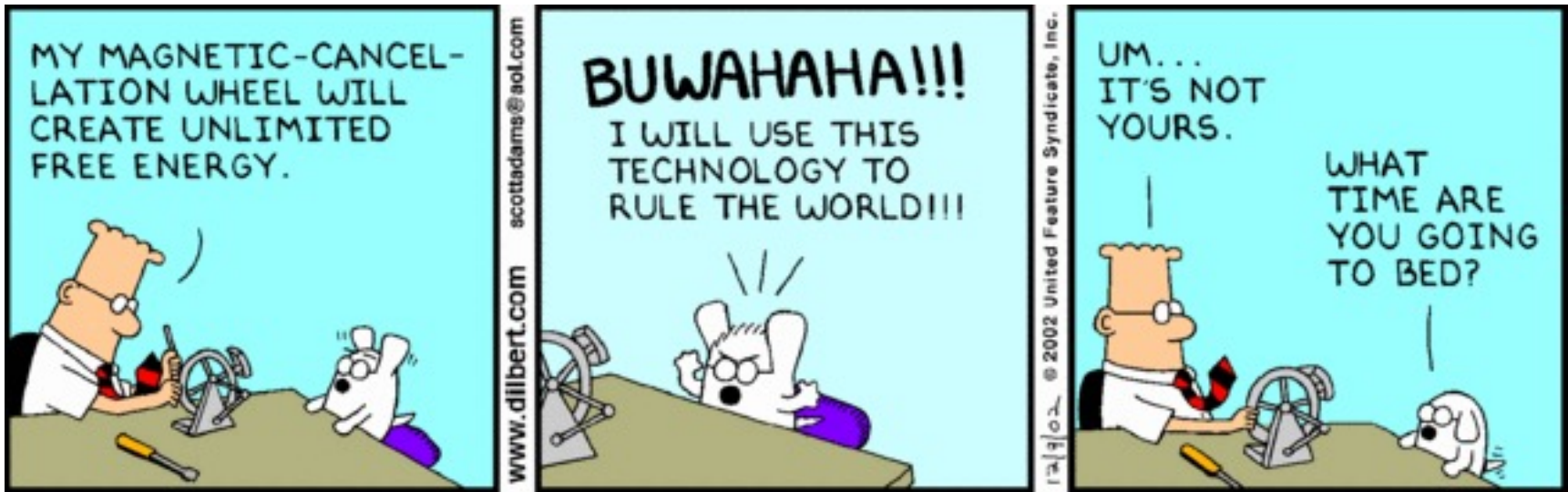


Sisteme Încorporate

Cursul 12

Energy Harvesting

Facultatea de Automatică și Calculatoare
Universitatea Politehnica București



<http://dilbert.com/strips/comic/2002-12-09/>

Tehnologia curenta permite aparitia unei noi clase de senzori si sisteme de control care folosesc energia recoltata din mediul inconjurator pentru a se alimenta

Aceste sisteme au cerinte foarte mici de consum de energie si sunt optimizate pentru un timp de viata foarte mare.

Recoltarea Energiei

- A existat inainte de inventarea surselor conventionale de energie (baterii sau generatoare electrice)
- Odata cu micsorarea dispozitivelor embedded si reducerea consumului, cercetarea de noi mijloace pentru recoltarea energiei a devenit un domeniu de interes.
- Surse de energie
 - RF
 - Energie Solara
 - Termoelectric
 - Vibratii
 - Omul



- Surse de radiatie ambientale
 - Passive RFID
- Recoltarea de energie biomecanica
 - Miscarea umana (genunchi, calcai etc.)
- Energie piezoelectrica
 - Surse de vibratii
- Energie piroelectrica
- Energie termoelectrica
- Energie electromagnetica
 - Inductia magnetica intr-o bobina (diferite tipuri de dinamuri)
- Energie electrostatica (capacitiva)
 - Modificarea activa a dimensiunilor unor condensatoare
- Recoltarea energiei metabolice a copacilor
 - <http://voltreepower.com/index.php>
- Recoltarea de energie din zaharurile din sange

Energy Harvesting

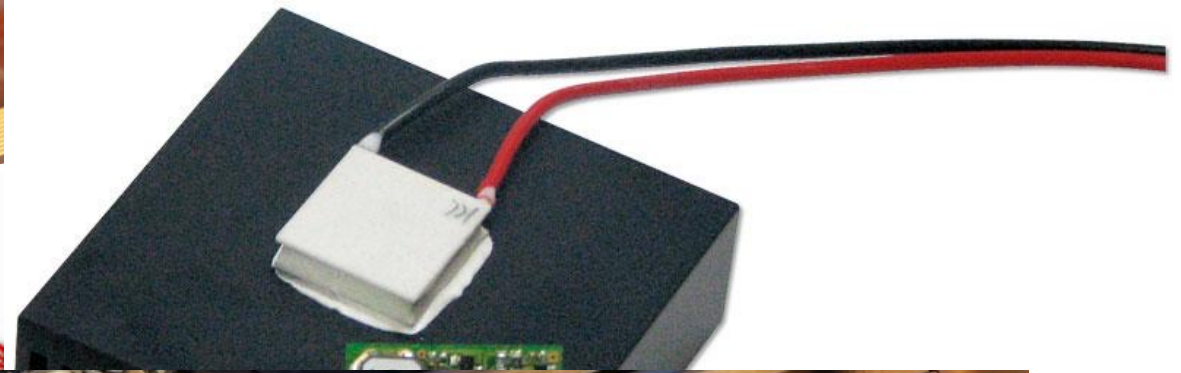
- Este o tehnologie care deschide noi posibilitati in portabilitate si durata de functionare a aplicatiilor
- Permite alimentarea neintrerupta a dispozitivelor electronice din locuri greu accesibile
- Teoretic, timpul de viata al unui dispozitiv poate fi prelungit la nesfarsit



Exemple

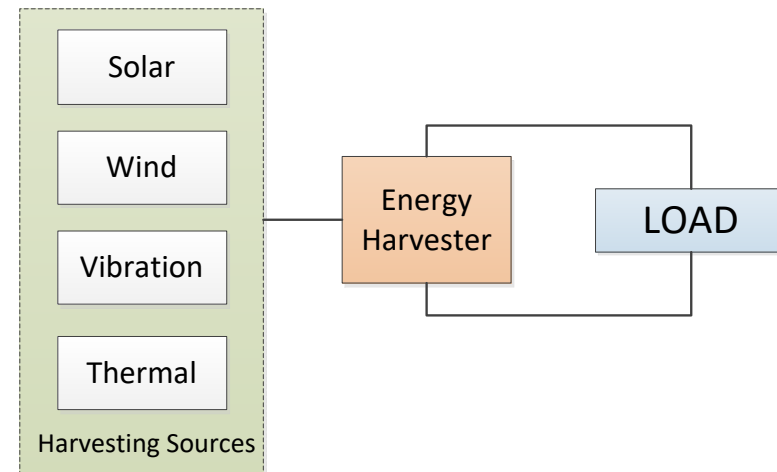


eZ430-RF2500-SEH
Solar Energy Harvester



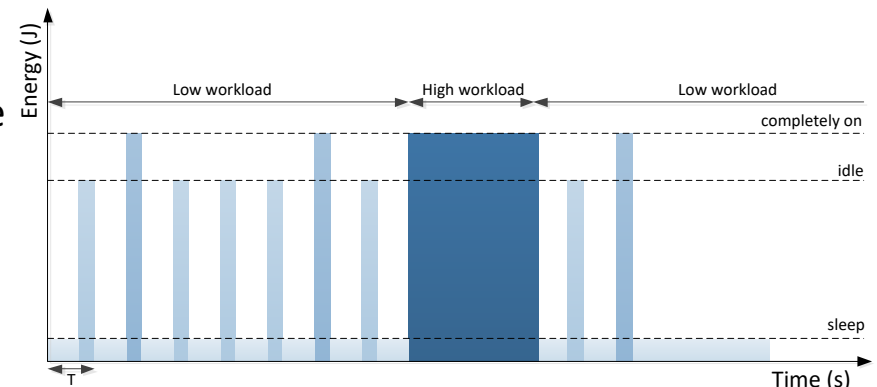
Energy Harvesting

- Proces prin care energia din mediul înconjurător este captată și stocată
- Tehnologie care deschide noi posibilități în portabilitate și durata de funcționare a aplicațiilor
- Permite alimentarea neîntreruptă a dispozitivelor electronice din locuri greu accesibile
- Teoretic, timpul de viață al unui dispozitiv poate fi prelungit pe o durată foarte lungă

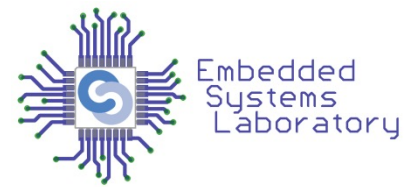


Considerente de design

- ▶ Energy Neutrality. Cum poate fi variat consumul de energie al rețelei a.î. să fie tot timpul mai mic decât rata cu care e produsă energia?
- ▶ Performance Balancing: Cum poate fi maximizată performanța unui sistem într-un buget energetic dat?

