

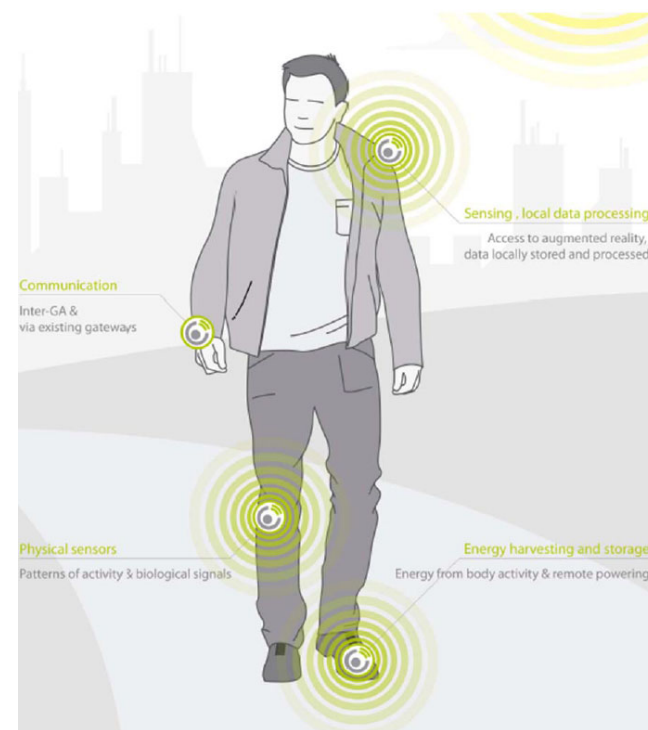
Energy harvesting & storage for IoT

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Ecole Polytechnique Fédérale Lausanne

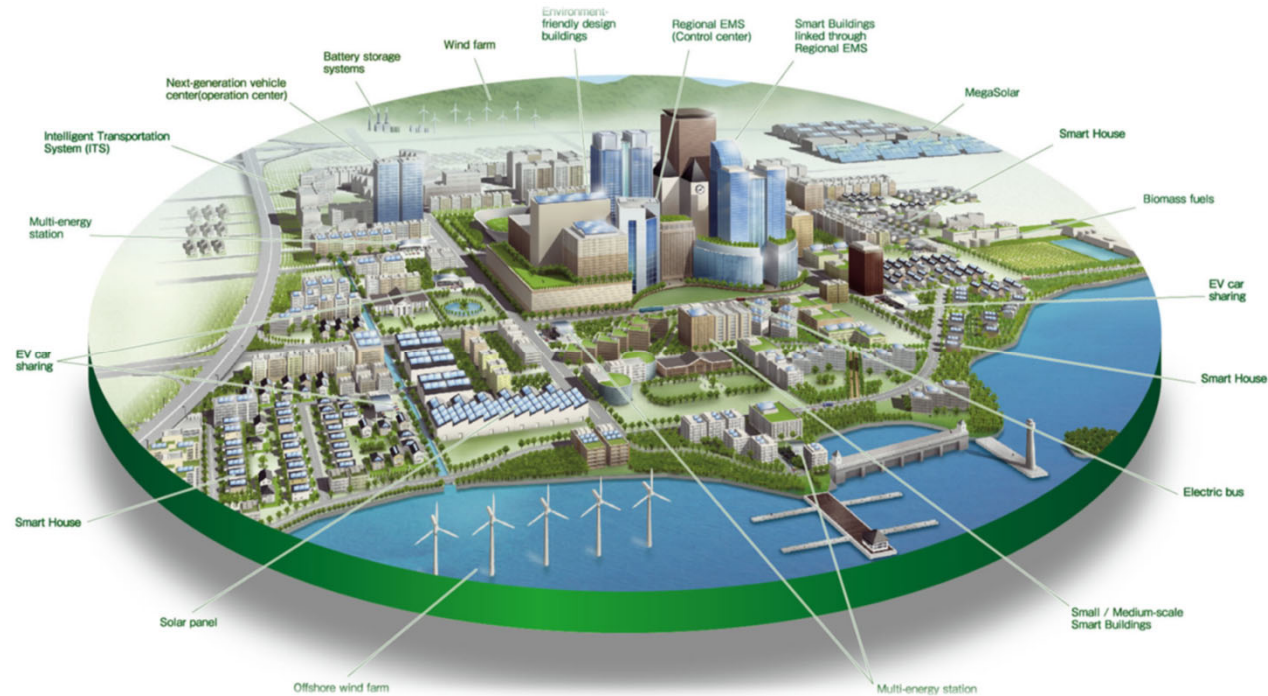
Outline

- Energy efficient technologies for wearables and IoT
- Energy scavenging:
 - from light
 - from vibrations
 - thermoelectrical generators
- Energy storage: supercapacitors
- Roadmaps



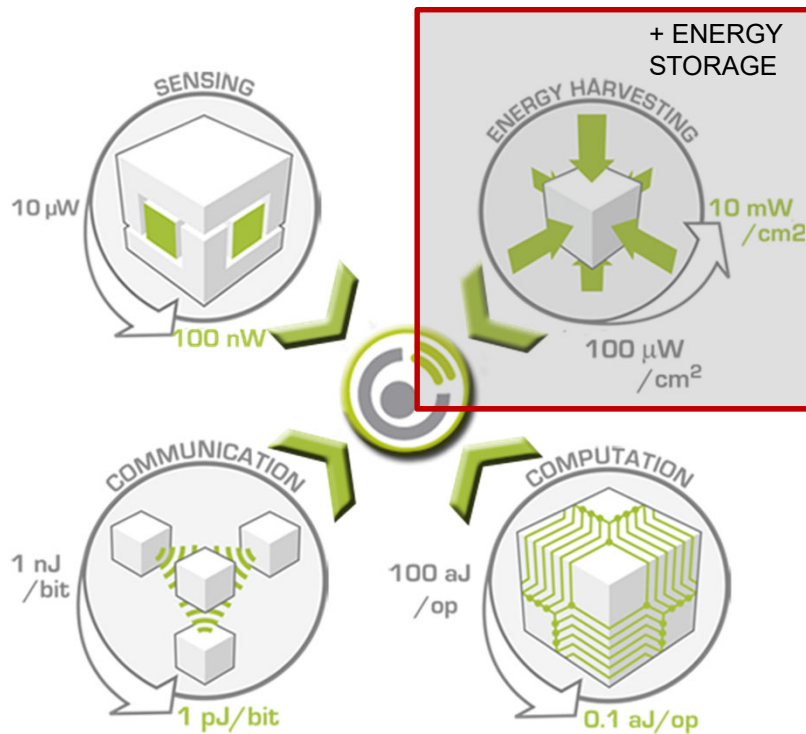
Autonomous Smart Systems

Form the next Exponential Technology for Internet of Things (IoT) and a Smarter Life!



What is Zero-Power?

