into available mobile phones and numerous charging mats available. Being driven by end users e.g. Starbucks and MacDonald's. Resonant systems commercially available e.g. WiTricity electric car charging.

Conclusions

- Optimum EH approach depends entirely on the application.
- Applications information essential.
- Holistic design of energy harvesting system essential.
- Whilst commercial solutions of energy harvesting technologies exist – many research challenges exist in applying the technology and improving performance
  - Nonlinear mechanical harvester for random vibrations
  - Improved lead free piezoelectric materials
  - Low cost flexible thermoelectric harvesters for wearable applications
  - Large area flexible printed antennas/coils for wireless power transfer
- ‘Silver bullet’ that revolutionises technologies highly unlikely

Conclusions

- Research focus on systems that can work of different types of harvesters and can accommodate typical EH characteristics e.g. intermittency, low/variable voltages, low/variable power levels.