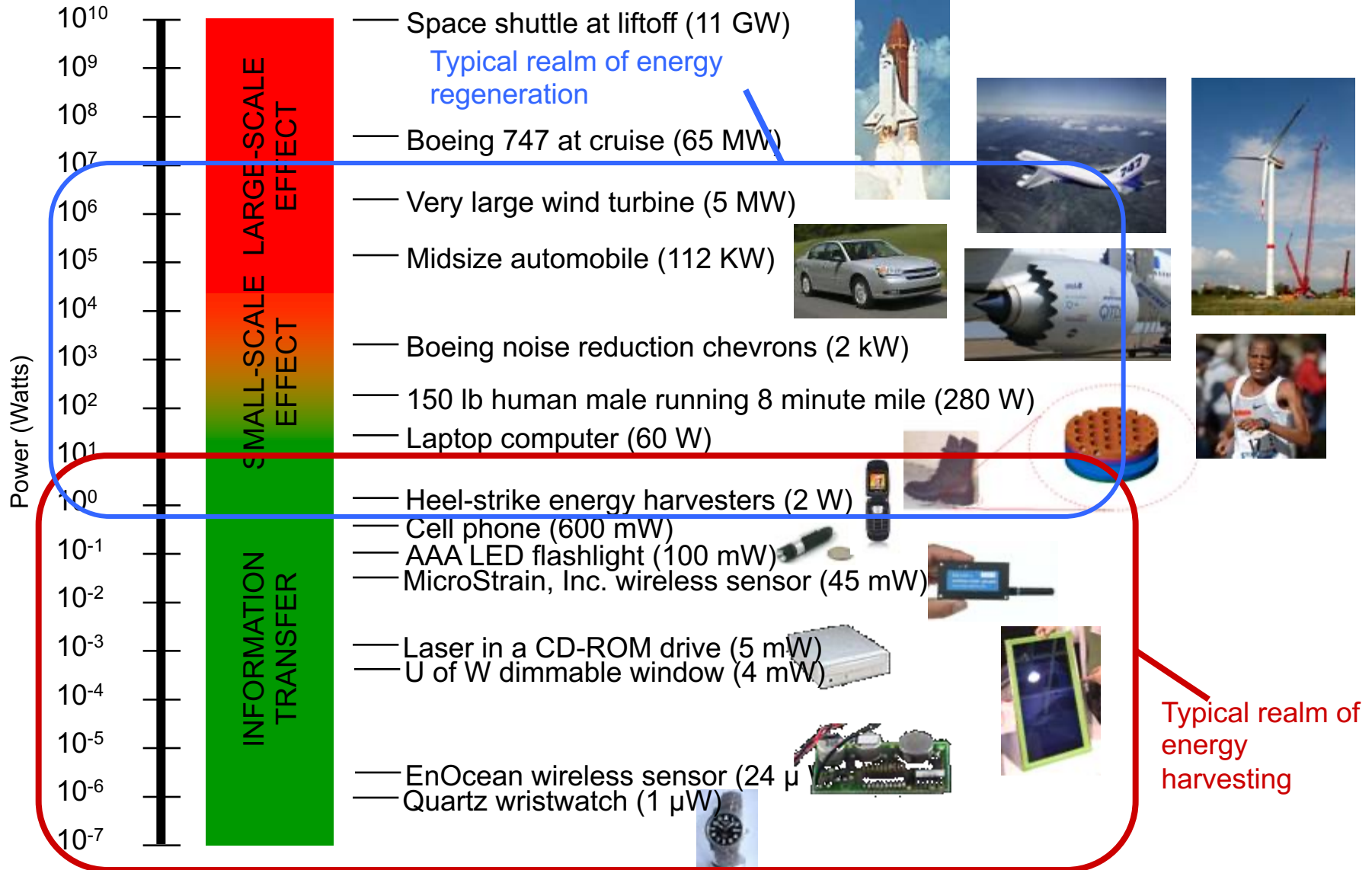


Energy Harvesting - Objective

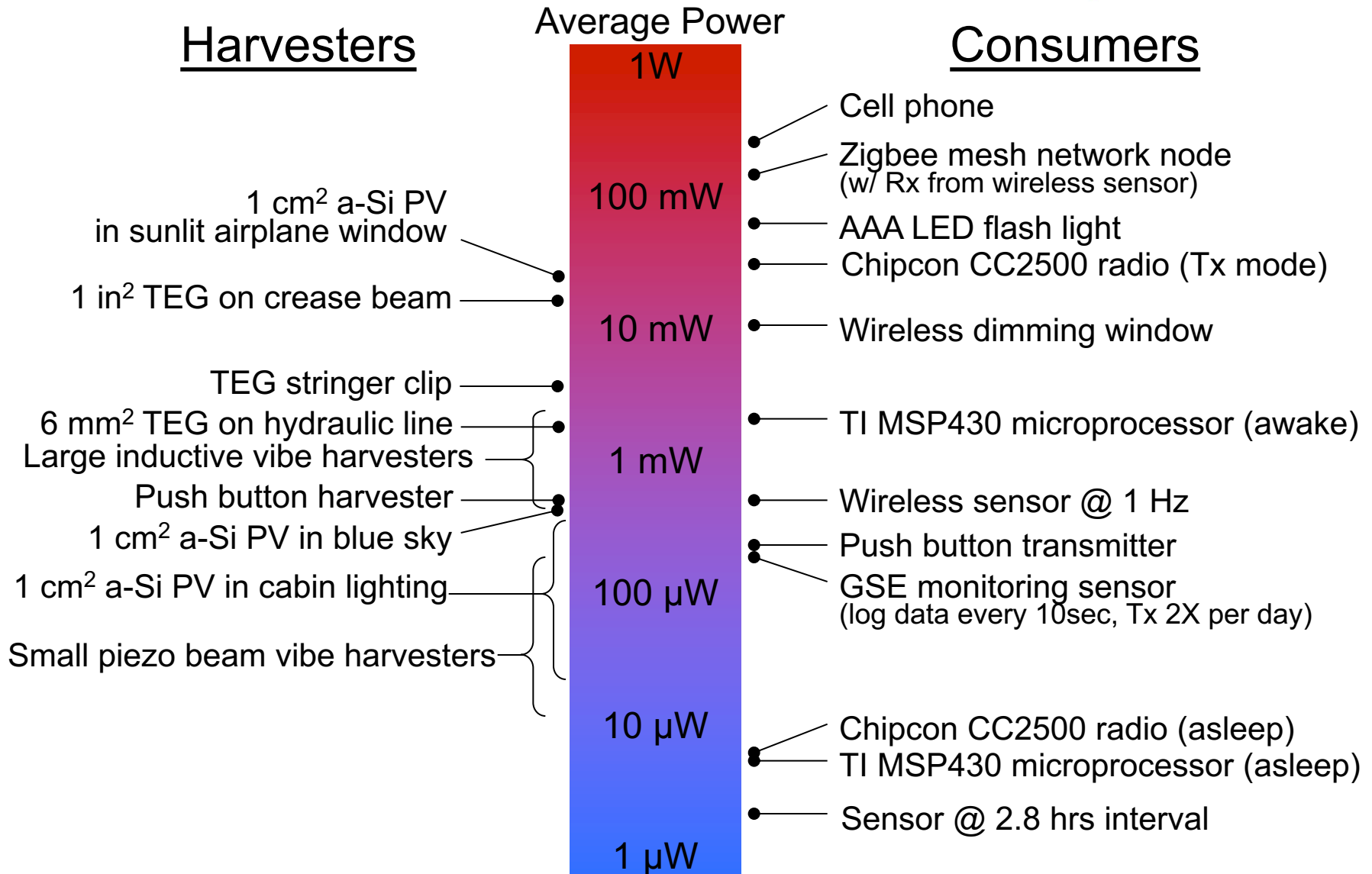
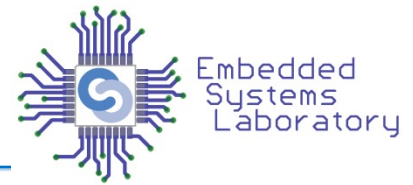


- Reducerea greutatii
 - Reducerea costurilor de instalare si intretinere
 - Sa permita introducerea rapida a functionalitatilor noi
 - Sa permita reconfigurarea rapida a rețelei
-
- **Se pune accent pe**
 - **Aplicatii care au cerinte limitate de latime de banda**
 - **Eliminarea cablurilor: distante mari de acoperit, articulatii flexibile, zone dificil de accesat, medii ostile**

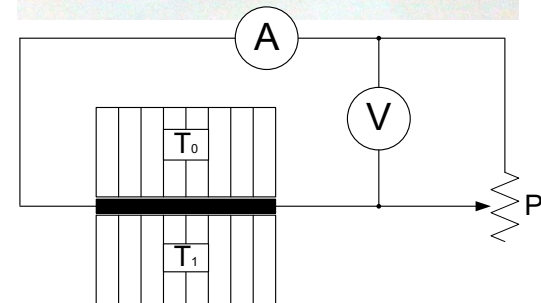
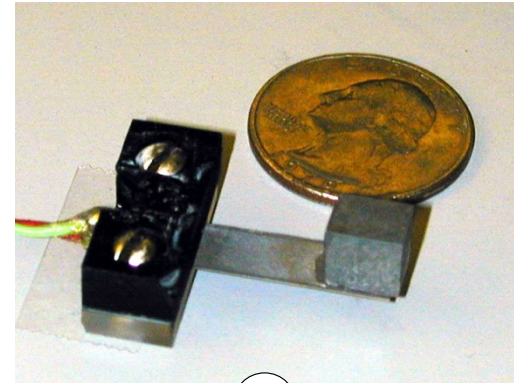
Examples of Power Generation and Consumption



Energy Harvesting Power Generation & Utilization



- Conversia piezoelectrică
 - Grindă elastică de material piezoelectric cu o greutate atașată la capătul mobil.
 - Energie maximă -> frecvența de rezonanță
 - $f = 120\text{Hz}$; $V = 4 - 6\text{V}$; $P = 800\mu\text{W}$
- Conversia termoelectrică
 - Folosește efectul Seebeck
 - $V = \alpha\Delta T$
 - Se pretează la medii cu diferențe mari de temperatură ($>30^\circ\text{C}$)
- Conversia fotovoltaică
 - Folosește celule de siliciu pentru a transforma energia luminoasă în energie electrică
 - Randament - 10-13%



Energia solara este o solutie?

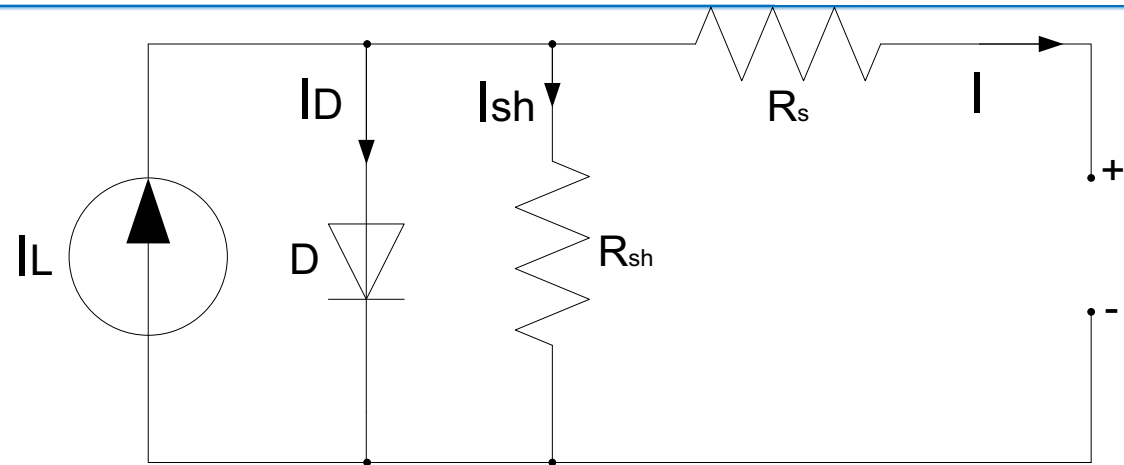
- Randament de conversie lumina-electricitate foarte scazut ($< 20\%$ pentru celule obisnuite cu siliciu cristalin)
- De fapt, randament $\sim 10\%$ pentru celule cu siliciu amorf (100mW/cm² la iluminare maxima sau 100uW/cm² in interior)



Conversia Fotovoltaică

$$I = I_L - I_D - I_{SH}$$

I = output current
 I_L = photogenerated current
 I_D = diode current
 I_{SH} = shunt current



$$V_j = V + IR_S$$

V = voltage across the output terminals
 I = output current
 R_S = series resistance

$$I_{dark}(V) = J_0 \left(e^{\frac{qV}{kT}} - 1 \right)$$

$$V_{oc} = \frac{kT}{q} \ln \left(e^{\frac{J_{sc}}{J_0}} + 1 \right)$$

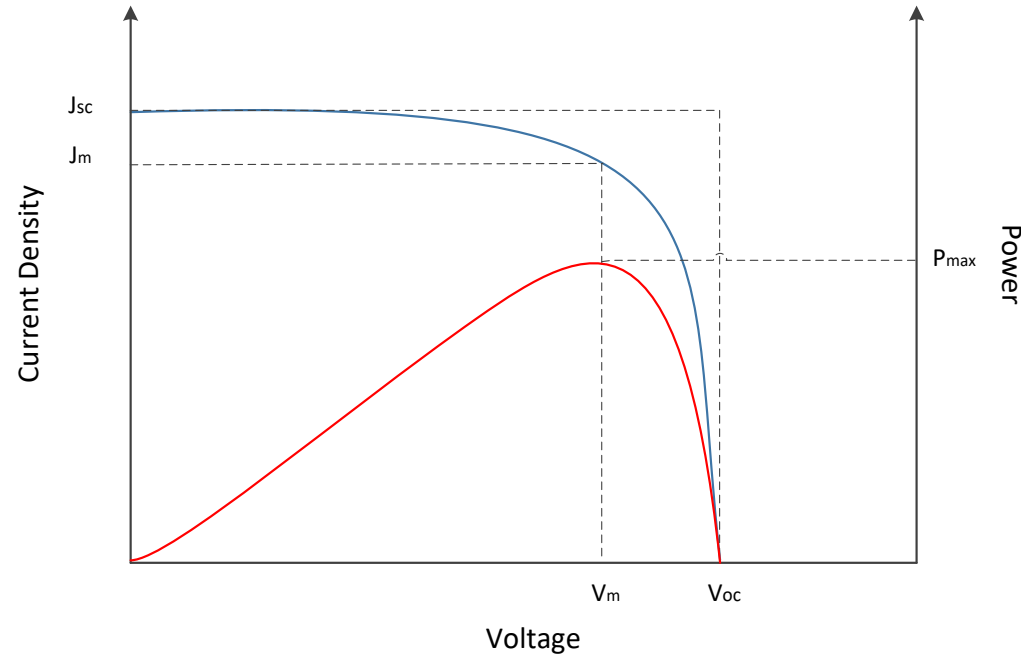
$$I_D = I_0 \left\{ \exp \left[\frac{qV_j}{nkT} \right] - 1 \right\}$$

$$I = I_L - I_0 \left\{ \exp \left[\frac{q(V + IR_S)}{nkT} \right] - 1 \right\} - \frac{V + IR_S}{R_{SH}}$$

Conversia Fotovoltaică

Parametrii ce descriu funcționarea unei celule:

- Eficiența
- Densitatea curentului de scurtcircuit
- Tensiunea de mers în gol
- Factorul de umplere

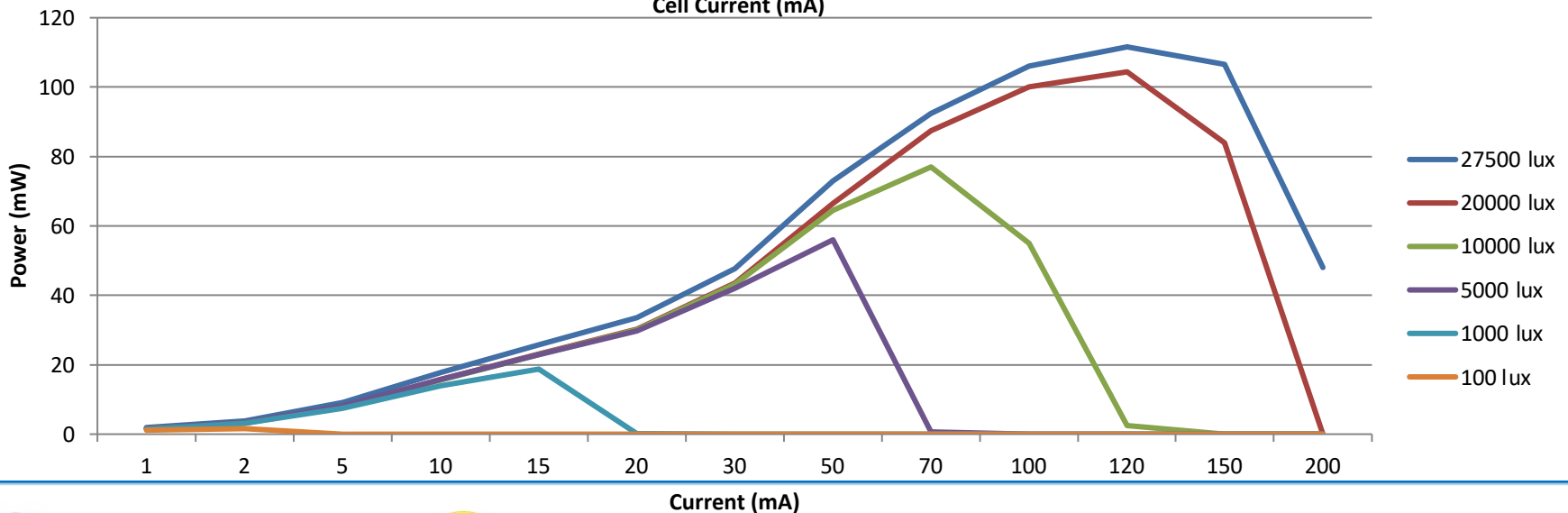
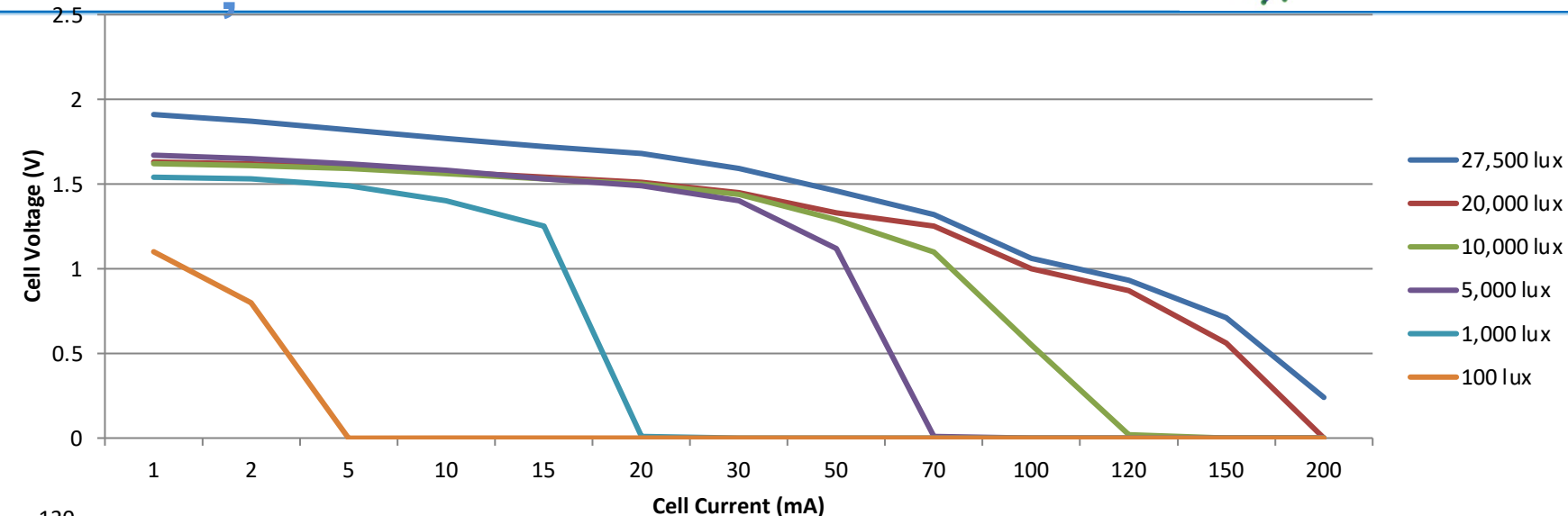