Zero-Power technology = Autonomous Smart Systems

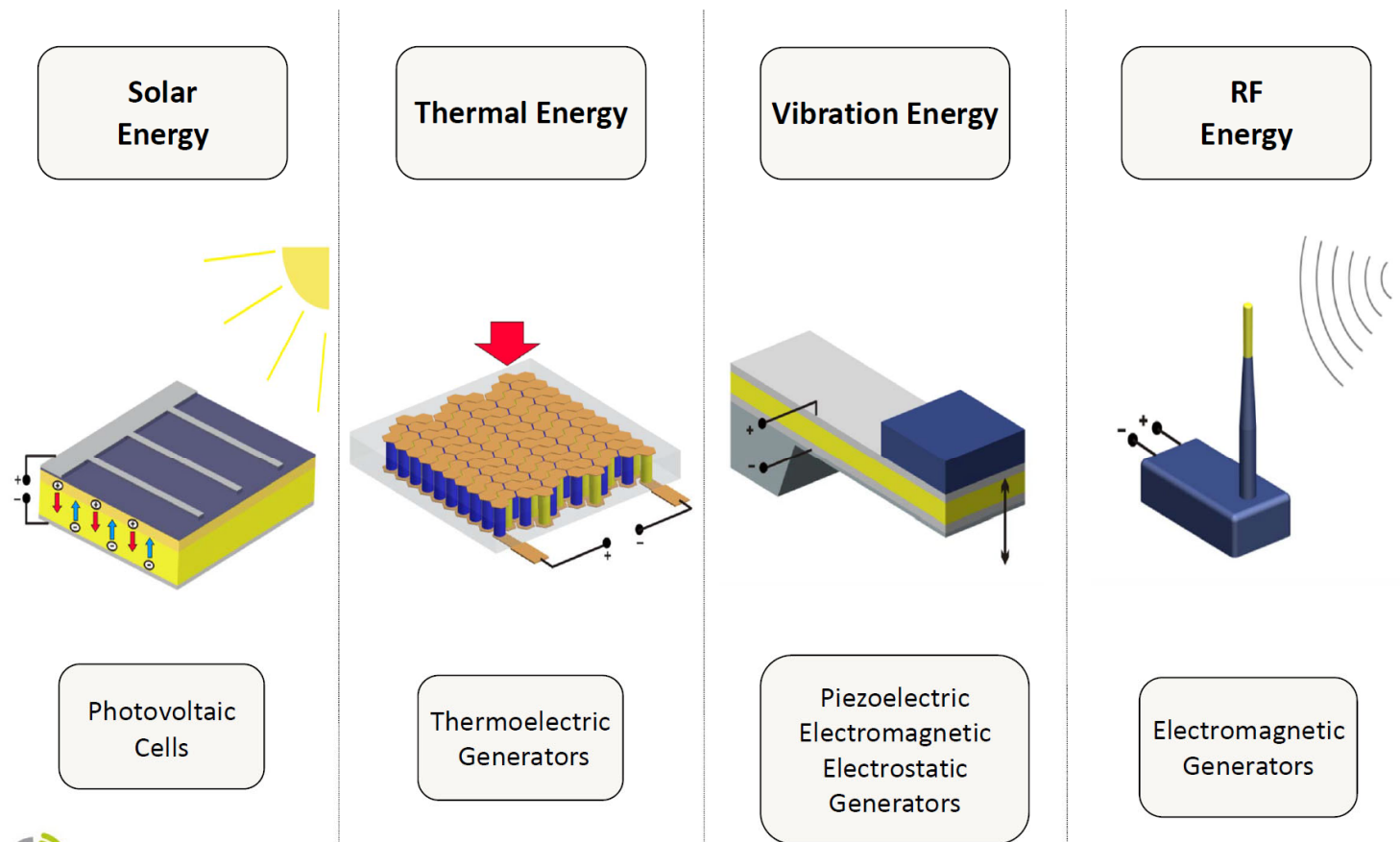


Big Energy Challenges for IoT

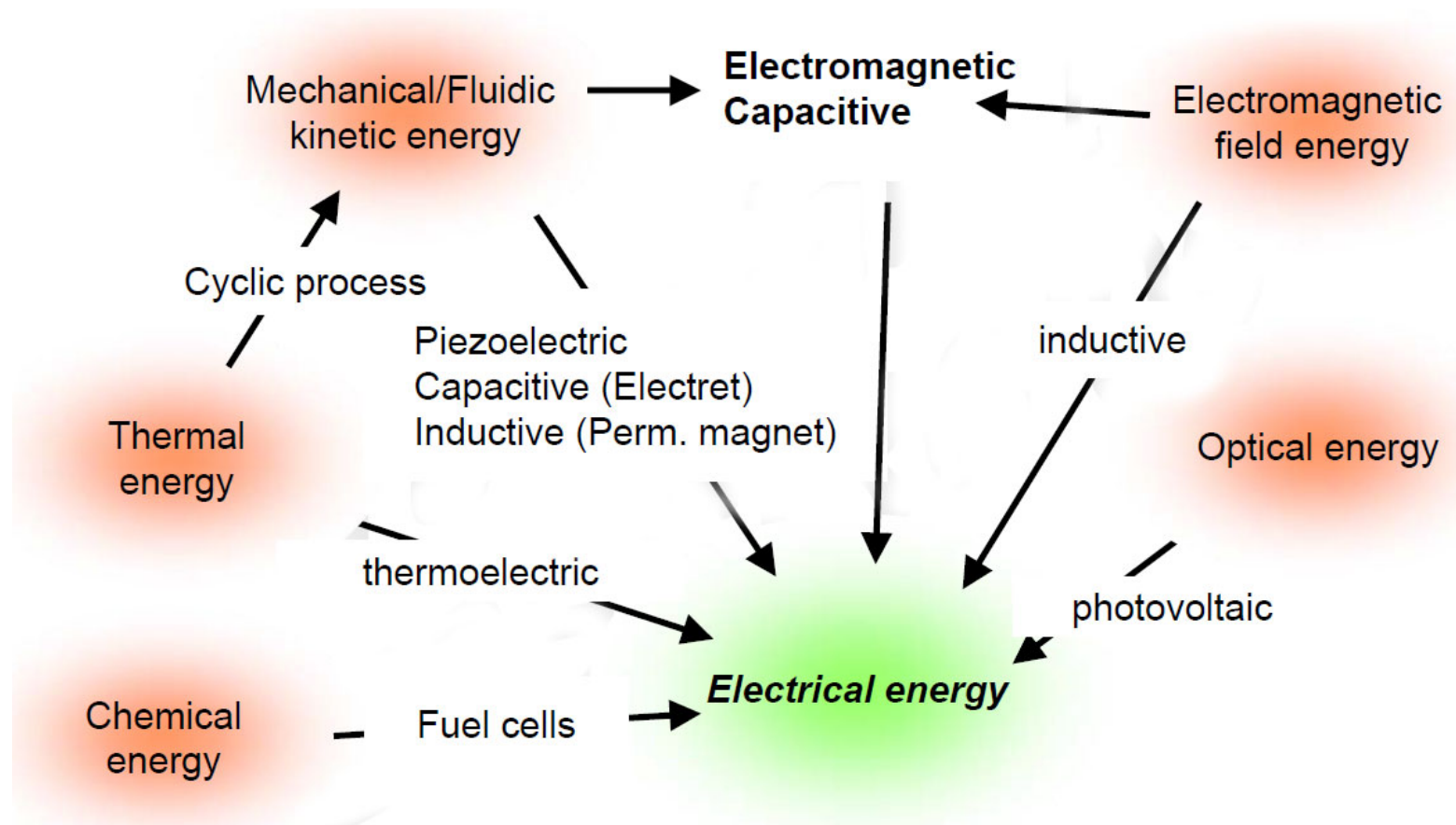
- x 1000 more energy efficient bit computation
- x 1000 more energy efficient bit transmission
- x 100 more efficient energy harvesting

© 2012: Guardian Angels for a Smarter Life

Types of energy harvesting



Mechanisms of conversion to electrical energy



Short Overview

Micropower energy harvesting

R.J.M. Vullers^{a,*}, R. van Schaijk^a, I. Doms^b, C. Van Hoof^{a,b}, R. Mertens^b

^a IMEC/Holst Centre, High Tech Campus 31, 5656 AE Eindhoven, The Netherlands

^b IMEC, Kapeldreef 75, 3001 Leuven, Belgium

Solid-State Electronics 53 (2009) 684–693

Table 2

Characteristics of various energy sources available in the ambient and harvested power.

Source	Source power	Harvested power
Ambient light		
Indoor	0.1 mW/cm ²	10 μW/cm ²
Outdoor	100 mW/cm ²	10 mW/cm ²
Vibration/motion		
Human	0.5 m @ 1 Hz 1 m/s ² @ 50 Hz	4 μW/cm ²
Industrial	1 m @ 5 Hz 10 m/s ² @ 1 kHz	100 μW/cm ²
Thermal energy		
Human	20 mW/cm ²	30 μW/cm ²
Industrial	100 mW/cm ²	1–10 mW/cm ²
RF		
Cell phone	0.3 μW/cm ²	0.1 μW/cm ²

Table 3

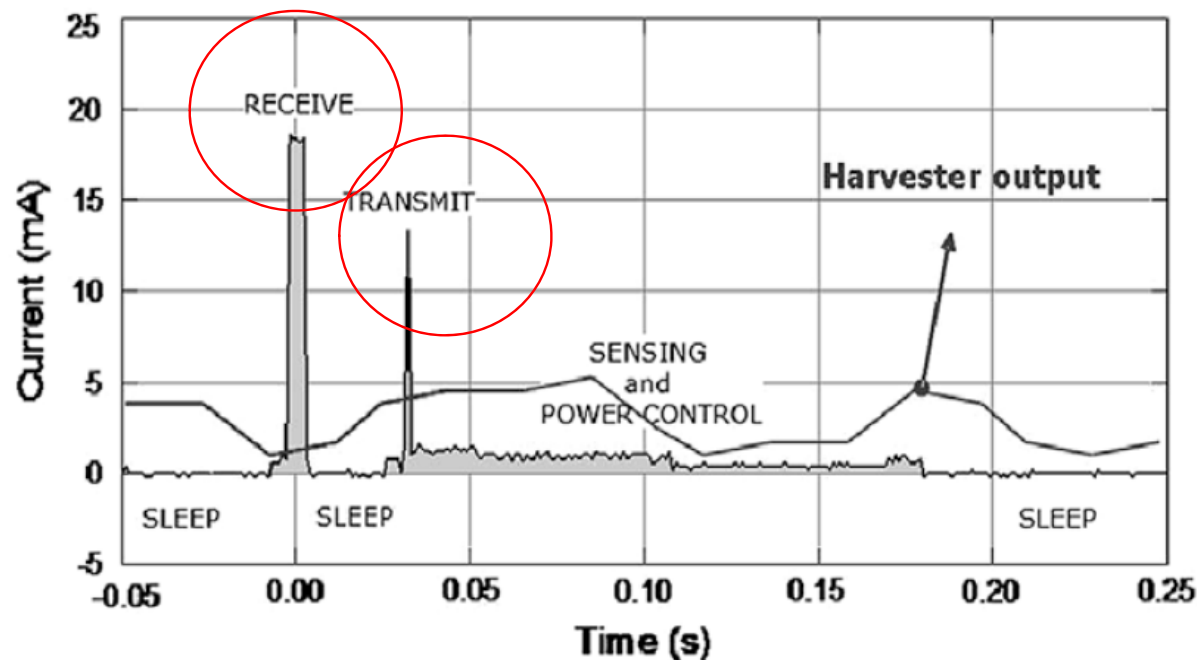
Characteristics of batteries and supercapacitors.

	Battery		Supercapacitor
	Li-ion	Thin film ^a	
Operating voltage (V)	3–3.70	3.70	1.25
Energy density (W h/l)	435	<50	6
Specific energy (W h/kg)	211	<1	1.5
Self-discharge rate (%/month) at 20 °C	0.1–1	0.1–1	100
Cycle life (cycles)	2000	>1000	>10,000
Temperature range (°C)	–20/50	–20/+70	–40/+65

^a Data calculated including the packaging.

Scenario 1: energy harvesting by WSN

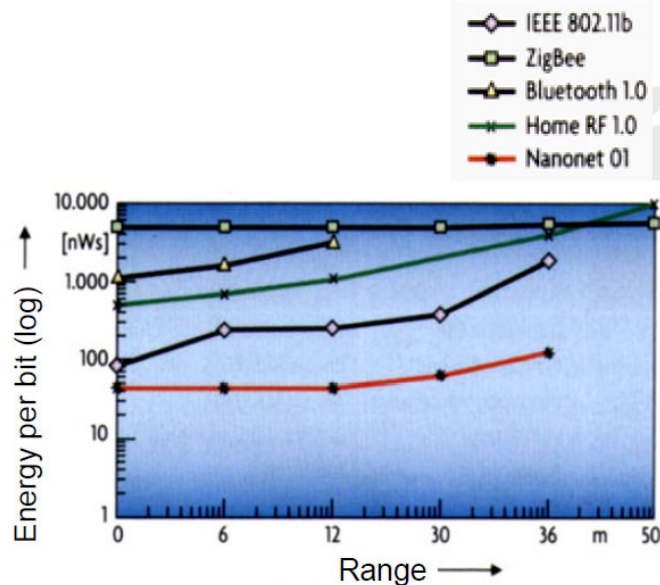
Peaks of 'receive' and 'transmit' cannot be supplied just by the harvester, even if the average energy consumption is very low.
Need: a **hybrid energy management strategy**.



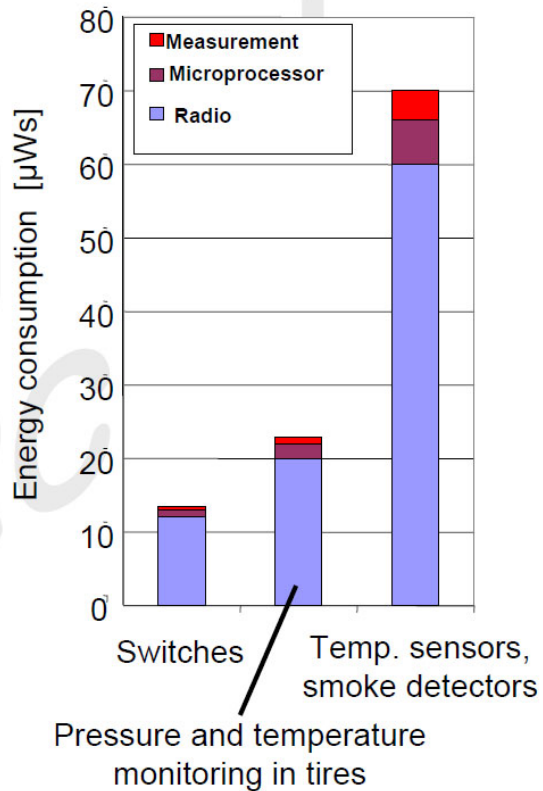
Where the energy goes?

Who is consuming so much? The communication links!

Energy consumption per bit for various radio transmission standards
(W. Haecker, *Elektronik* 22/2002, p. 48)

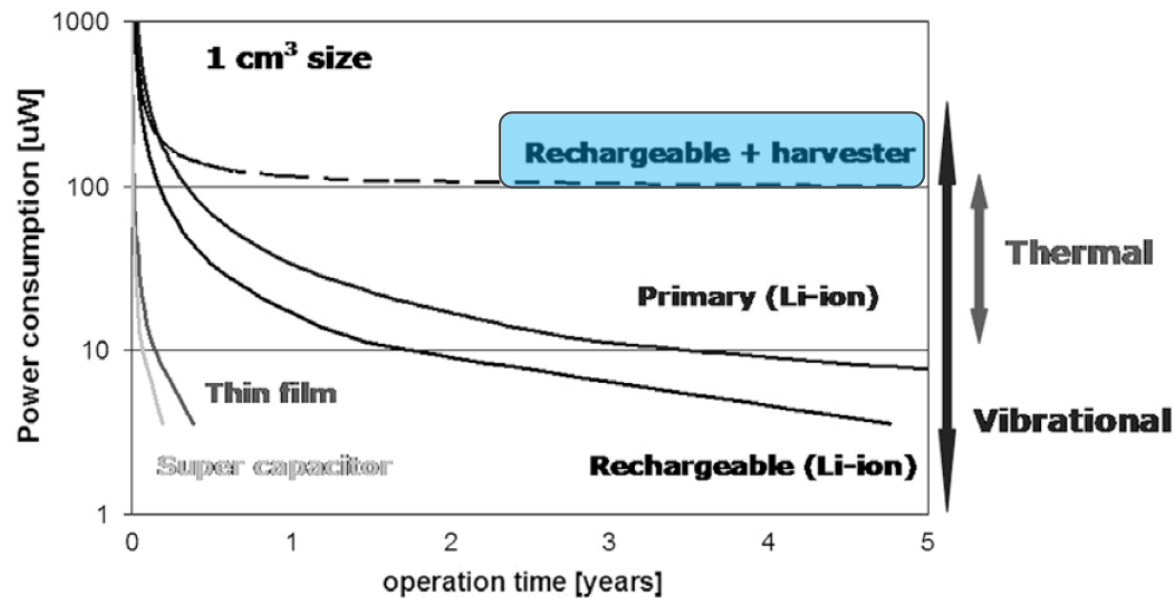


Fraction of the various functionalities from the energy consumption of a microsystem (F. Schmid, *EnOcean*, 2003)



