Energy-Neutral Distributed Sensing

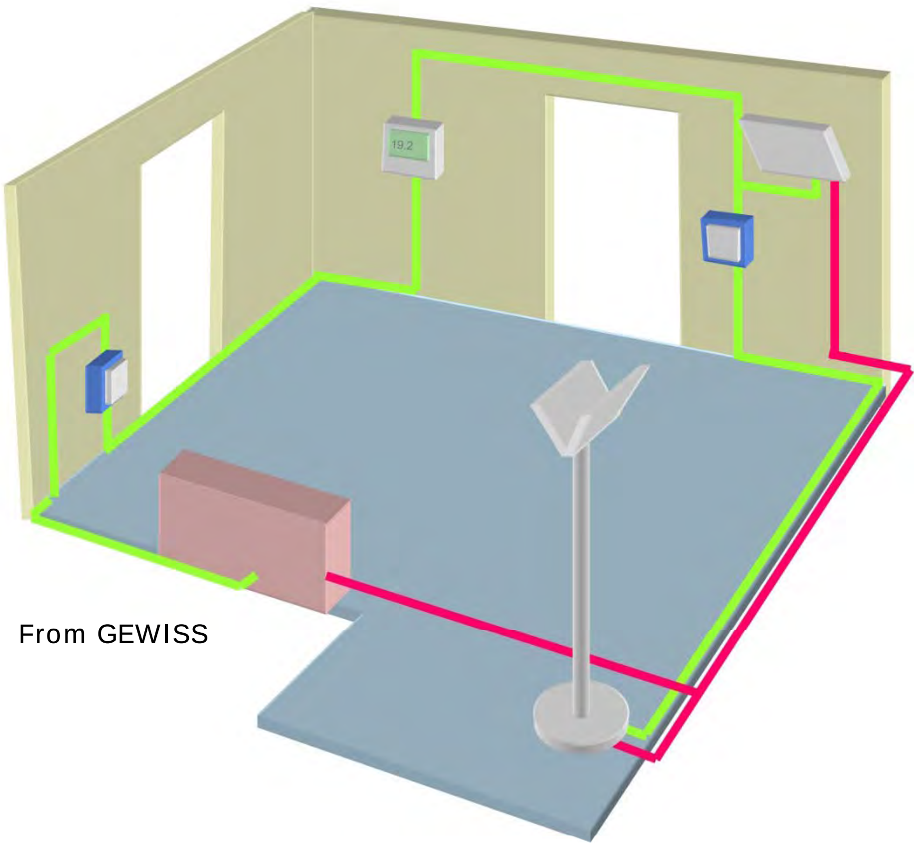
Luca Benini, Davide Brunelli

Luca.benini@unibo.it, davide.brunelli@unibo.it

DEIS Università di Bologna

Support from
Artist-Design NoE & Telecom Italia

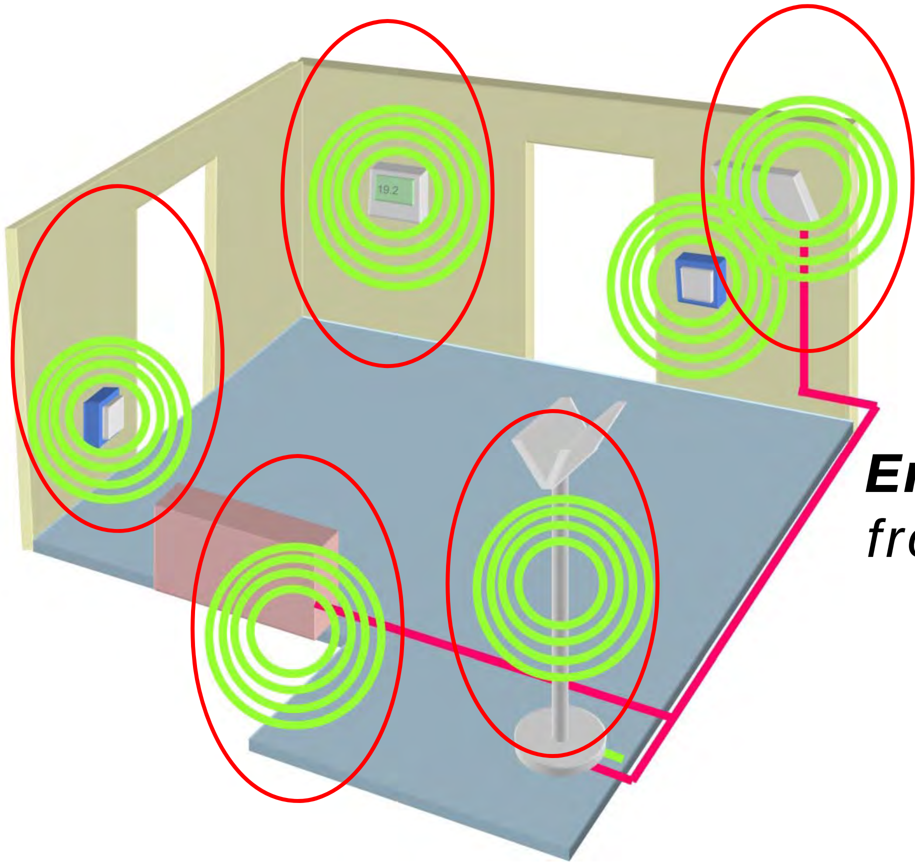
Building automation today



From GEWISS

- Power grid distributed only to appliances
- All Sensors, controls and appliances connected by a single, low power bus (e.g. Knx, lonworks, BACnet, chorus,..)