$$FF = \frac{P_m}{P_{max}} = \frac{J_m V_m}{J_{sc} V_{oc}}$$

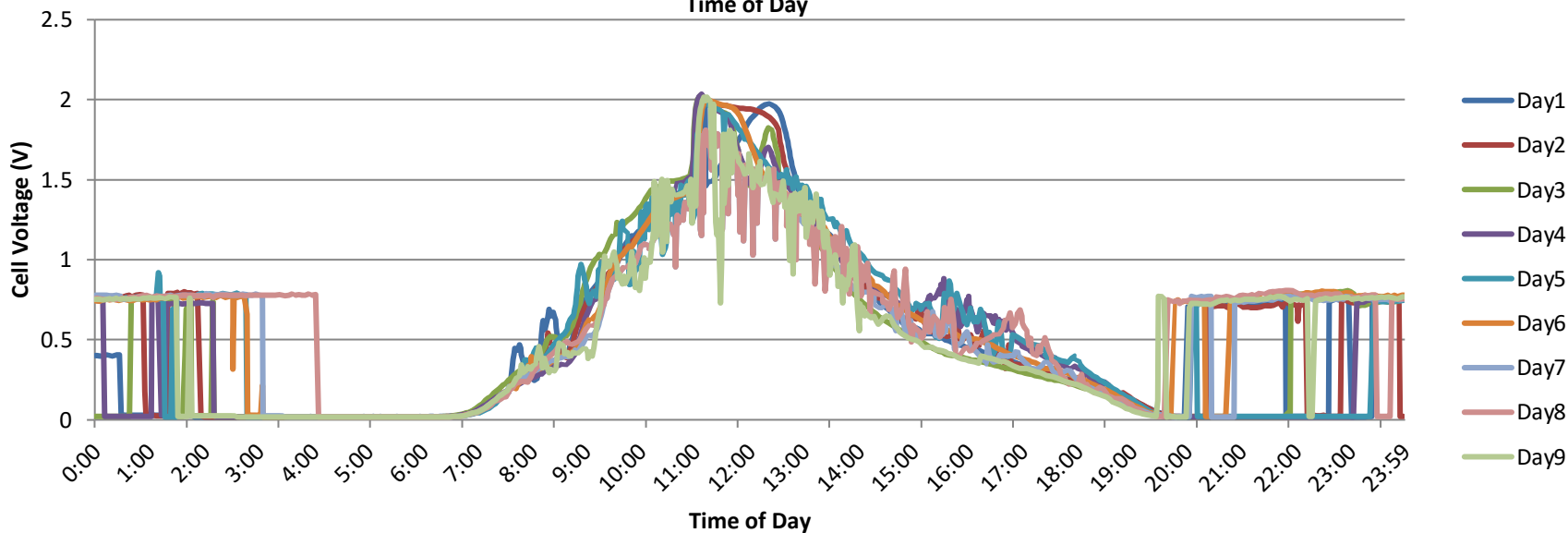
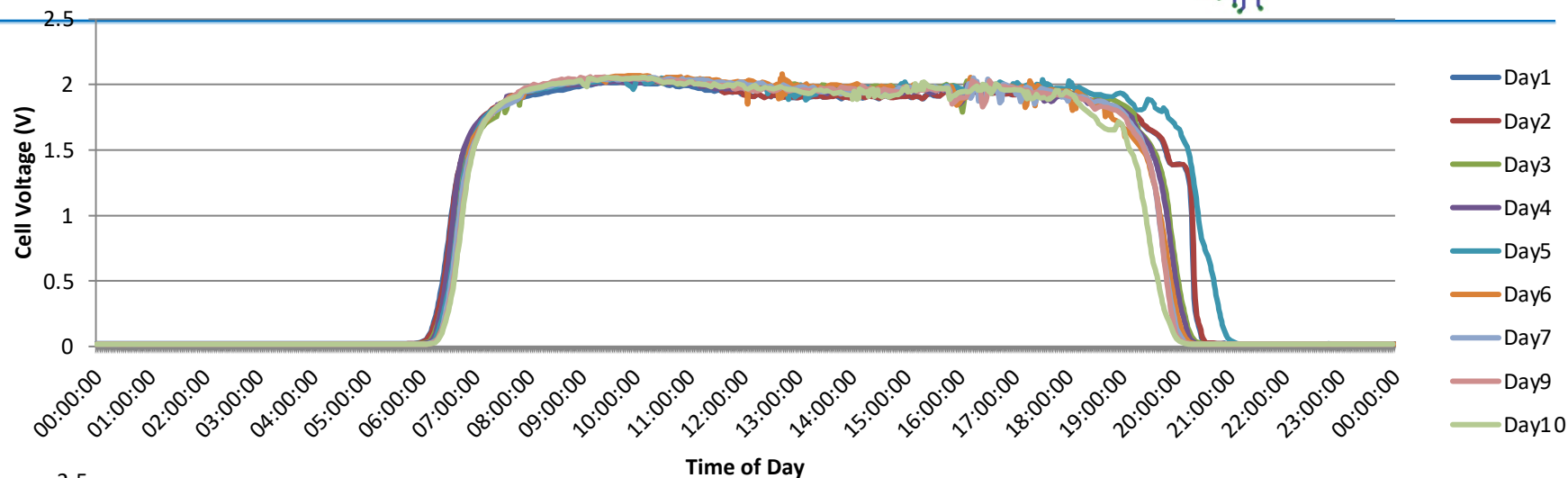
$$\eta = \frac{P_m}{P_l} = \frac{J_m V_m}{P_l}$$

$$\eta = \frac{J_{sc} V_{oc} FF}{P_l}$$

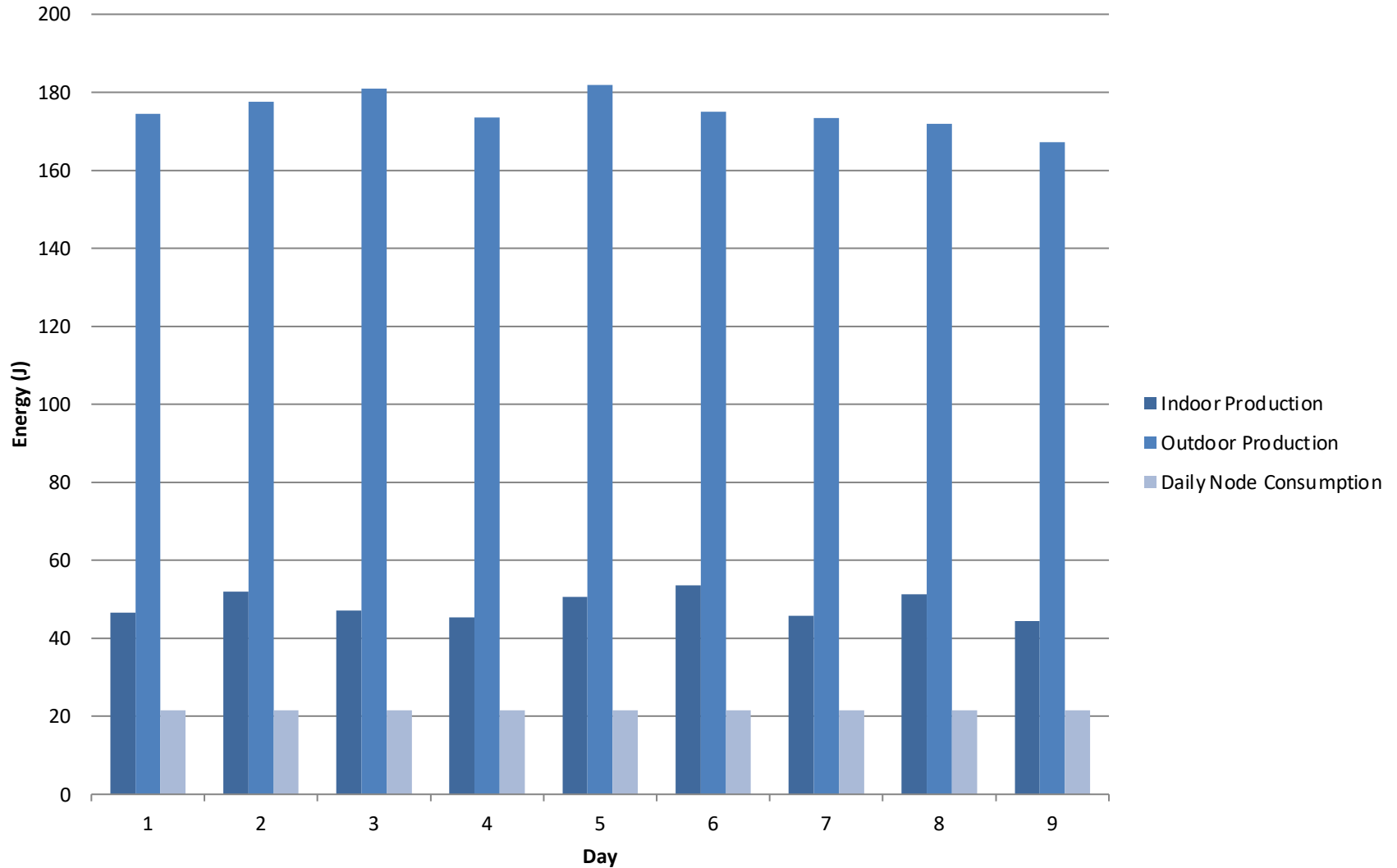
Conversia Fotovoltaică – Eficiență



Conversia Fotovoltaică – Profil Putere Produsă



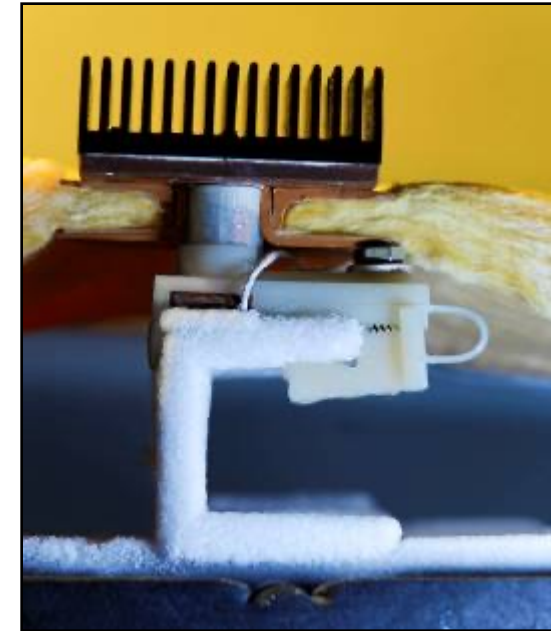
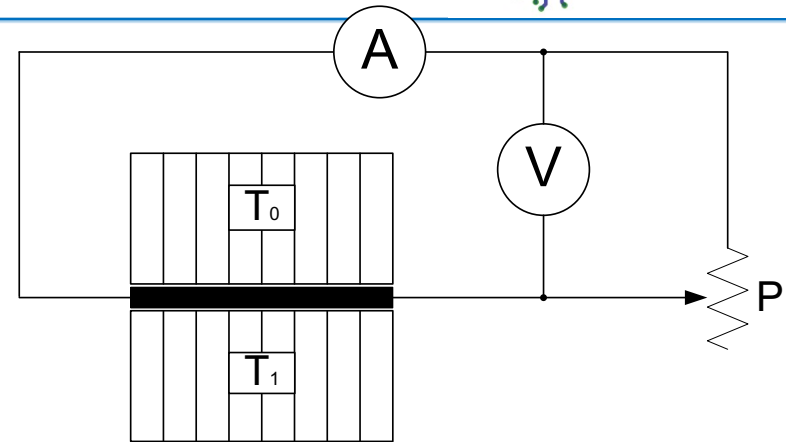
Independenta Energetica



- Obiectele care au un gradient de temperatura pot genera energie
- Efectul Seebeck – generarea de electricitate din diferenta de temperatura
 - Ceasul ATMOS
 - Seiko Thermic

Conversia Termoelectrică

- Folosește efectul Seebeck
- Tensiunea generată este direct proporțională cu diferența de temperatură dintre laturile elementului
- Se pretează la medii cu diferențe mari de temperatură ($>30\text{C}$)