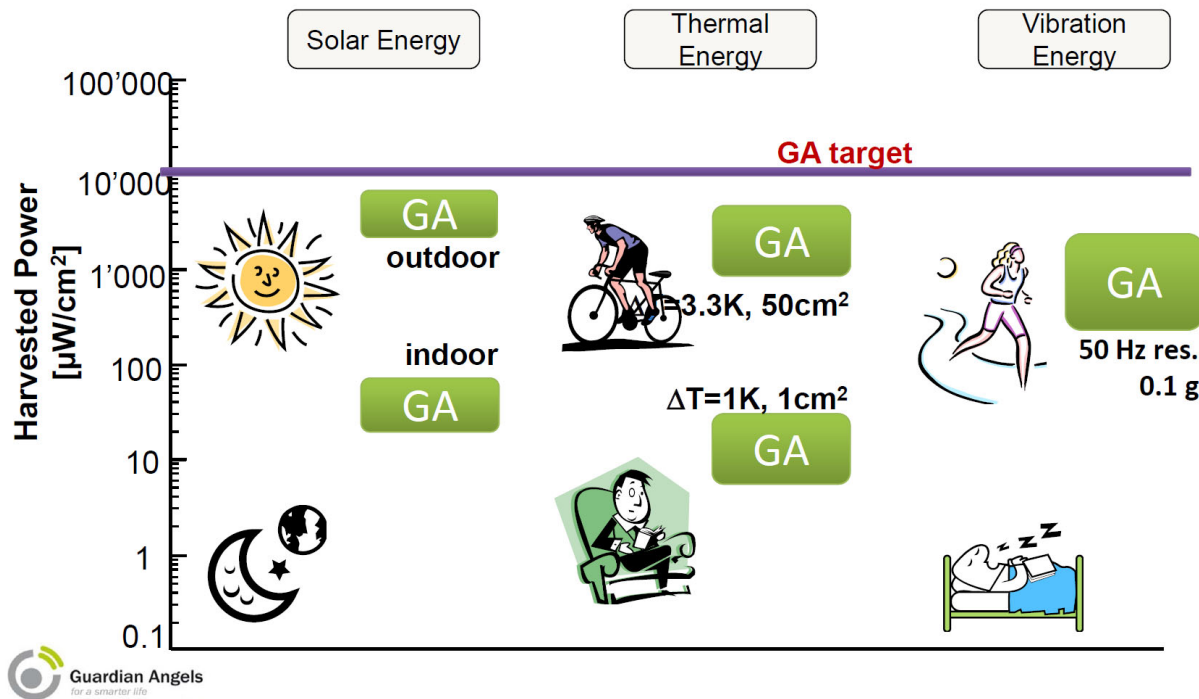
Scenario 2: energy harvesting + rechargeable batteries

- A more realistic solution: rechargeable battery + harvester.
- Battery lifetime and operation extended to months or years for 100microWatts sensor nodes.



Energy harvesting

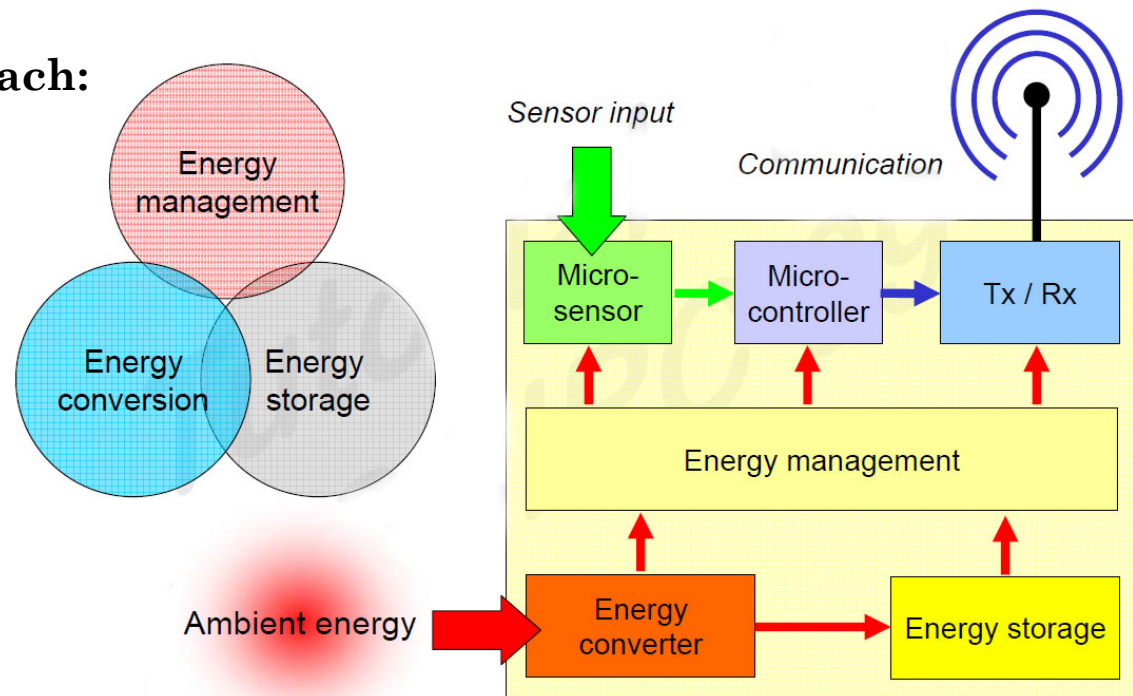
- Challenge: continuous operation under dynamic conditions.
- Choose multi-harvesting interfaces, storage and form factors according to applications – **NO SINGLE UNIVERSAL SOLUTION AVAILABLE!**



Energy scavenging is a system level problem!

- Complete and correct approach:

- Energy conversion
- Energy storage
- Energy management



Source: prof. Manoli, IMTEK, Tutorial ESSCIRC 2009.

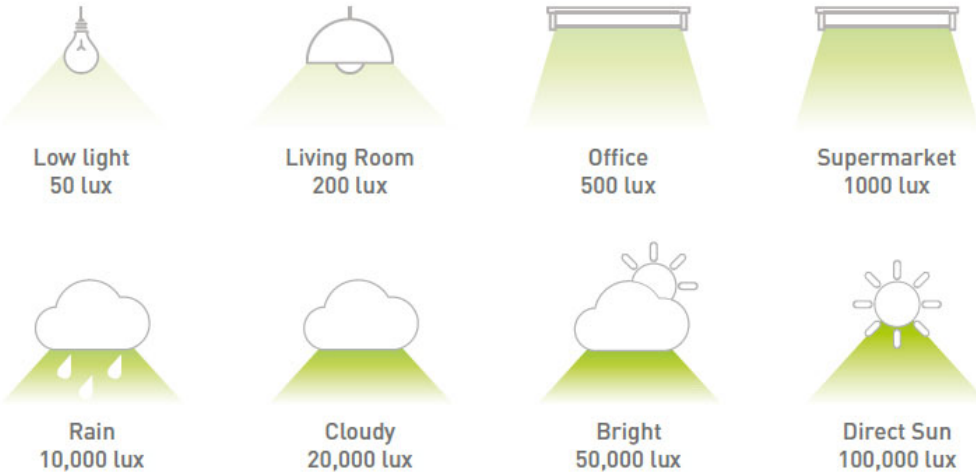
Energy scavenging from light

Challenge:

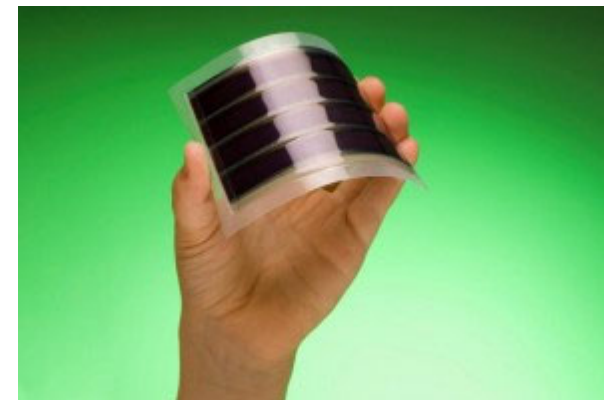
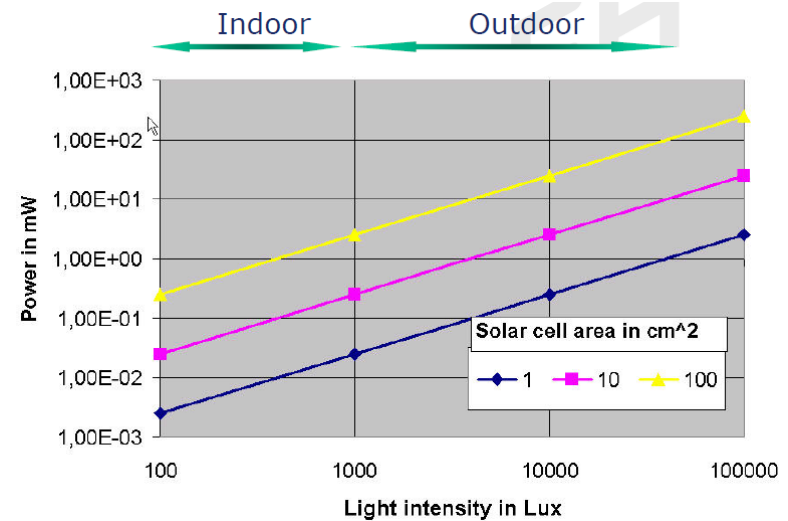
Indoor versus Outdoor!

Flexible solar cells:

indoor Dye Sensitized Solar Cells (DSSC) that are flexible and boast superior low light performance (Gcell).