  - Modular, scalable and safe
- Deployment cost is high
  - Retrofitting existing buildings is often impossible
  - Modification of an existing layout is expensive and labor-intensive

Energy-Neutral Sensing & Control



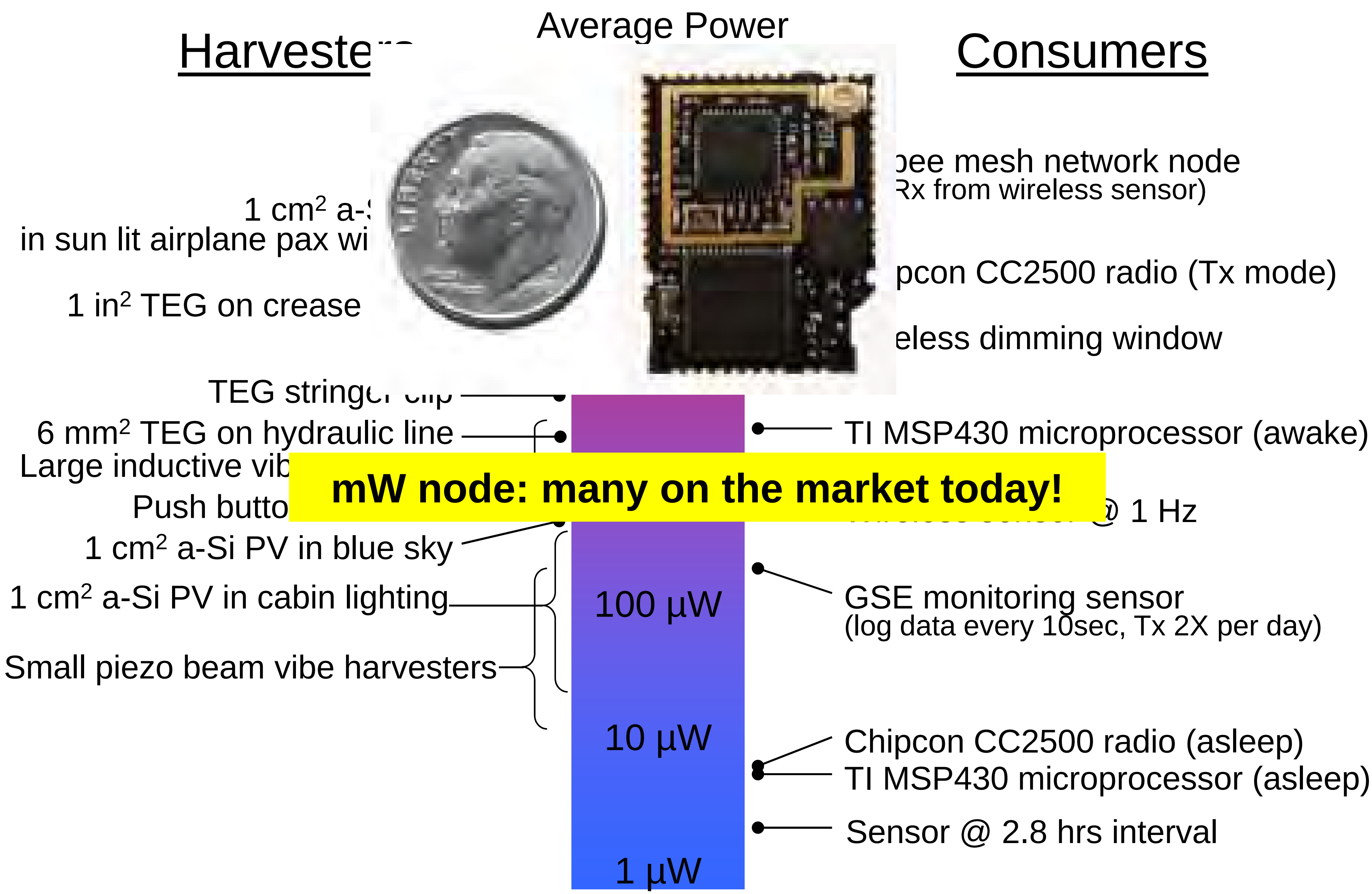
E(from power grid) = 0

- No power and data cable for sensors and controls
  - Easy to install (in the optimal position)
  - Retrofitting is feasible and inexpensive
  - Battery-powered operation → maintenance