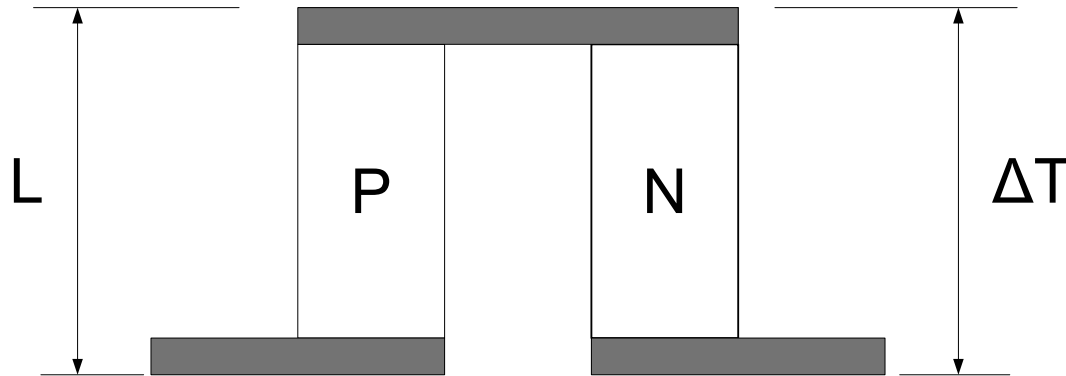
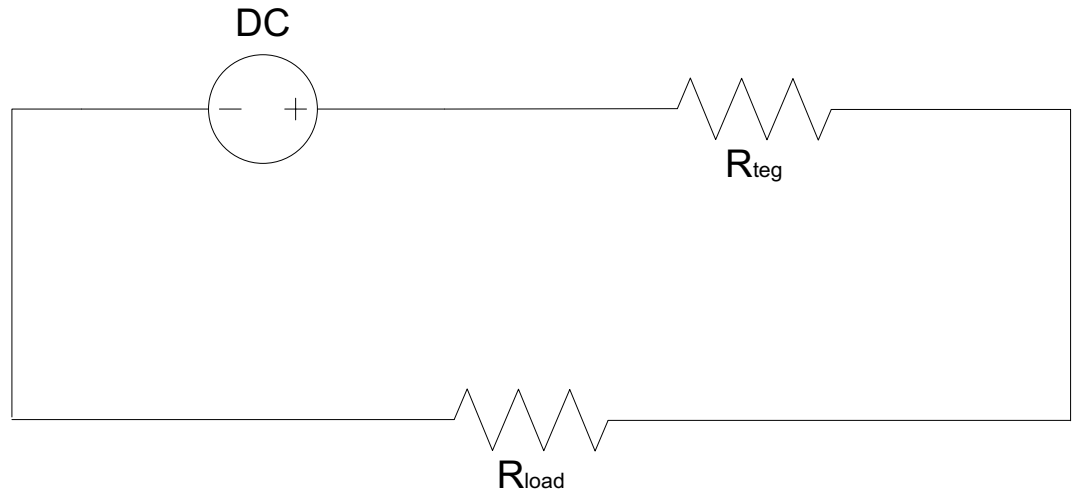


Generatorul Termoelectric

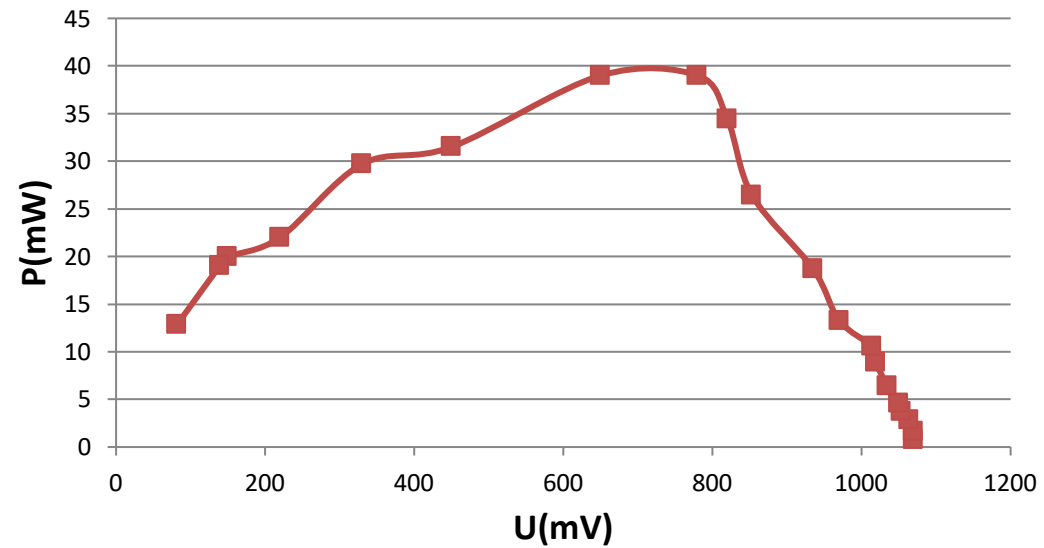
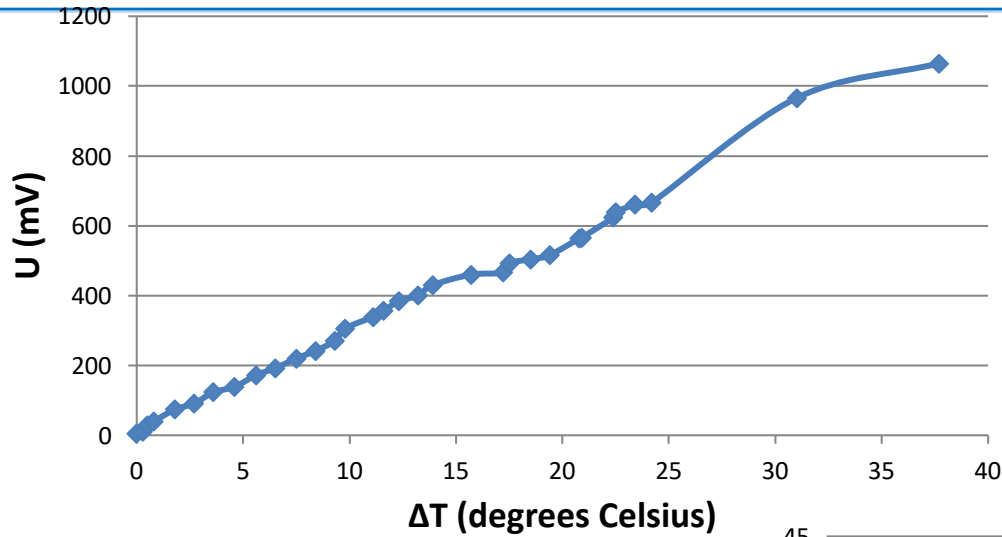
$$V = \alpha \Delta T$$

$$R_{TEG} = 2n\rho \left(\frac{L}{A} \right)$$

$$P_i = \frac{(2\alpha \Delta T)^2}{4R_{TEG}}$$

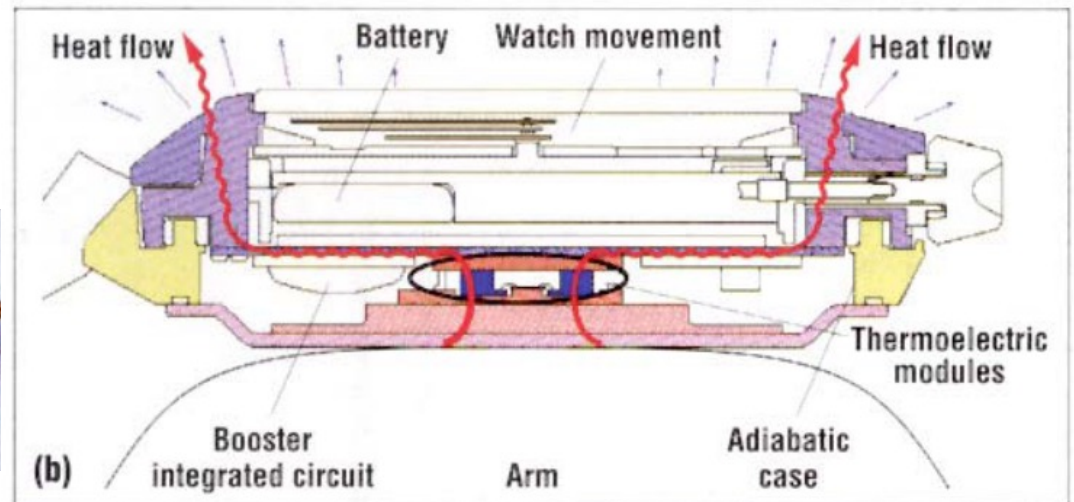
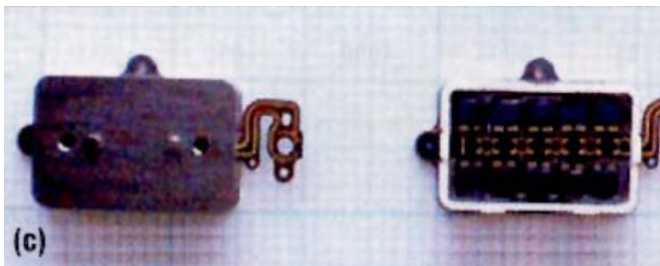


Generatorul Termoelectric



Seiko Thermic

- Primul ceas care foloseste efectul Seebeck pentru alimentarea proprie
- 10uA la 3V pentru diferenta de 5 grade C



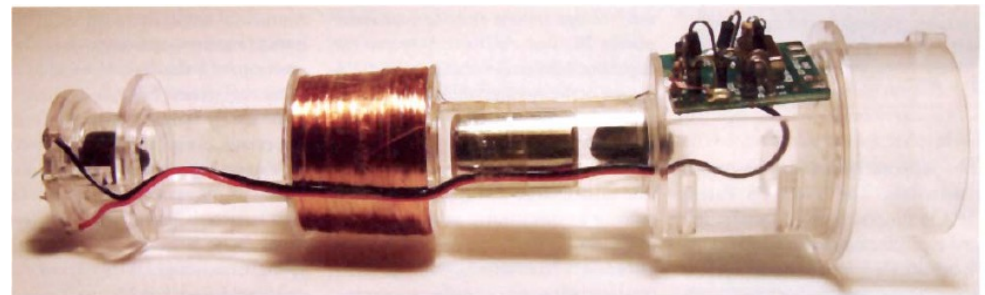
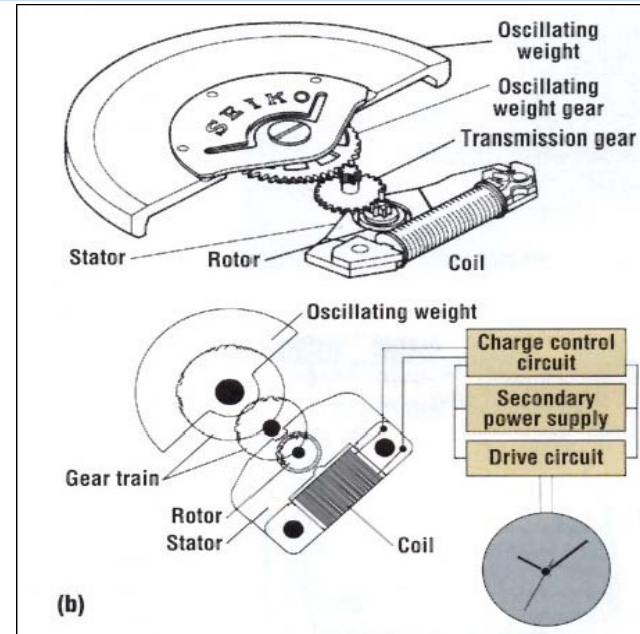
Powerwatch



www.powerwatch.com

Recoltarea din Vibratii

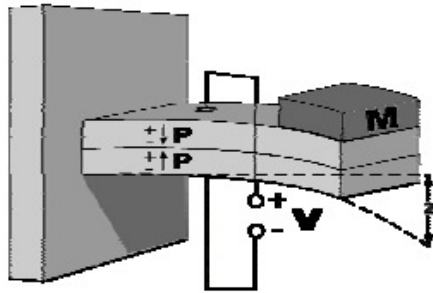
- Ceas cu generator cinetic
- Rotorul poate atinge 100.000rpm
- 15.000rpm -> 6mA @ 1.6V
- Generator bazat pe inductie pentru lanterna (200mW)



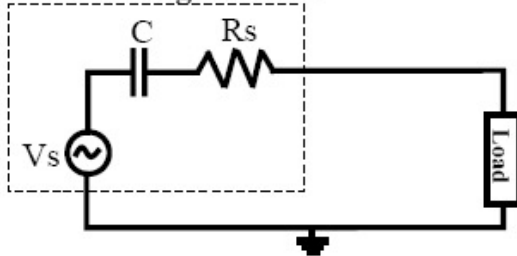
Recoltarea din Vibratii

- Piezoelectric

Aplicarea de presiune asupra materialului produce acumularea de sarcina.