Classical thin film cell



Solar cell energy efficiency (2021)

TABLE 2 Characteristics of different solar cell types

Generation	Solar cell type	Efficiency	Power density (W/m ²)	References
First	Mono-crystalline	17% – 18%	111 – 142	18
First	Poly-crystalline	12% – 14%	111 – 125	19
Second	Amorphous Silicon	4% – 8%	50 – 77	20
Second	Copper Indium di-Selenide	16% – 23%	91 – 111	21
Second	Cadmium Telluride	9% – 11%	77 – 91	20
Third	Nano-crystal/Quantum Dot	7% – 9%	—	22
Third	Polymer	3% – 10%	—	23
Third	Dye Sensitized	9% – 12%	—	24
Third	Concentrated	≈ 33% – 46%	—	25
Third	Perovskite	≈ 28%	—	26,27

DOI: 10.1002/er.7626

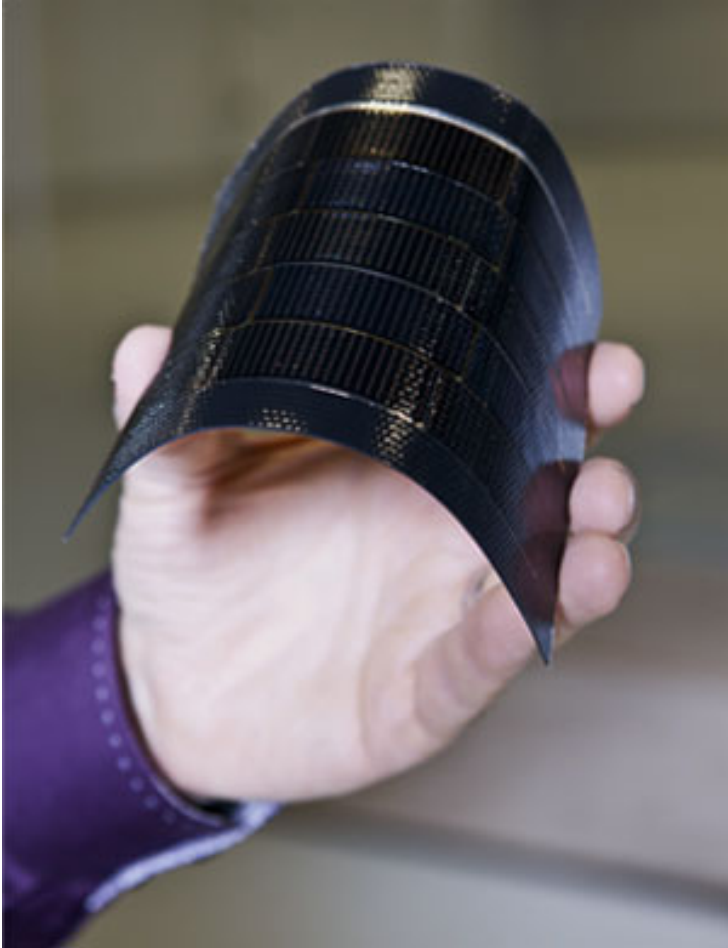
REVIEW PAPER

INTERNATIONAL JOURNAL OF ENERGY RESEARCH WILEY

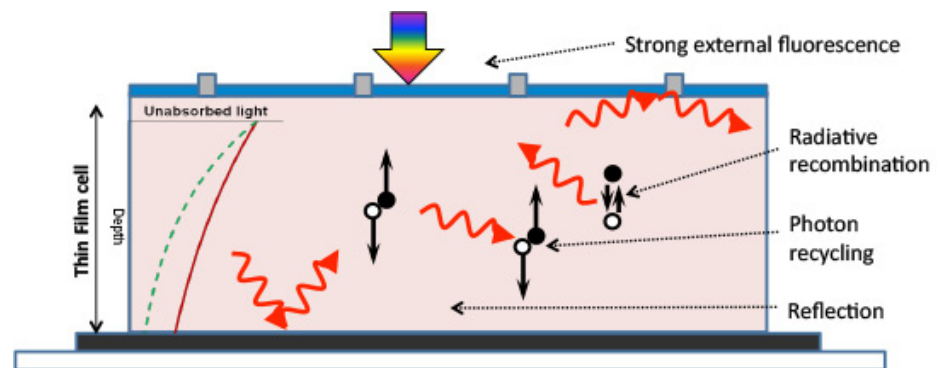
Review of contemporary energy harvesting techniques and their feasibility in wireless geophones

Naveed Iqbal^{1,2} | Mudassir Masood^{1,3} | Ali Arshad Nasir^{1,3} |
Khurram Karim Qureshi^{1,3}

Alta's flexible solar cell



- Yablonoitch's technique of "epitaxial liftoff," which uses acids to precisely separate thin films of gallium arsenide (GaAS) from the wafers on which they are grown:
- Direct band gap material +observed phenomenon called "Photon Recycling". Photons bounce off the back of the solar cell which allows them to be recaptured by the material and converted to electricity
- Alta Devices broke three world records: single junction cell performance at 28.8%, single junction module performance at 24.1%, and dual junction cell performance at 30.8%



Energy scavenging from vibrations

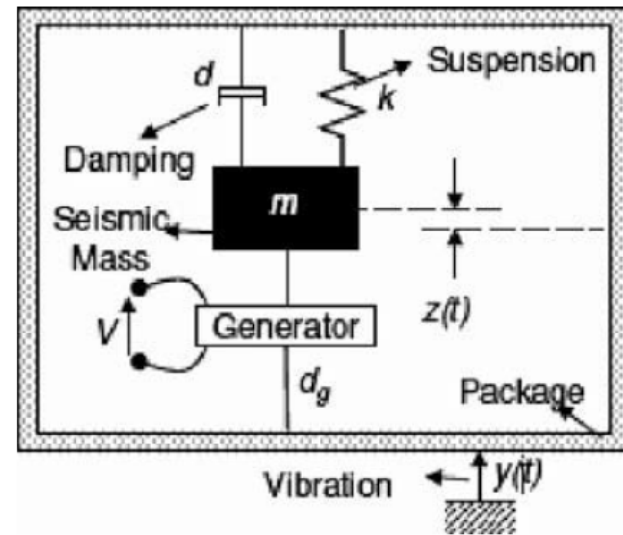
- Resonant vibration harvesters are by far the most widely investigated
- Resonant harvesters can be treated as a velocity damped mass spring system:

$$m\ddot{z} + (d + d_g)\dot{z} + kz = m\ddot{y}$$

z represent the motion of the mass, d_g the damping due to the transfer of mechanical energy to the electrical load, d the one due to parasitic effects, e.g. presence of air, friction of sliding surfaces and similar, k the spring constant of the suspension, m the moving mass and y the amplitude of the frame movement in z direction

Challenges:

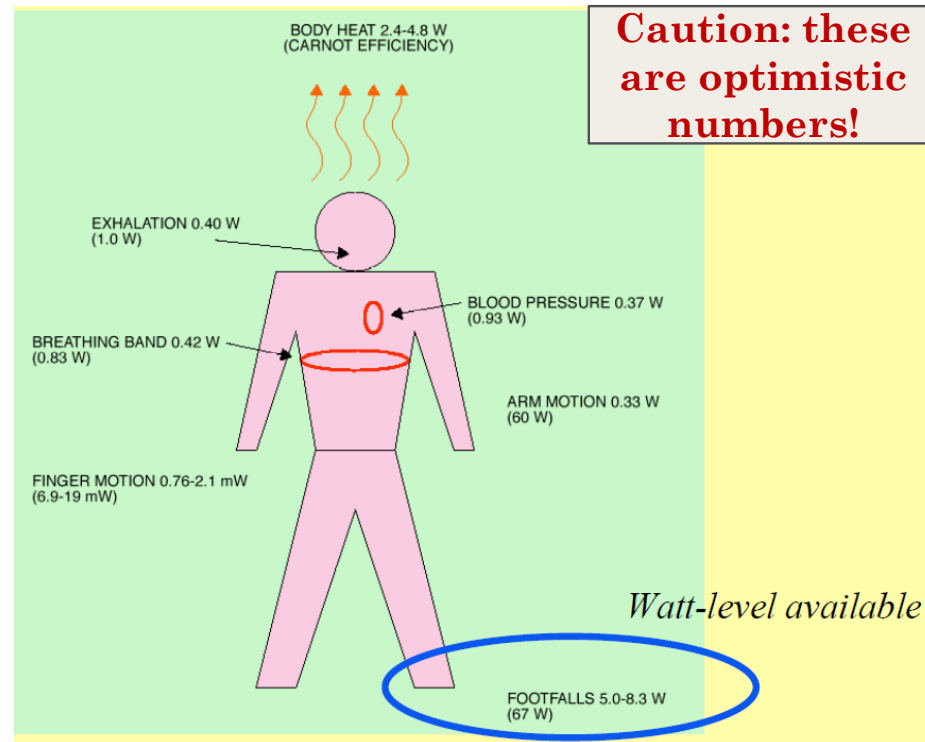
- **Frequencies not exactly known!**
- **Amplitudes?**
- **We need 100's of microWatts**
- **Efficient for large masses**
- **Good for automotive and for sport applications.**



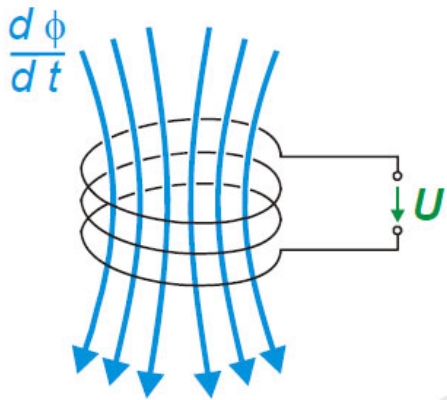
Motion harvesting: human energy >100's W

Where to tap the power?

Activity	Kilocal/hr	Watts
sleeping	70	81
lying quietly	80	93
sitting	100	116
standing at ease	110	128
conversation	110	128
eating meal	110	128
strolling	140	163
driving car	140	163
playing violin or piano	140	163
housekeeping	150	175
carpentry	230	268
hiking, 4 mph	350	407
swimming	500	582
mountain climbing	600	698
long distance run	900	1,048
sprinting	1,400	1,630



Electromagnetic harvesting (by movement)



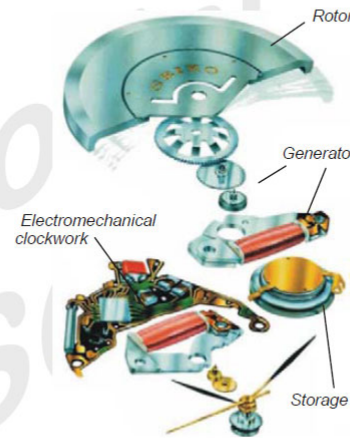
Generation of an AC current by an alternative field by movement: output power $\sim \mu\text{Watt}$ to mWatt

$P = 50 \text{ mW}$ @ 1g acceleration
The size of an apple!

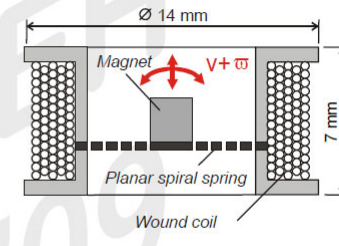


Perpetuum PMG17 ATEX/IECEX

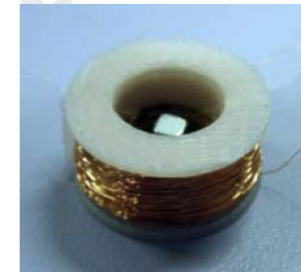
$P = 5 \mu\text{W}$



Rotatory converter from Seiko Kinetic

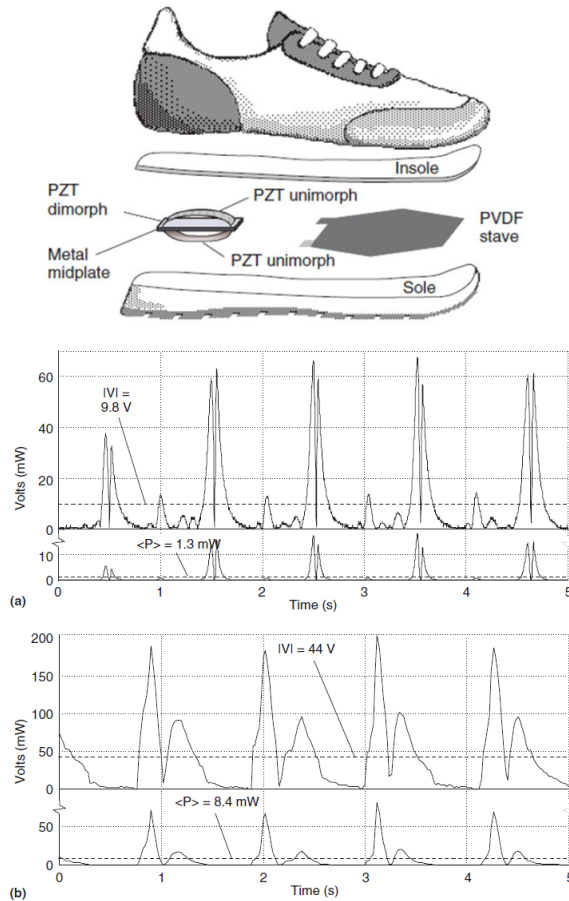


$P = 800 \mu\text{W}$



Multimodal oscillating converter, University of Hongkong, 2002

MIT's piezoelectric shoes (1998)



Rich Meier et al.,
A piezoelectric energy-harvesting shoe system for podiatric sensing, 2014 Conference of the IEEE Engineering in Medicine and Biology Society.