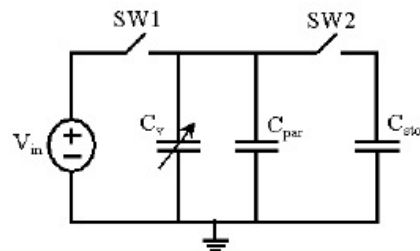
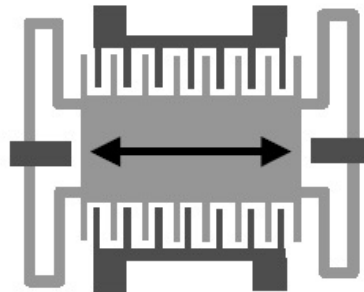


Piezoelectric generator



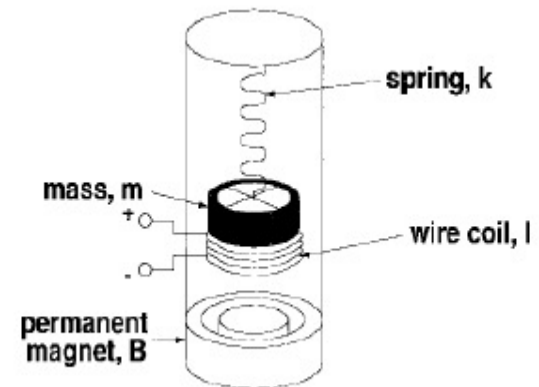
- Capacitiv

Modificarea capacitatii produce modificarea tensiunii in circuit



- Inductiv

Miscarea unei bobine in camp magnetic genereaza tensiune



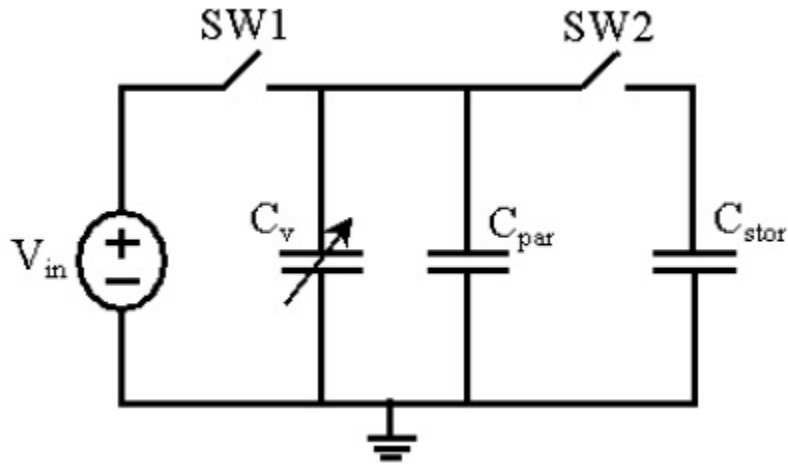
Conversie capacitiva

$$C = \frac{\varepsilon_o A}{d} \quad V = \frac{Q}{C} \quad E = \frac{1}{2} QV$$

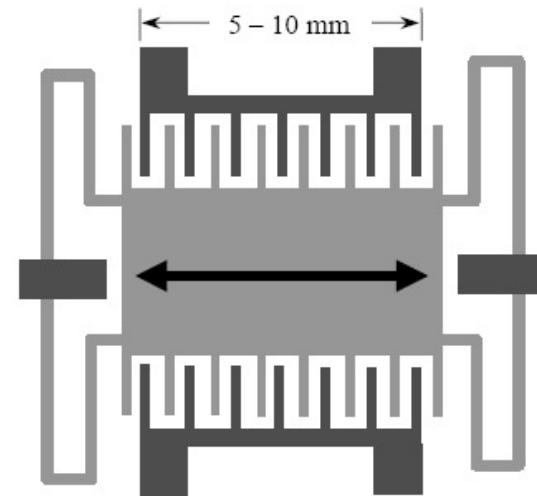
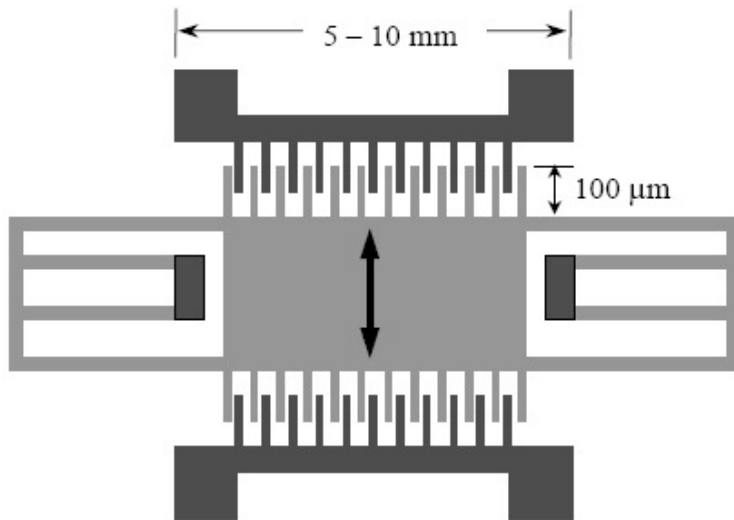
- Proiectez un condensator care-si schimba A si d in functie de vibratii
- Daca Q este constant, V va creste dupa formula:

$$\frac{V_{\max}}{V_{\min}} = \frac{C_{\max} + C_{par}}{C_{\min} + C_{par}}$$

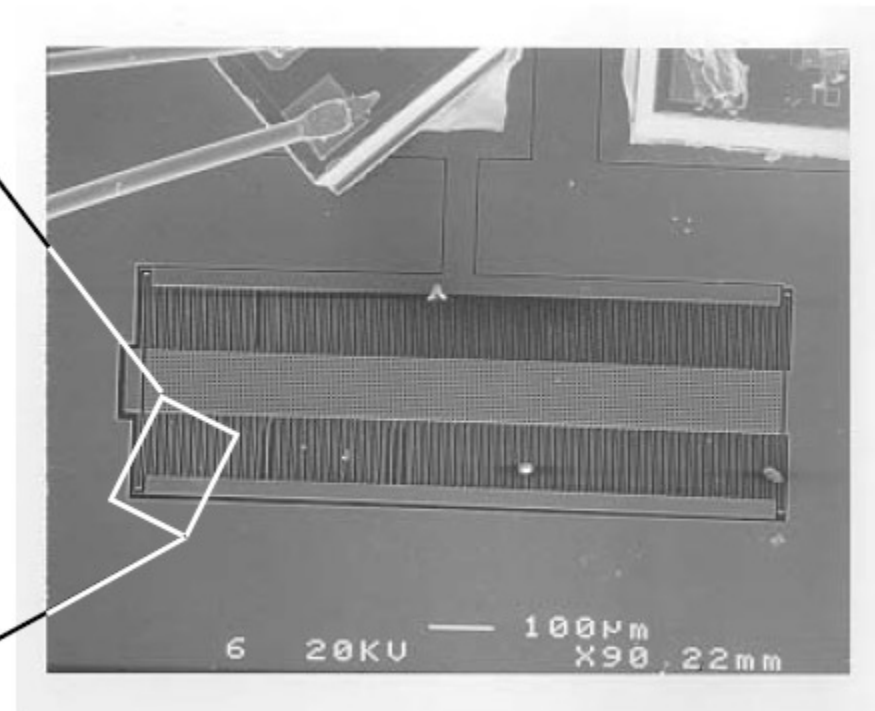
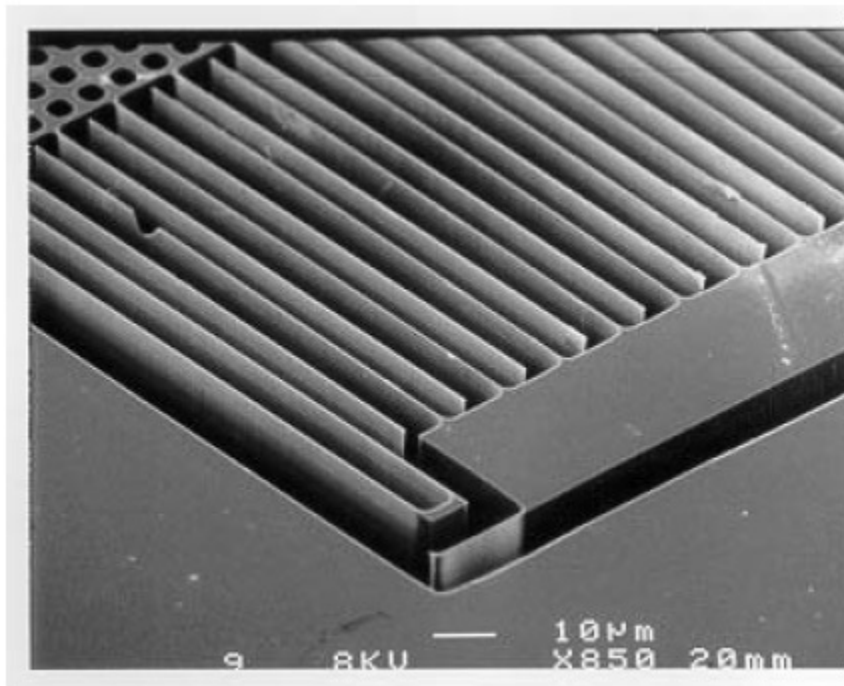
Tipuri de convertoare capacitive



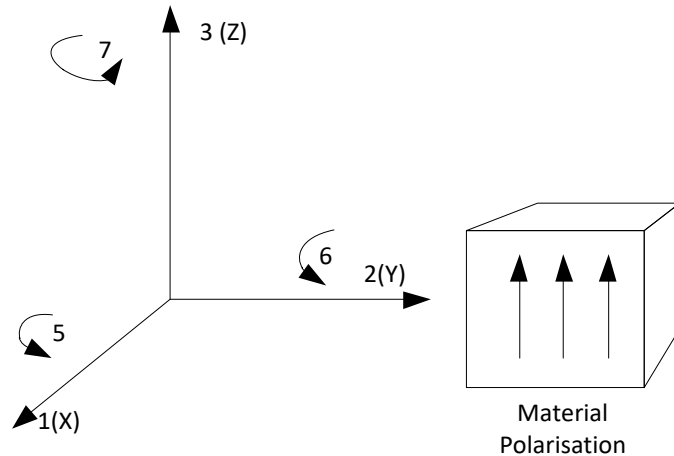
$$E = \frac{1}{2} V_{in}^2 (C_{max} - C_{min}) \left(\frac{C_{max} + C_{par}}{C_{min} + C_{par}} \right)$$



Convertor Capacitiv - Berkeley

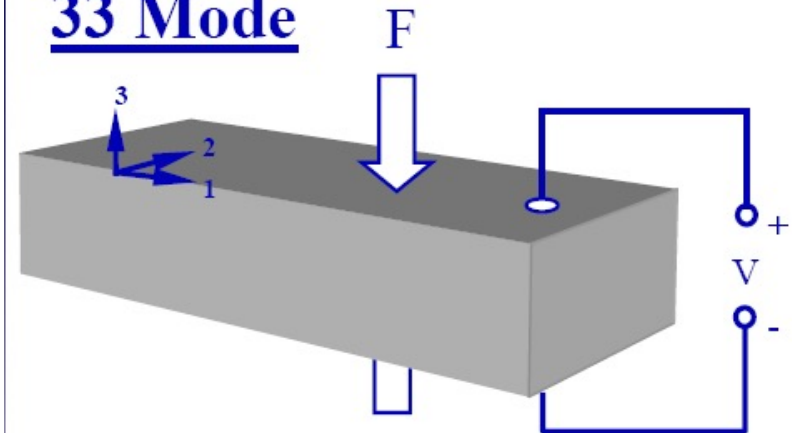


Conversia piezoelectrică

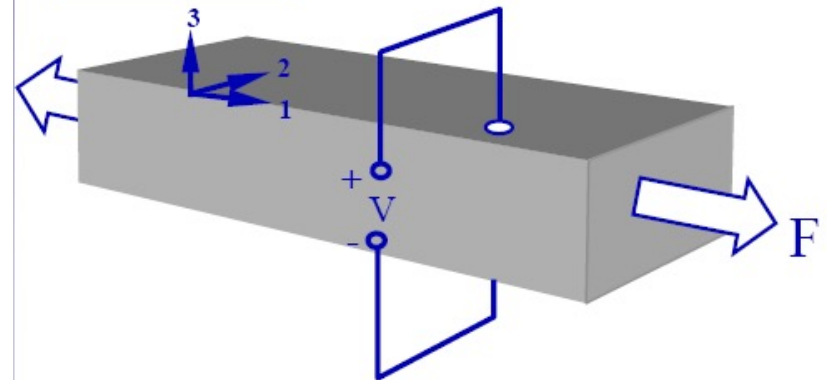


- Grindă elastică de material piezoelectric cu o greutate atașată la capătul mobil.
- Vibrează cu o anumită frecvență
- Energie maximă -> frecvența de rezonanță

33 Mode



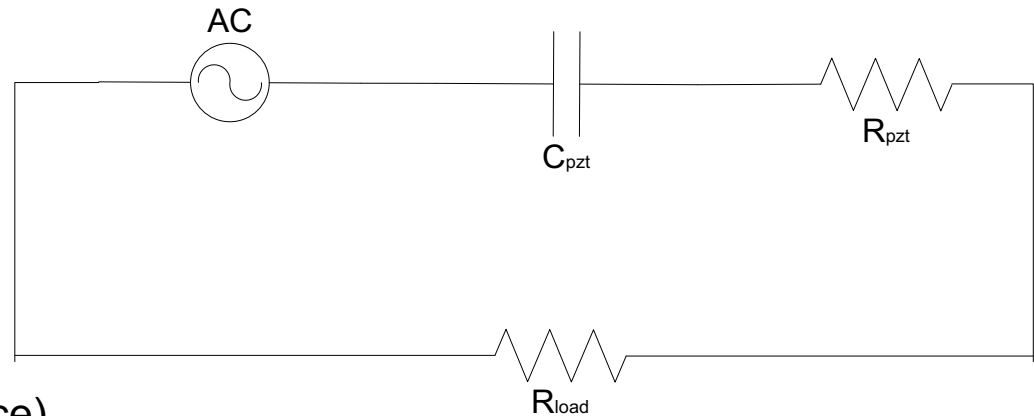
31 Mode



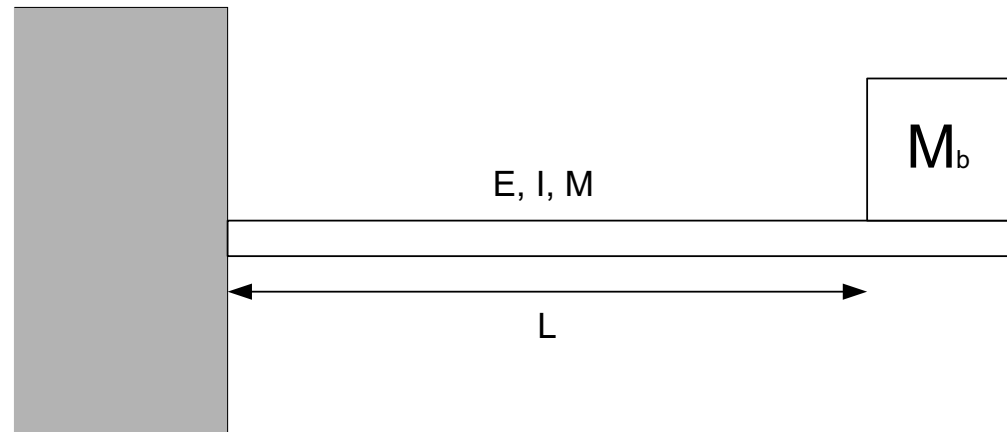
Conversia Piezoelectrică

$$V_{open} = -\frac{td}{\epsilon S} S \quad I_{sc} = fdASY$$

- d - piezoelectric strain coefficient
- t - thickness of the piezoelectric material
- S – strain
- s - resistance to deformation (compliance)
- ϵ - dielectric constant
- Y – Young Modulus



$$f_n = \sqrt{\frac{3YI}{L^3(M_b + 0.24M)}}$$



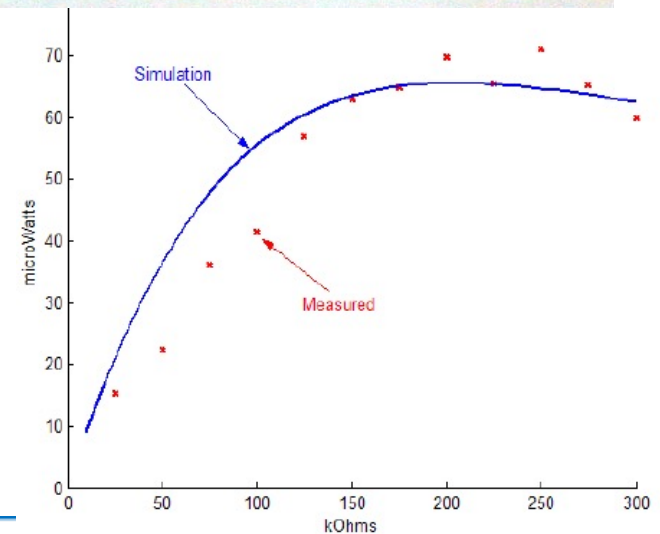
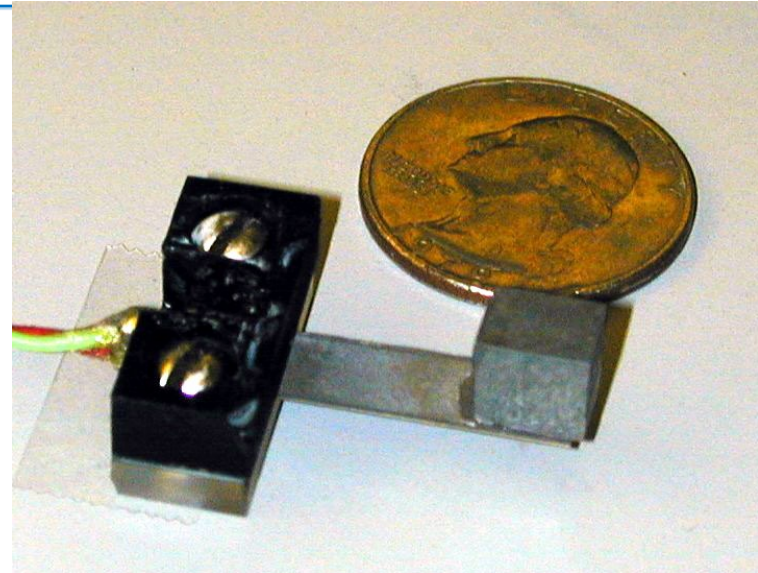
Conversia piezoelectrica

$$P = \frac{1}{2} V_{open} \frac{1}{2} I_{sc} = \frac{1}{4} \left(\frac{td}{\epsilon S} \right) (fdASY) = \frac{fVk}{s} S^2$$

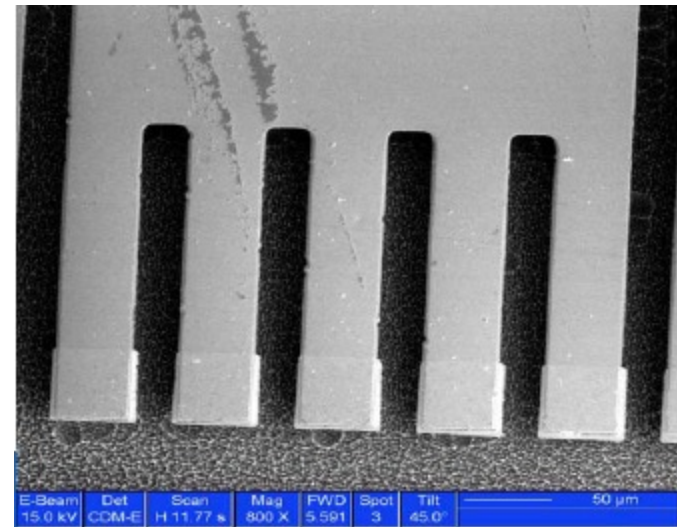
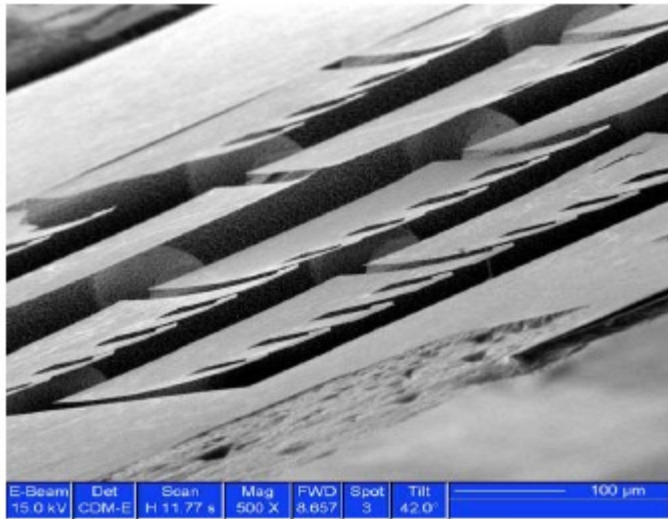
- $P \sim M$
- $P \sim A^2$
- $P \sim 1/\omega$
- Exemplu: $f = 120\text{Hz}$

$V = 4 - 6\text{V}$

$P = 800\mu\text{W}/\text{cm}^3$

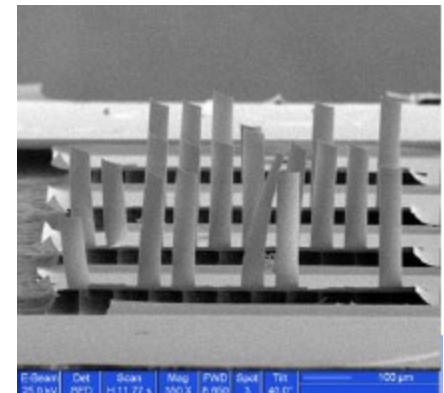


Cantilever Structure

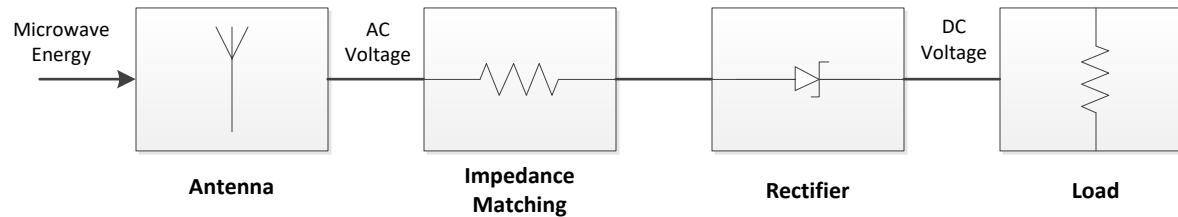


Structuri microscopice de grinzi piezoelectrice fabricate folosind tehnologia aplicata la circuitele CMOS clasice.

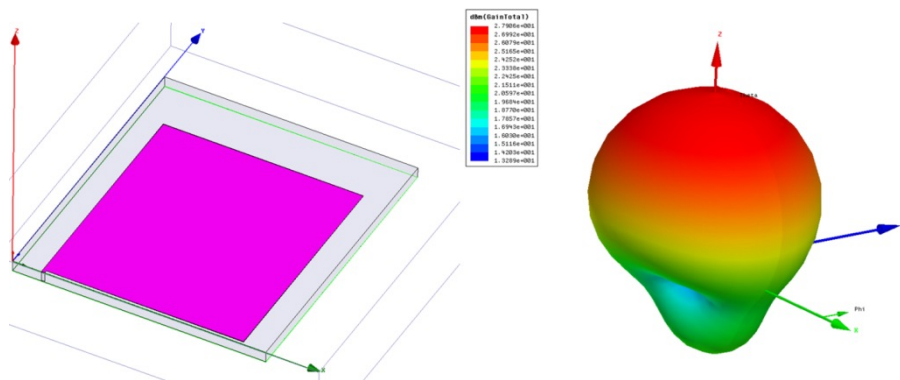
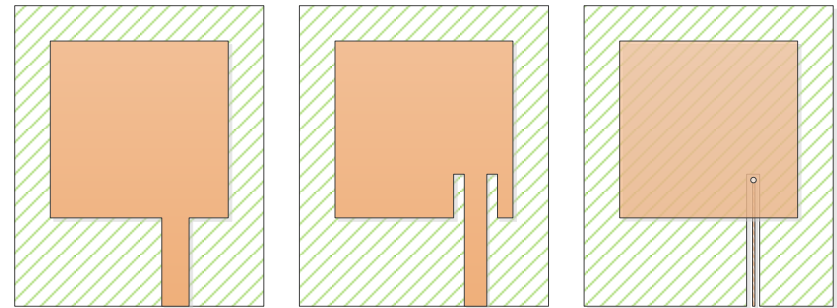
- Frecventa de rezonanta 250-2500Hz
- Densitate de energie de 200mW/cm³



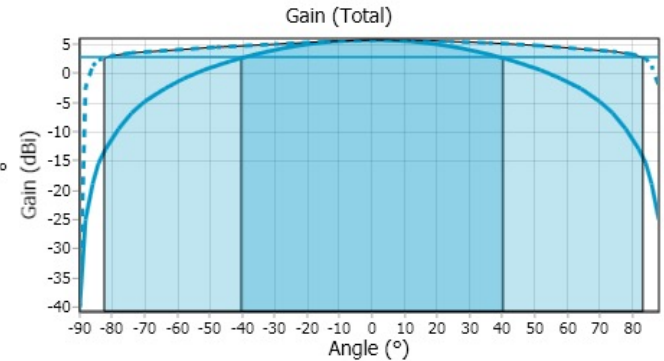
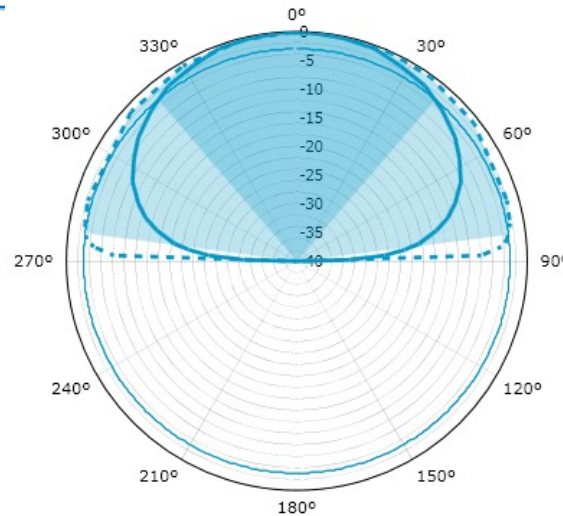
RF Harvesting



- Recoltarea energiei din radiația electromagnetică
- Antena – tensiune indusă
- Rectificare

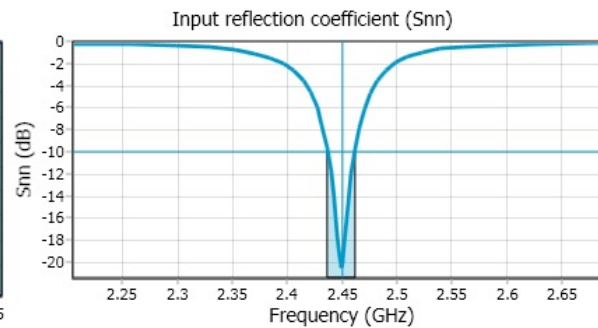
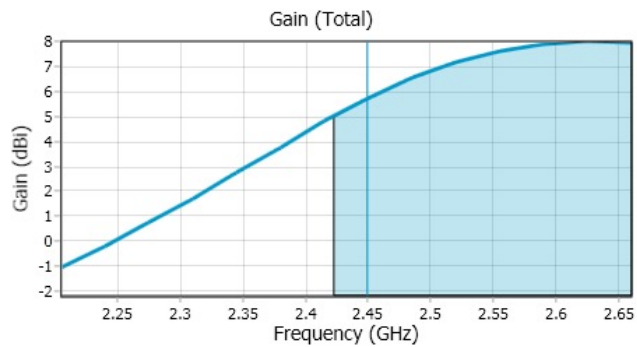


RF Harvesting



Peak gain @ angle (freq) [$\varphi = 0^\circ$]	—	5.730 dBi @ $\theta = 0^\circ$ (2.45 GHz)
Peak gain @ angle (freq) [$\varphi = 90^\circ$]	- - - -	5.766 dBi @ $\theta = 8^\circ$ (2.45 GHz)
Main 3dB beamwidth ($\varphi = 0^\circ$)	—	80.84°
Main 3dB beamwidth ($\varphi = 90^\circ$)	- - - -	165.7°

Peak gain @ angle (freq) [$\varphi = 0^\circ$]	—	5.730 dBi @ $\theta = 0^\circ$ (2.45 GHz)
Peak gain @ angle (freq) [$\varphi = 90^\circ$]	- - - -	5.766 dBi @ $\theta = 8^\circ$ (2.45 GHz)
Main 3dB beamwidth ($\varphi = 0^\circ$)	—	80.84°
Main 3dB beamwidth ($\varphi = 90^\circ$)	- - - -	165.7°