10-20 μJ of energy per step

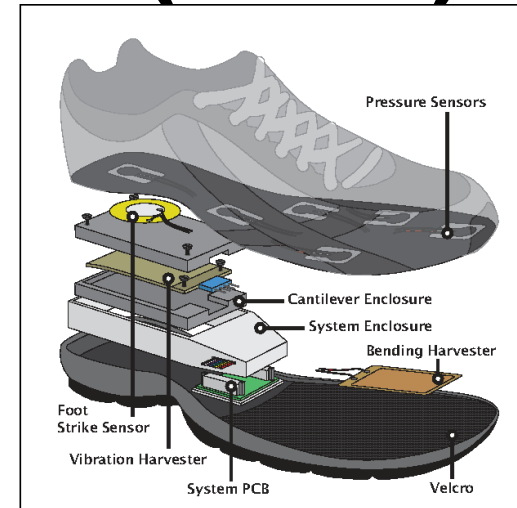


Fig. 1. Expanded view of the shoe system and all integrated components.

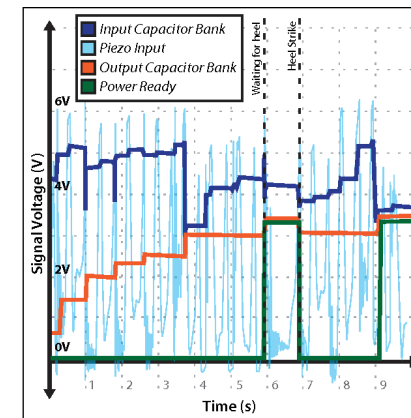
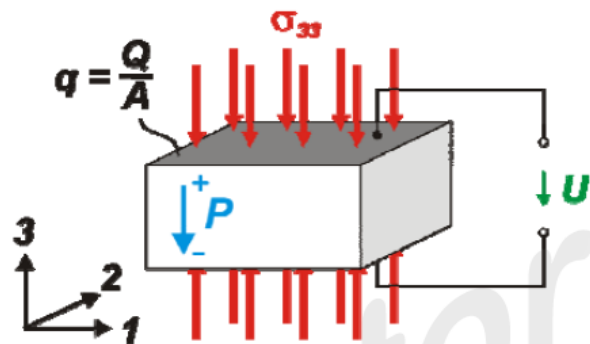
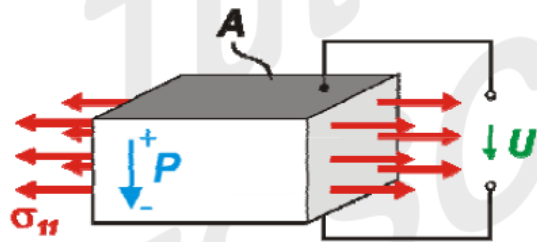


Fig. 3. A time-domain graph of energy capture in lab walking test. Note

Piezoelectric conversion/harvesting



Vertical mode: $q_3 = d_{33} \cdot \sigma_{33}$



Transversal mode: $q_3 = d_{31} \cdot \sigma_{11}$

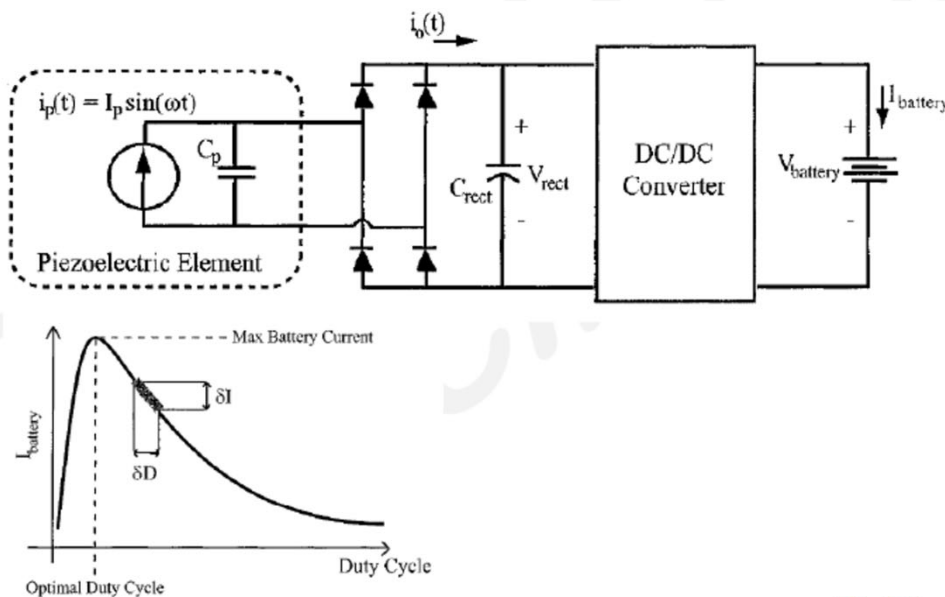
Comparison of piezoelectric materials					
Property	Units	PVDF Film	PZT	Barium Titanate	EMFI PP Film
		at 28 microns)			(at 70 microns)
Density	10[3]kg[-3]	1.78	7.5	5.7	330
Relative Permittivity	e/e[0]	12	1200	1700	1.2
d31 Piezoelectric Constant	10[-12]C/N	23	110	78	2
g31 Voltage Constant	10[-3]Vm/N	216	10	5	
k31 Electromechanical Constant	% at 1kHz	12	30	21	
P Pyroelectric Constant	Cm[-2]K	30		0.25 to 0.45	
Acoustic Impedance	10[6] kgm[-1]s[-1]	2.7	30	30	
Youngs Modulus	Nm[-2]	2-4			<1
Surface Resistivity	ohm/sq	0.1			<2
Dynamic Range	Pa	1-5 x 10[9]			<1 x 10[6]
Temperature Range	C	-40 to 100 (130 with some copolymers)			-40 to 50
Glass Transition Temperature	K	223			278

- Charge based converter
- Generation of AC current by dynamic mechanical stress
- Output voltage: 1V...100 V
- Output power: μ W...mW

Circuit interfaces for piezoelectric harvesting (1)

Iterative load matching

- Equivalent input resistance varies with duty cycle
- Iterative control is power extensive



[G. Ottman *et al.*, 2002]

Summary: state of the art, piezoelectric harvesting & electromagnetic (coil)

TABLE 7 Piezoelectric energy harvesters

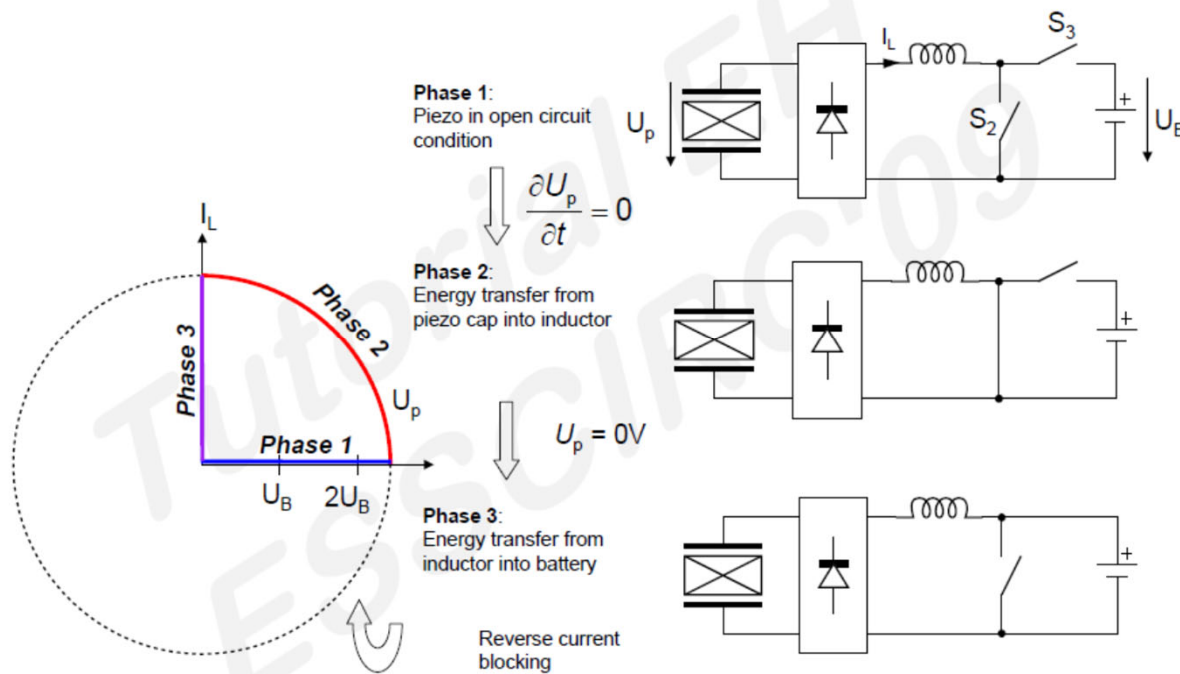
Freq. (Hz)	Acceleration (m/s ²)	Load (kΩ)	Max. power output (μW)	AC voltage output (V)
126	5	50	5.3	2.6
113	2.5	200	115.2	8.6
976	10	5.1 × 10 ⁵	2.45 × 10 ⁻⁵	—
1.39 × 10 ⁴	—	5.2 × 10 ³	1	2.4
214	19.6	510	1.288	2.292
255.9	24.5	510	2.675	1.792
870	9.8	—	1.4	1.6
572	19.6	—	60	—
150	9.8	11	2.7 × 10 ⁴	17
461.15	19.6	6	2.15	—
125	1.96	1 × 10 ⁴	0.12	—
183.8	7.36	16	0.32	0.101
1700	—	5.6	650	—
97	1.96	2 × 10 ³	0.136	1
608	9.8	21.4	2.16	0.898
107	2.5	55.90	222	3.428
107	2.5	11.91	586	2.627
150	5	5.2 × 10 ³	1.01	2.4
2580	18.36	56	1.8 × 10 ³	—
120	2.5	—	375	—
80	—	333	2	1.2
229	—	—	3.98	3.93

TABLE 8 Electromagnetic energy harvesters

Freq. (Hz)	Acceleration (m/s ²)	Load (kΩ)	Max. power output (μW)	AC voltage output (V)
322	2.7	—	180	—
20.8	1.96	1.35 × 10 ³	118.3	—
52	1.7	—	120	—
30	1.47	50	20	0.8
100	1.96	—	240	—
12	29.4	40.8	71.26	0.47
369	—	—	0.6	1.38 × 10 ⁻³
62	—	—	1.77	—
30	—	—	254	—
40	—	—	153	—
52	0.59	4	46	—
128	—	6	404	—

Interfaces for piezoelectric harvesting (2)