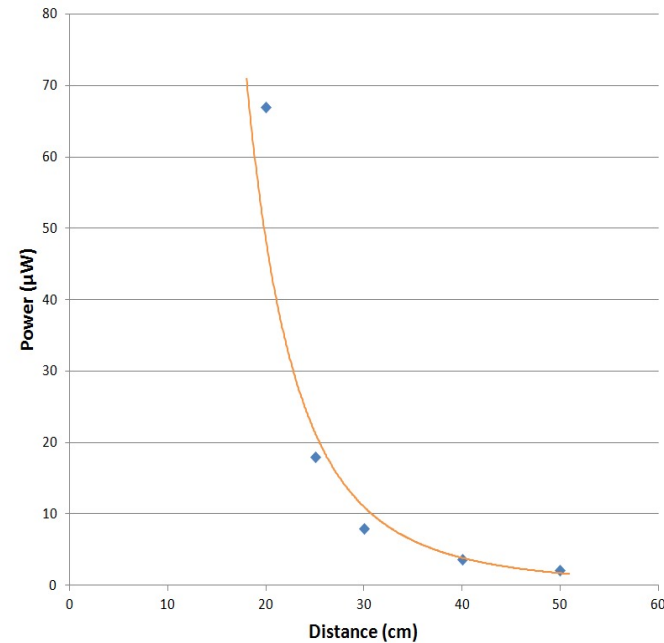
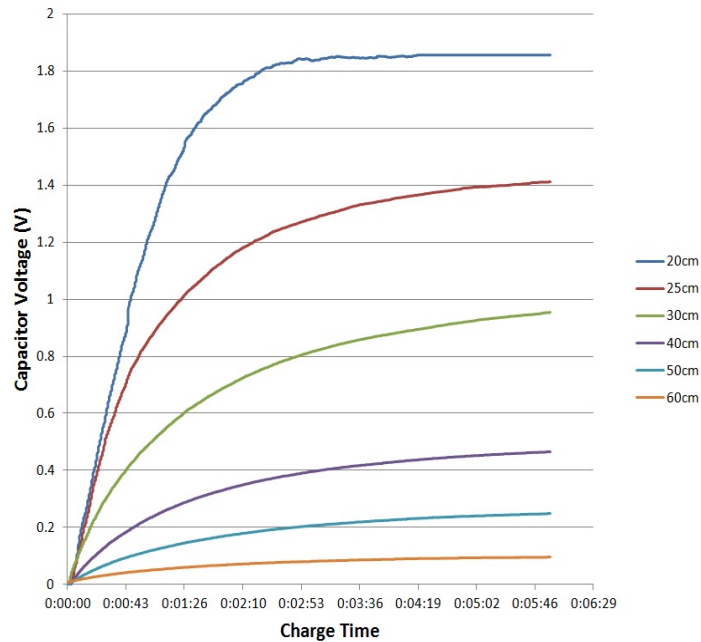
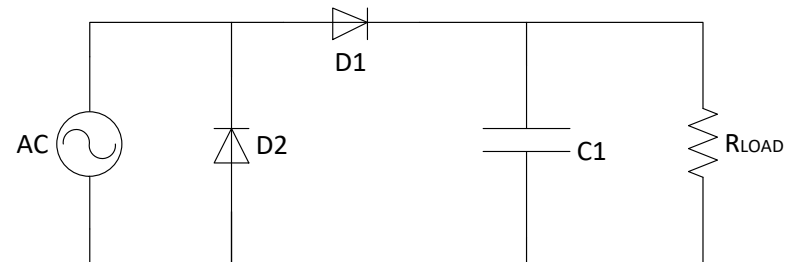
Peak gain @ frequency ($\theta = 0^\circ$; $\varphi = 0^\circ$)	—	7.986 dBi @ 2.625 GHz
3dB beamwidth ($\theta = 0^\circ$; $\varphi = 0^\circ$)	—	indeterminate

Reference impedance @ port 1	—	50 Ω
Frequency at which S11 = -10 dB	—	2.437 GHz 2.461 GHz
Minimum S11 value	—	-20.47 dB @ 2.450 GHz

RF Harvesting

$$\eta = \frac{P_{DC}}{P_{recv.}} = \frac{V_{DC}}{R_{load}^2 \cdot P_{recv.}}$$

$$P_{recv.} = P_T \cdot G_T \cdot G_R \cdot \left(\frac{\lambda}{4\pi R}\right)^2$$



- Sistemul Embedded
 - Sistem închis
 - Producători (P_s) și consumatori (P_c) de energie
- Excesul de energie pentru un nod la momentul t

$$E(t) = \int_0^t (P_s(t) - P_c(t)) dt$$

- Sistemul este independent d.p.d.v. energetic dacă

$$E(t) > 0 \forall t > 0$$

- Harvester fără stocare de energie

$$P_s(t) \geq P_c(t)$$

- Harvester cu mediu de stocare ideal

$$\int_0^T P_c(t) dt = \int_0^T P_s(t) dt + B_0 \quad \forall T \in [0, \infty)$$

- Harvester cu mediu de stocare ne-ideal

$$B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{leak}(t) dt \geq 0 \quad \forall T \in [0, \infty) \quad (1)$$

$$B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{leak}(t) dt \leq B \quad \forall T \in [0, \infty) \quad (2)$$

- Funcții $(\rho, \sigma_1, \sigma_2)$: $\rho T - \sigma_2 \leq \int_{\tau}^{T+\tau} P(t)dt \leq \rho T + \sigma_1$
- $P_s(t) = f(\rho_1, \sigma_1, \sigma_2)$; $P_c(t) = f(\rho_2, \sigma_3, \sigma_4)$
- Înlocuind în (1) și (2), obținem:

$$B_0 + \eta \cdot (\rho_1 T + \sigma_1) - (\rho_2 T - \sigma_4) - \rho_{leak} T \leq B$$

$$B_0 + \eta \cdot (\rho_1 T - \sigma_2) - (\rho_2 T + \sigma_3) - \rho_{leak} T \geq 0$$

- Condiții limită

– $T = 0$

$$\left. \begin{array}{l} B_0 \geq \eta \cdot \sigma_2 + \sigma_3 \\ B_0 + \eta \cdot \sigma_1 - \sigma_4 \leq B \end{array} \right\} \Rightarrow B \geq \eta \cdot (\sigma_1 + \sigma_2) + \sigma_3 - \sigma_4$$

– $T \rightarrow \infty$

$$\eta \cdot \rho_1 - \rho_{leak} \geq \rho_2$$

$$\eta \cdot \rho_1 - \rho_{leak} \leq \rho_2$$

Evaluarea Surselor de Energie Regenerabilă

Randamentul a trei metode de energy harvesting a fost evaluat experimental

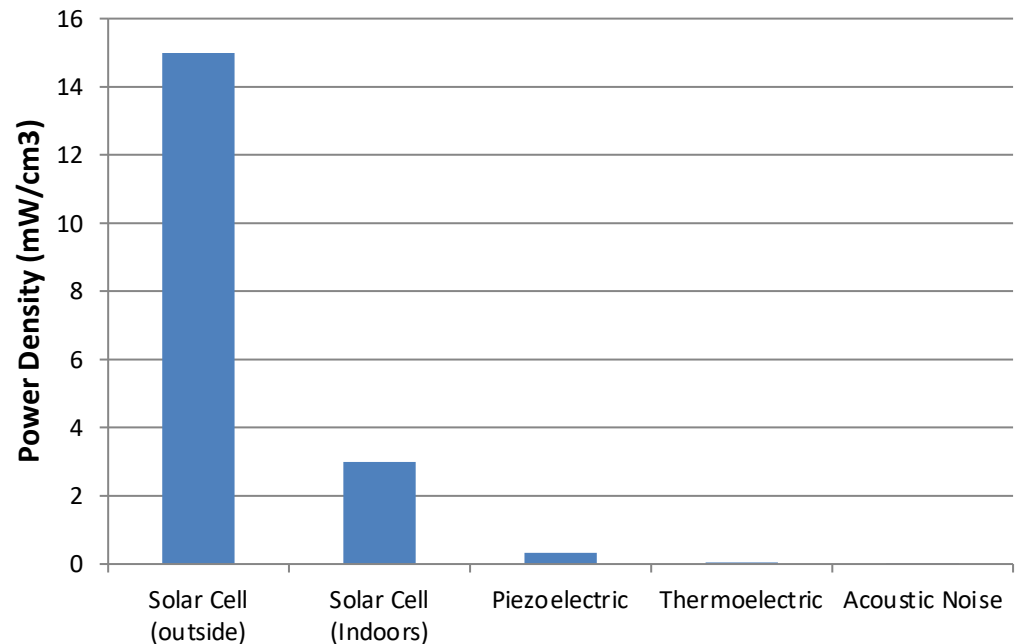
- Fotovoltaic
- Termoelectric
- Piezoelectric

Metrică – densitatea de energie

Recoltarea fotovoltaică a dat cele mai bune rezultate

Atunci când nu este disponibilă, celelalte metode pot fi implementate

Harvesting Technology	Power Density
Solar Cells(outdoors at noon)	15mW/cm ³
Piezoelectric (shoe inserts)	330uW/cm ³
Vibration(microwave oven)	116uW/cm ³
Thermoelectric(10°C)	40uW/cm ³
Acoustic noise (100dB)	960nW/cm ³

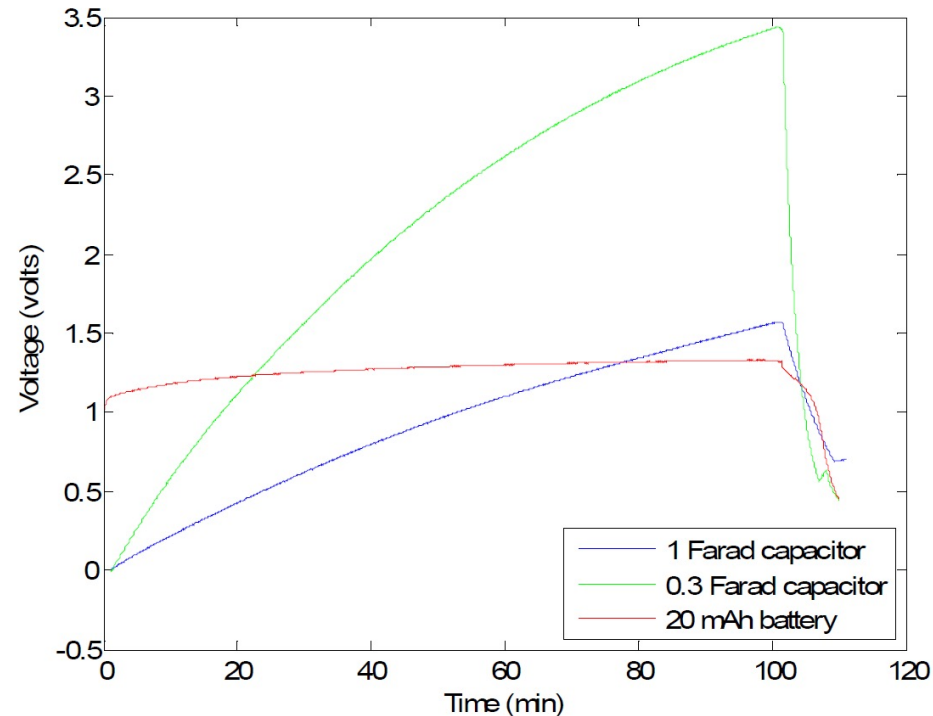


Acumulatori

- Tehnologie matură
- Stochează sarcina electrică electrochimic
- Preț scăzut și disponibilitate mare
- Folosite pe scară largă în WSN
- Timpi mari de încărcare
- Se degradează odată cu trecerea timpului
- Au un număr finit de cicluri încărcare/descărcare

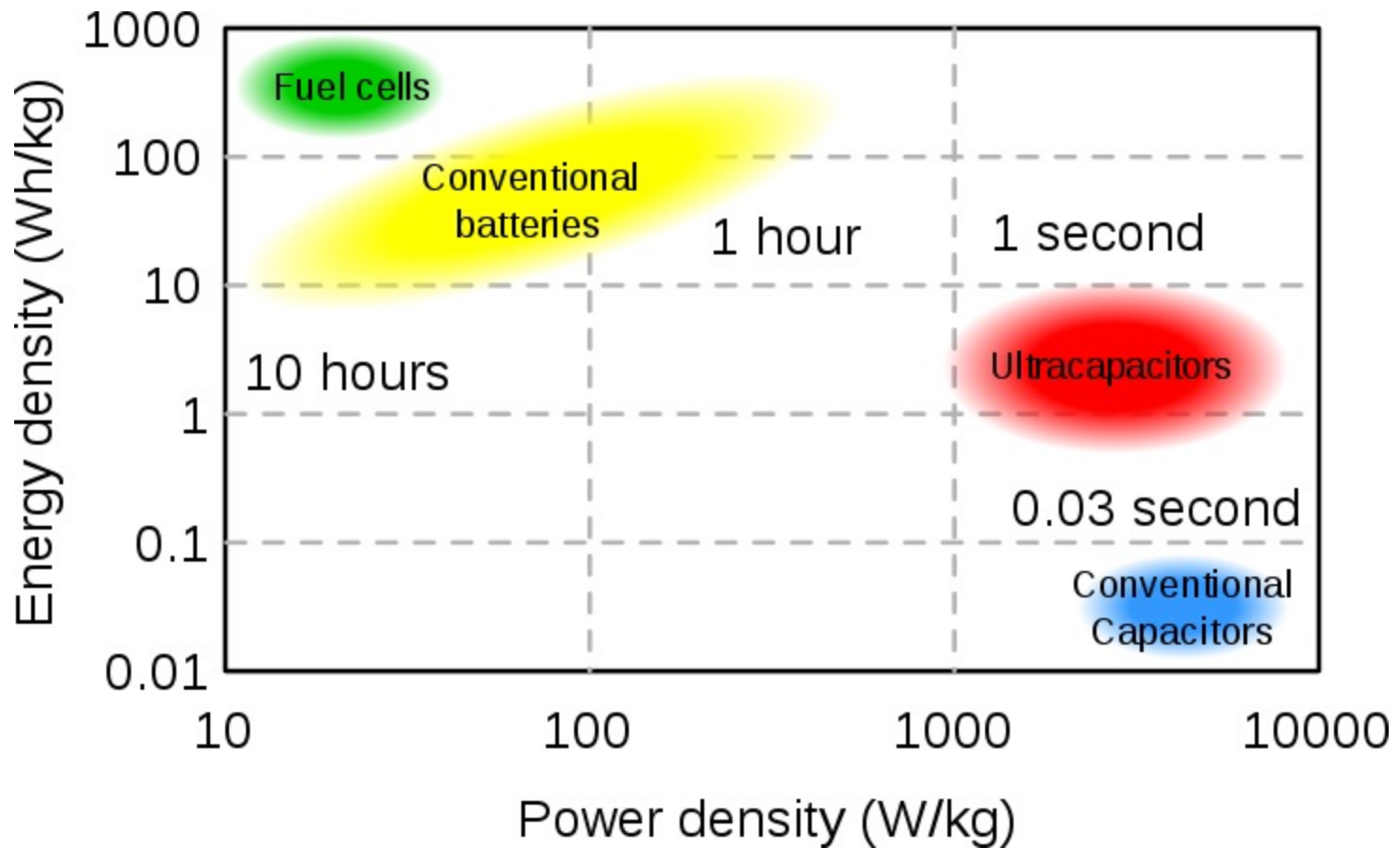
Supercondensatoare

- Tehnologie emergentă
- Stochează sarcina electrostatic, sub formă de ioni
- Capacități foarte mari (1F-1000F)
- Timpi reduși de încărcare și descărcare
- Nu se degradează cu trecerea timpului
- Preț (mai) ridicat

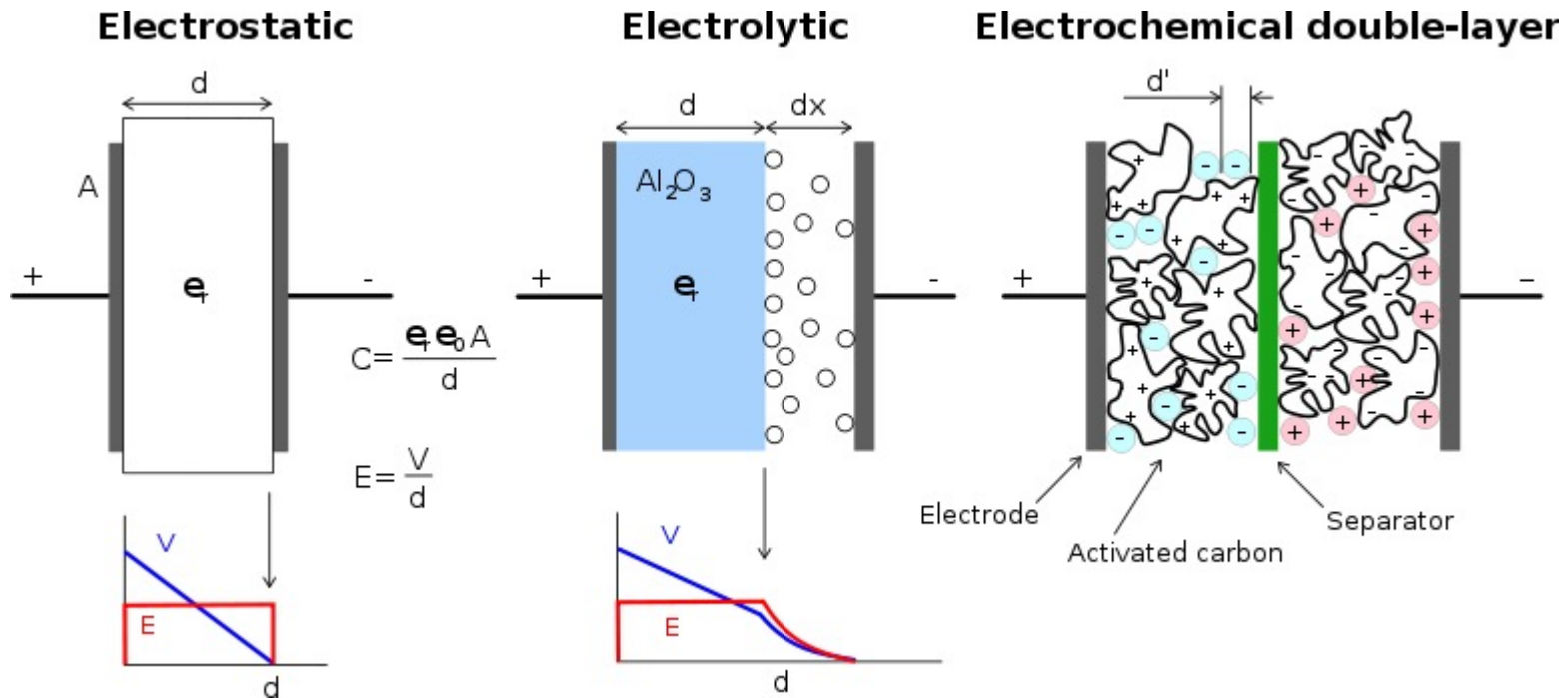


Folosirea celulelor electrochimice nu este optimă pentru nodurile senzoriale

Stocarea energiei

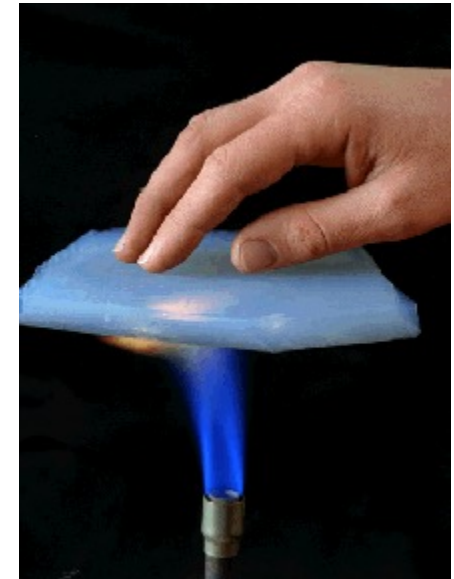
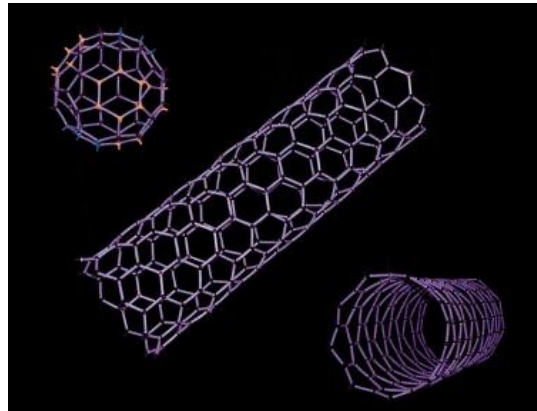
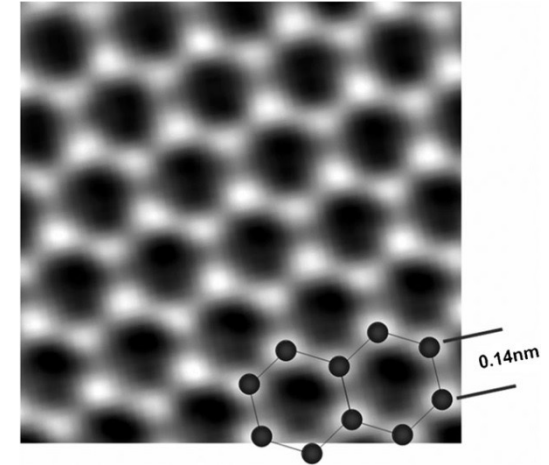


Condensatoare

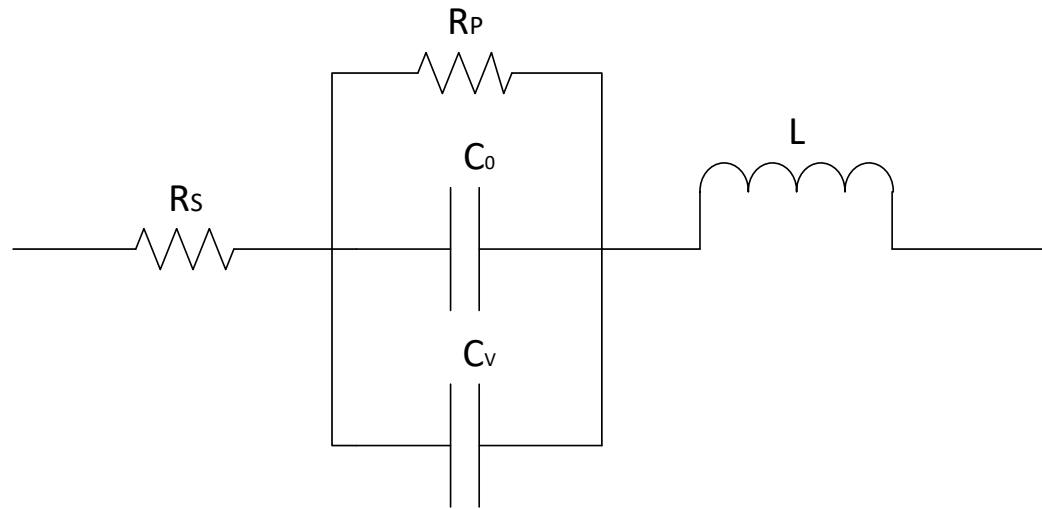


Supercondensatoare

- Dielectric
 - Carbon activat
 - Grafen
 - Nanotuburi
 - Aerogel



$$C = \varepsilon_0 \varepsilon_r \frac{A}{D} \quad P_{max} = \frac{V^2}{4R_S}$$

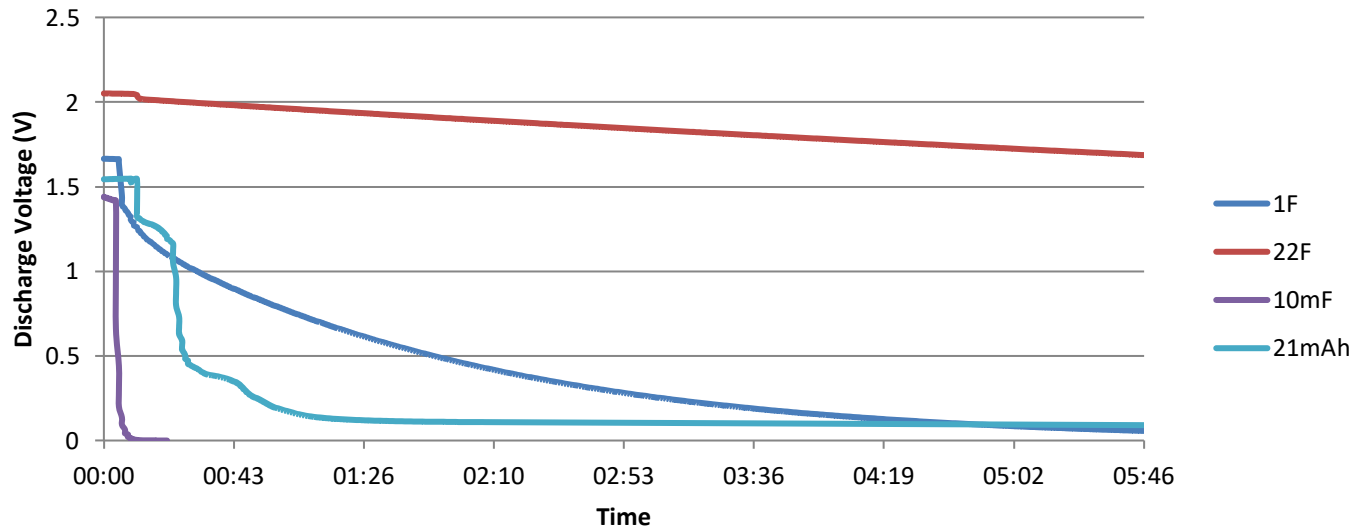
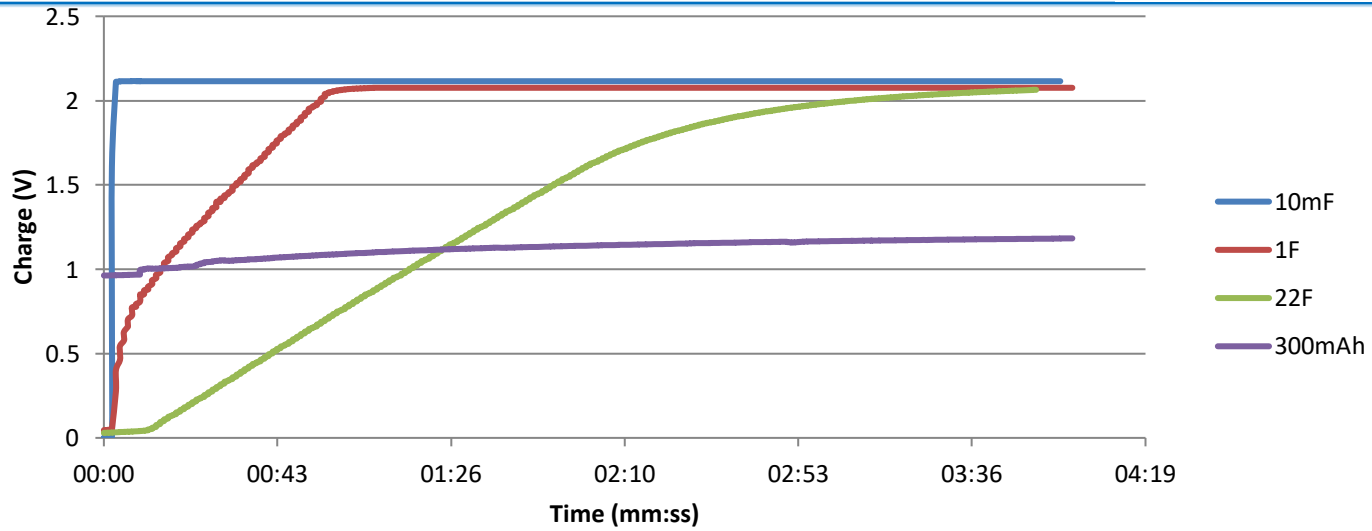


- Capacitate suplimentară
ce depinde de tensiunea de alimentare

$$i(t) = \frac{dQ}{dt} = \frac{d(CV)}{dt} = \frac{d(C_0V + K_V V^2)}{dt} = (C_0 + 2K_V V) \frac{dV}{dt}$$

$$E(V) = \int P(V) dV = \left(C_0 + \frac{4}{3} K_V V \right) \frac{V^2}{2}$$

Supercondensatoare



Medii de stocare

- Baterii
 - + Cost redus
 - + Densitate mare de energie
 - + Tehnologie sigură și testată în timp
 - Diferite regimuri de încărcare
 - Cicli de încărcare reduși
 - Curent de leakage
- Supercondensatoare
 - + Circuite de încărcare simple
 - + Densitate de energie mare (< baterii)
 - + Număr foarte mare de cicli de încărcare
 - Cost mare
 - Curent de leakage
 - Tensiune de operare mică
- Hibridi baterie-condensator
 - Lithium-ion capacitor