Burst energy extraction



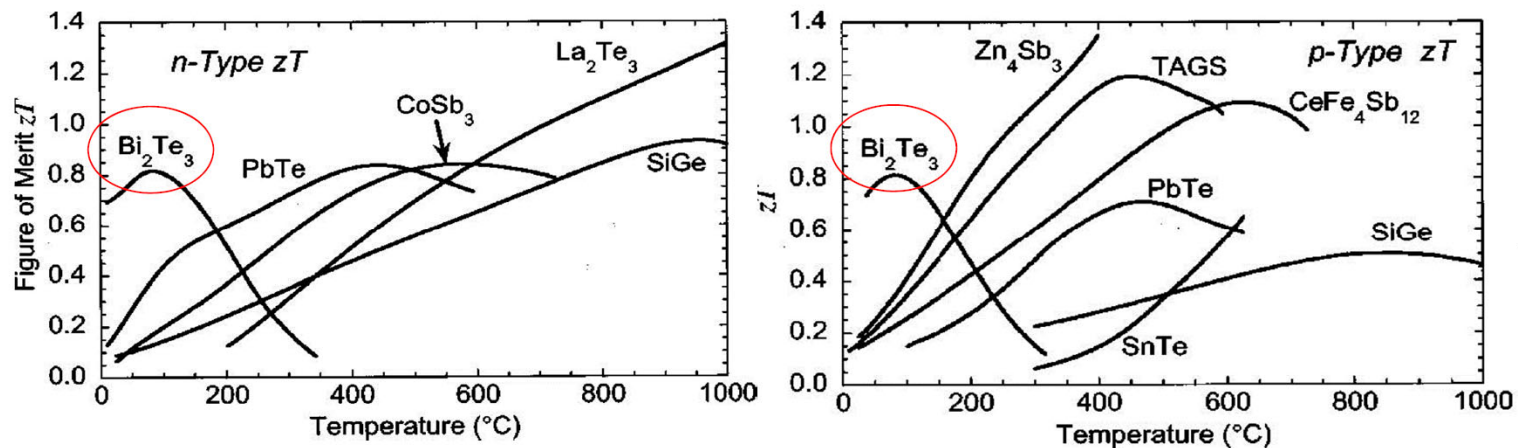
[T. Hehn *et al.*, 2008]

Thermoelectrical (TEG) harvesting: materials

The figure of merit z expresses a materials suitability for TE conversion:

$$zT = \frac{\alpha^2 \sigma}{\lambda} T$$

α = Seebeck coefficient
 λ = thermal conductivity
 σ = electrical conductivity



Which material system? Bismut-Telluride (Bi_2Te_3) with best properties between $25^\circ C$ and $150^\circ C$

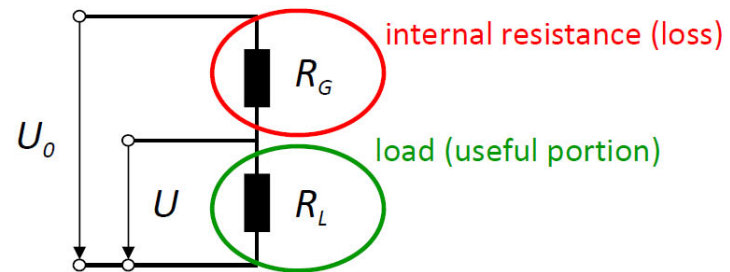
TEG performance factors

Open Circuit voltage: $U_0 = m \alpha \Delta T_G$

P_{\max} (matched load $R_L=R_G$):

$$P_0 = UI = \frac{U_0^2}{4R_G} = \frac{m^2 \alpha^2}{4R_G} \Delta T_G^2$$

- U_0 = Seebeck voltage
- m = Number of thermocouples
- α = Seebeck coefficient of thermocouple
- ΔT_G = Temperature difference across generator

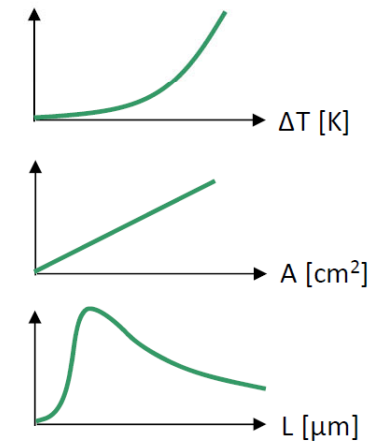


Output power depends on:

- Temperature difference \Rightarrow **QUADRATIC**
- TEG size \Rightarrow **LINEAR**
- TEG thickness \Rightarrow **OPTIMIZED**

Example:

**Efficiency Factor: $10 \mu\text{W}/\text{cm}^2/\text{K}^2$, $\Delta T=10\text{K}$, TEG size: $10 \times 10 \text{cm}^2$,
 \rightarrow 100mW output power**

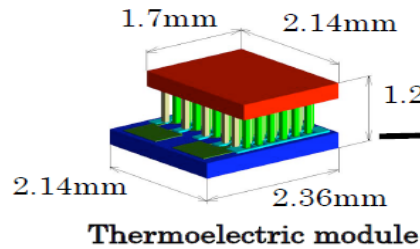


Example

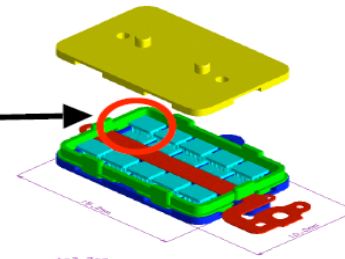
Seiko SII Thermic[®] Heat-Powered Watch



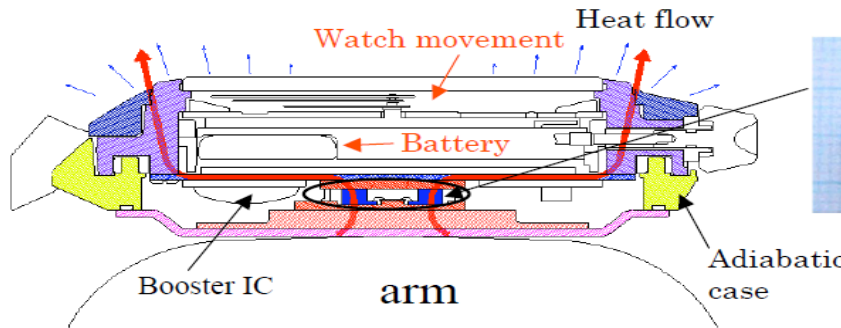
Thermal energy watch



Thermoelectric module



Thermoelectric unit

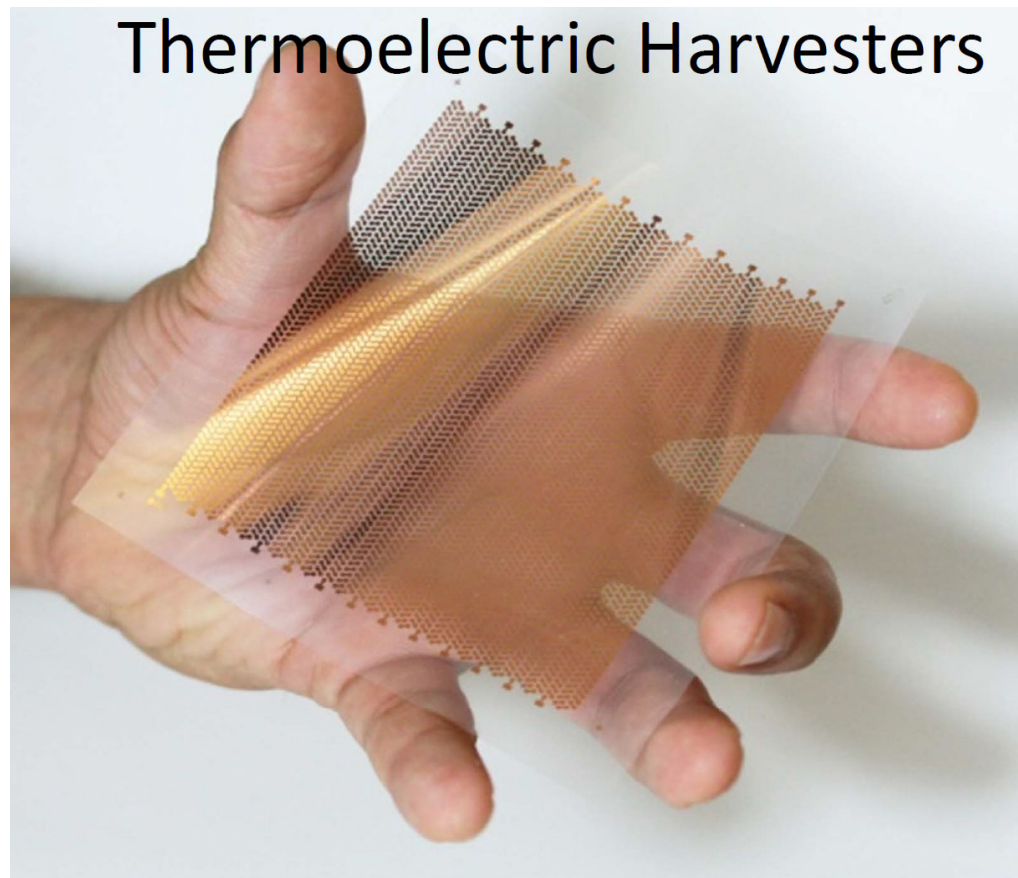


Thermoelectric (Photo)

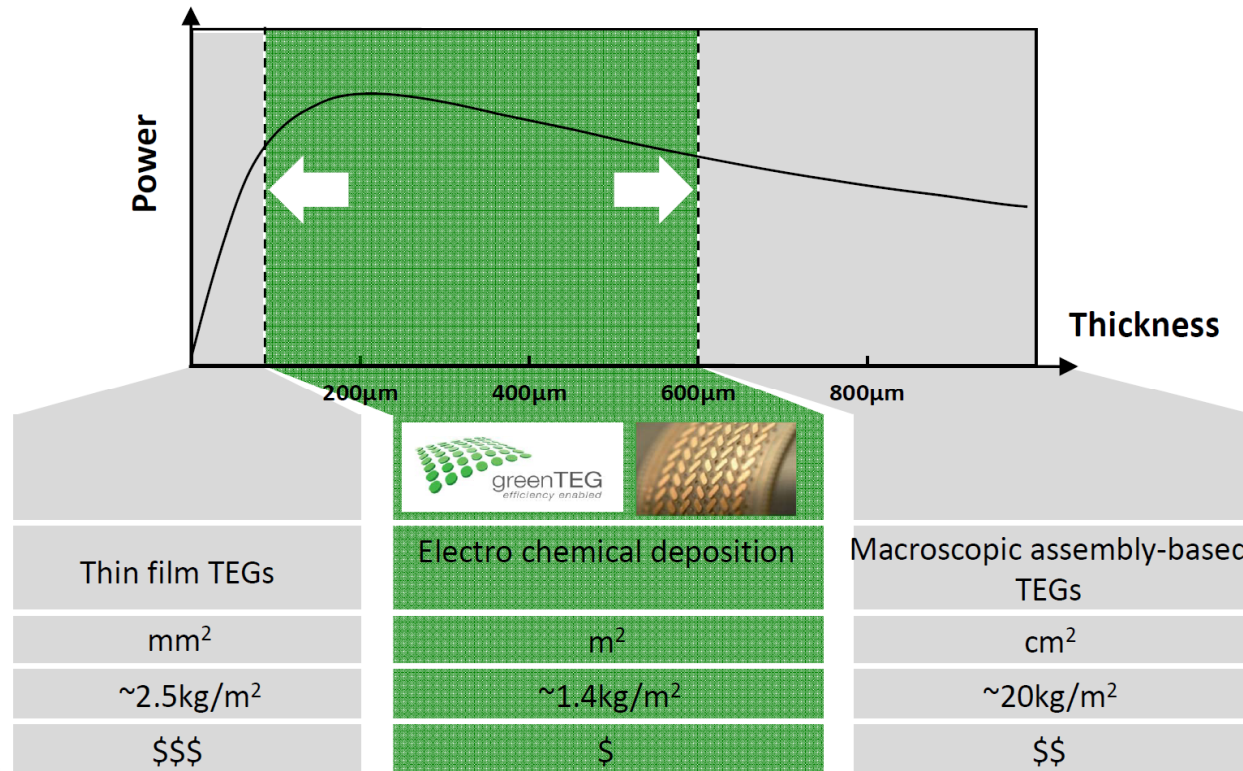
- Uses 10 Thermoelectric modules and a booster IC
 - Runs off body heat
- Low ΔT , limited surface area, low efficiency -> Microwatts...*

Thermoelectrical harvesters

- On foil technology

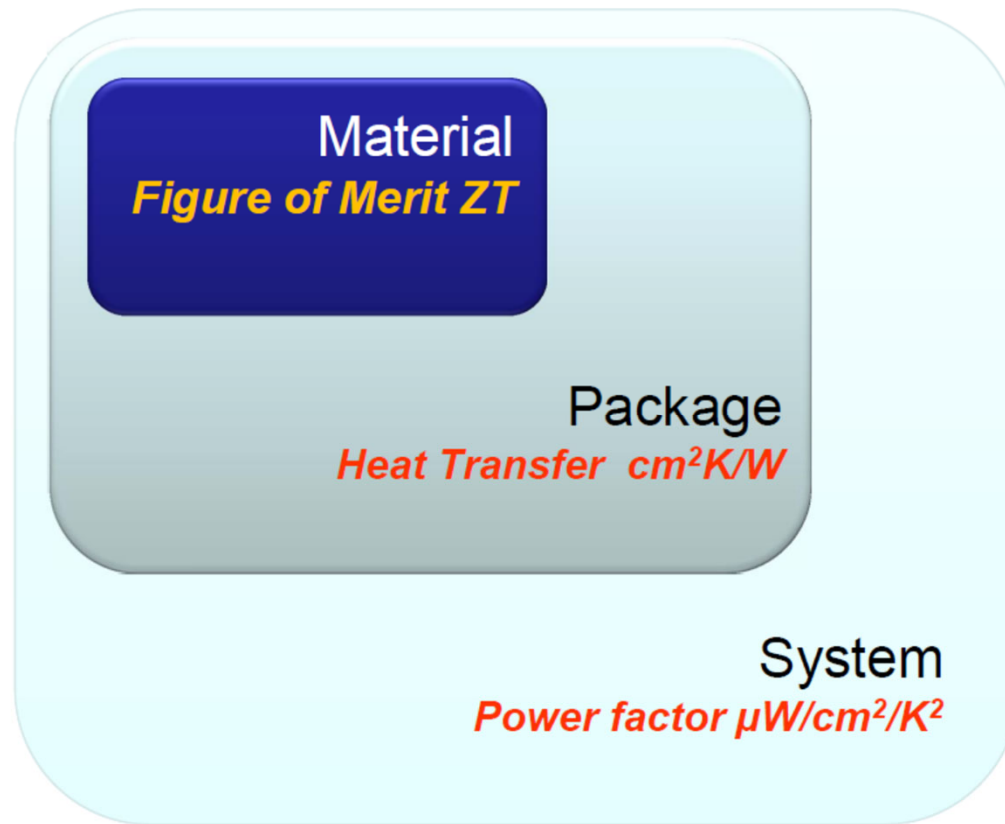


TEG microsystem optimize power and cost



Source: Ch. Hierold, ETHZ.

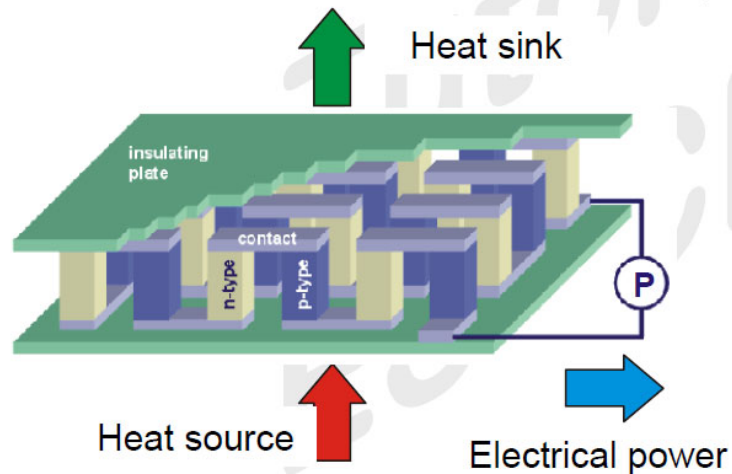
TEG efficiency: material to system



Thermoelectric conversion from Hot ICs?

Harvesting of dissipated thermal energy in hot electronic chips.

$$\Delta U = \alpha \cdot \Delta T$$



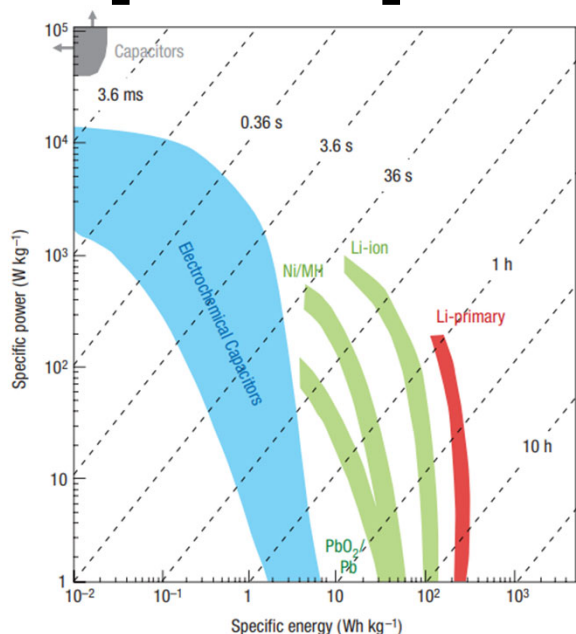
Seebeck coefficients of relevant material couples:

	α [$\mu\text{V}/\text{K}$]
Al / p-Poly-Si	195
Al / n-Poly-Si	110
p-Poly-Si / n-Poly-Si	190...320
p-Bi _{0,5} Sb _{1,5} Te ₃ / n-Bi _{0,87} Sb _{0,13}	200...420

Characteristics

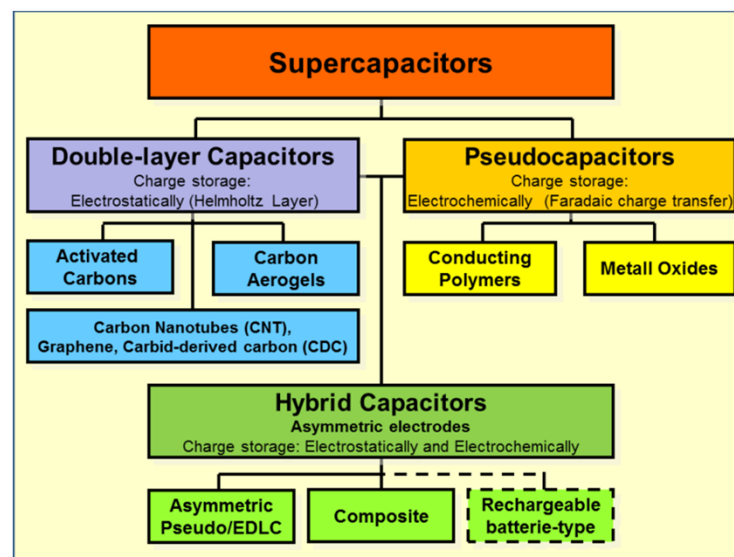
- Generation of DC current, but...
- ... polarity changes with direction of temperature gradient!
- Output voltage: around 100 mV
- Output power: some μW

Supercapacitors: rationale



Supercapacitors:

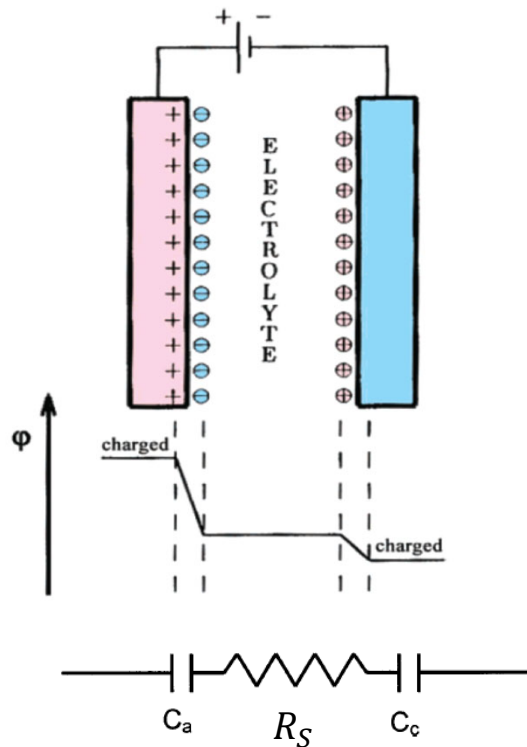
- Higher power density
- Much faster charge and discharge rate
- Environmentally friendly
- Extremely low internal resistance High efficiency (97-98%)
- Over a million charge-discharge cycles



Batteries:

- Higher energy density
- Typically 200–1000 charge-discharge cycles
- Contain highly reactive and hazardous chemicals
- Negatively effected by low temperatures

Supercapacitors

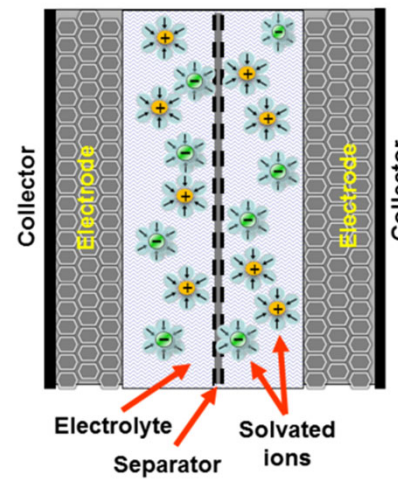


$$1/C = 1/C_a + 1/C_c$$

$$Energy = \frac{1}{2} C V^2$$

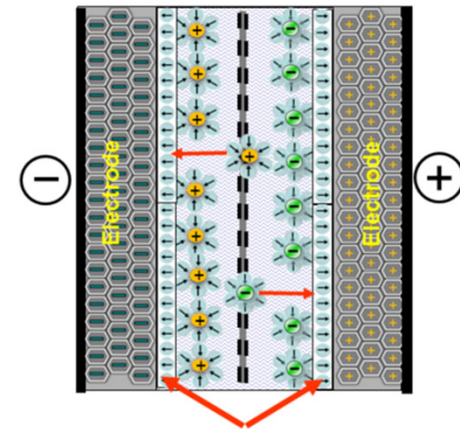
$$Power = \frac{V^2}{4R_s}$$

Capacitor discharged



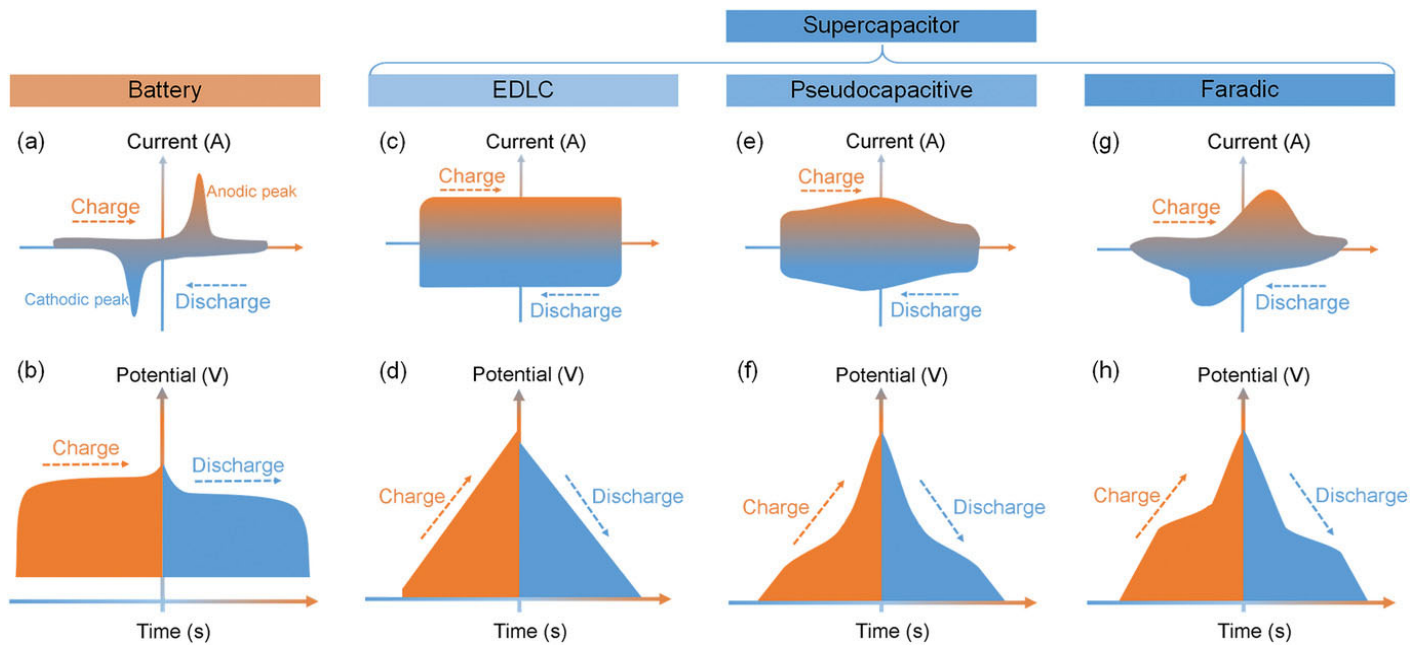
Random distribution of ions

Capacitor charged



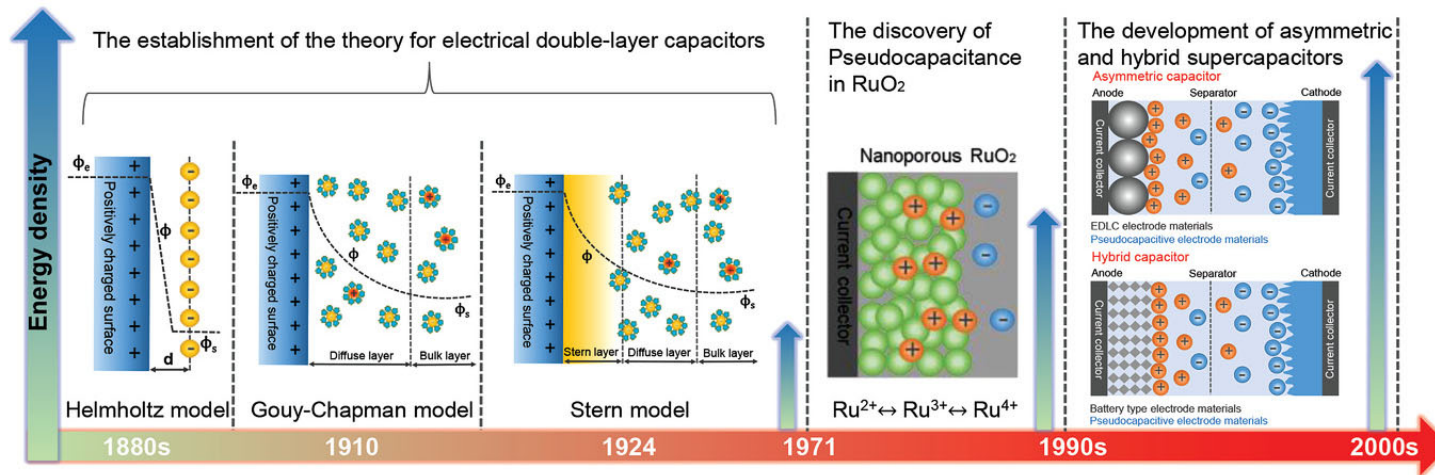
Inner Helmholtz plane
(polarized solvent molecules)
Mirror image of charge distribution
of ions in opposite polarity

Supercapacitors



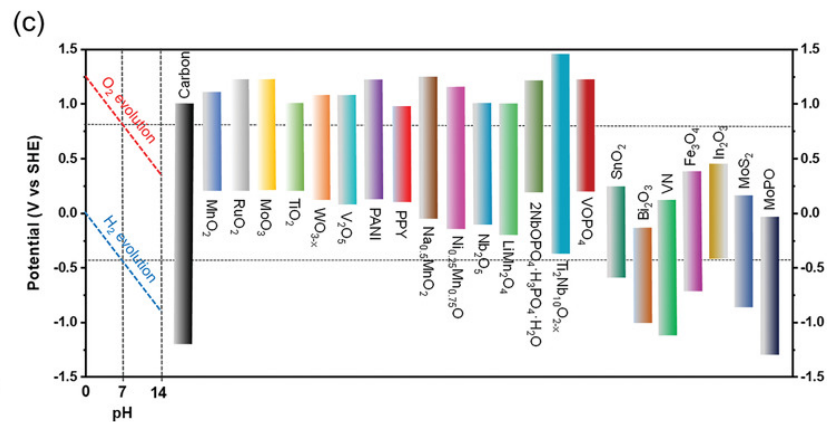
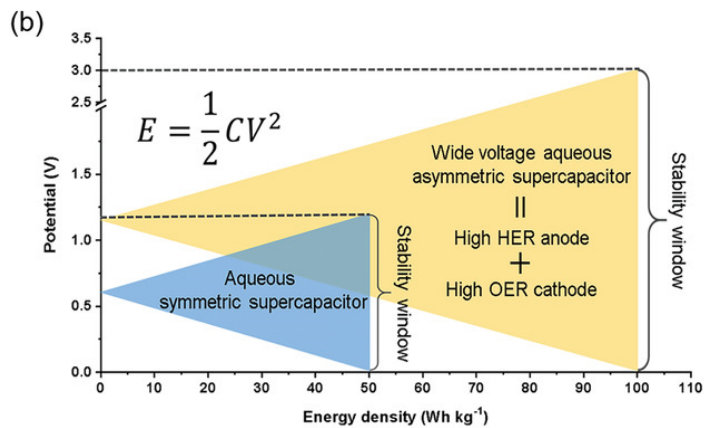
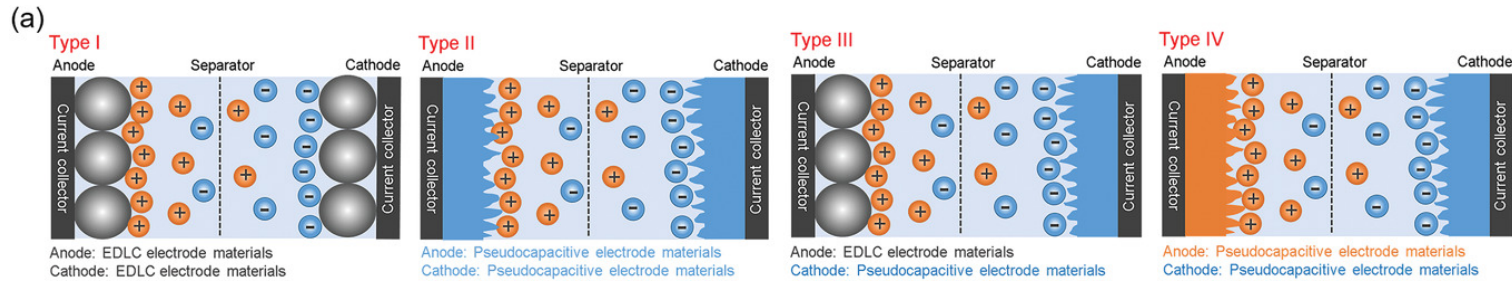
Energy-storage materials can be categorized as EDLC materials, pseudocapacitive materials, and Faradaic materials.

Supercapacitors



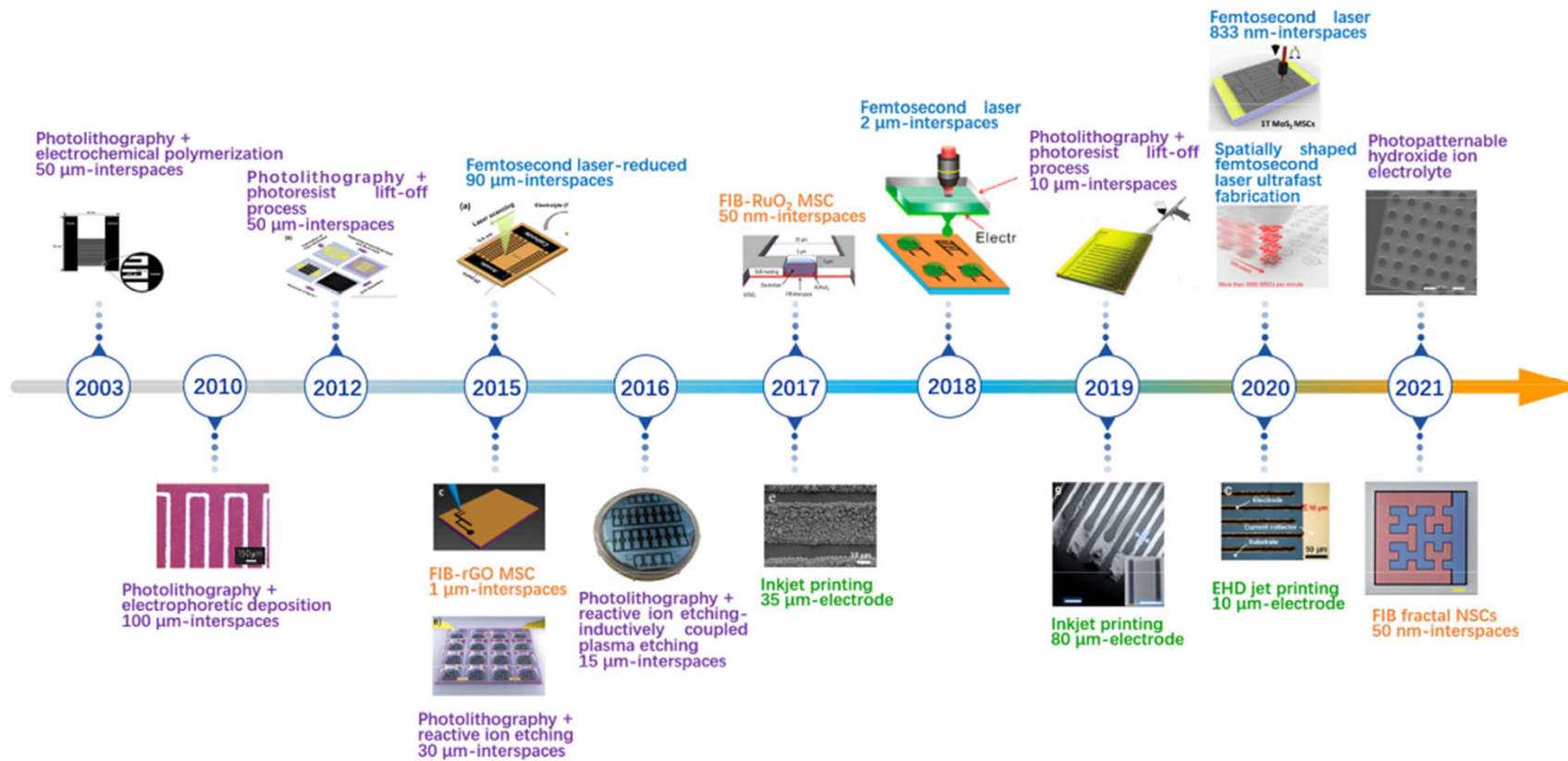
Various energy-storage mechanisms have been developed in SCs systems using different materials.

Supercapacitors- voltage window



Pseudocapacitive electrode materials such as RuO_2 and MnO_2 store charge through Faradaic electron transfer and non-Faradaic charge storage.

Roadmap



Sen Wang et al., *Nano Research Energy* (2022).

Schematic sensor-node architecture for sustainable IoT