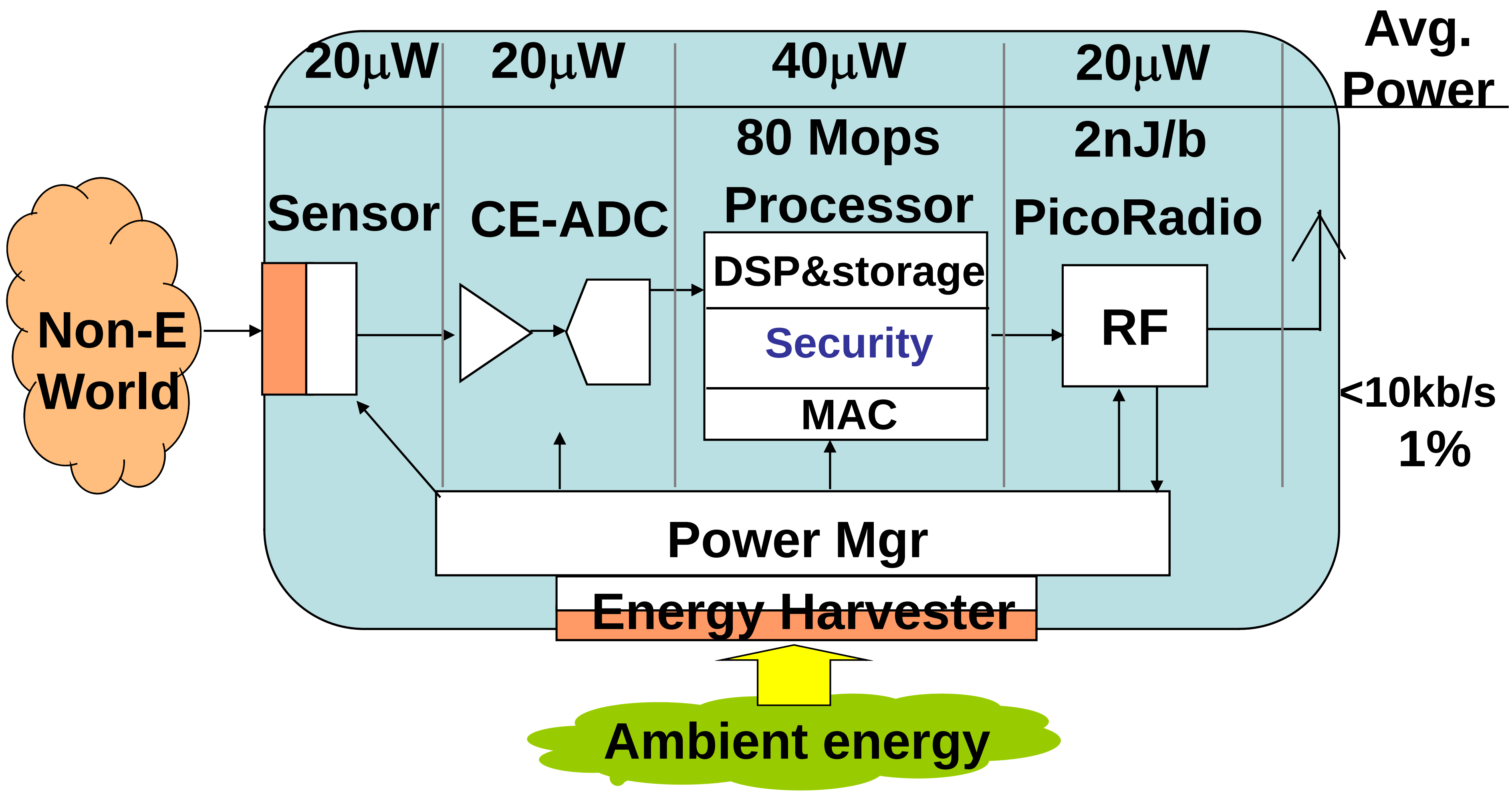
Energy-neutral → *harvest energy from the surrounding environment*

- Photovoltaic (outdoor, indoor)
- Inductive coupling
- RF energy
- Air flow
- Motion, vibration

Quantifying the challenge



Sensor Node Evolution



Objective: 100 µW Avg → Energy neutrality becomes "easy"

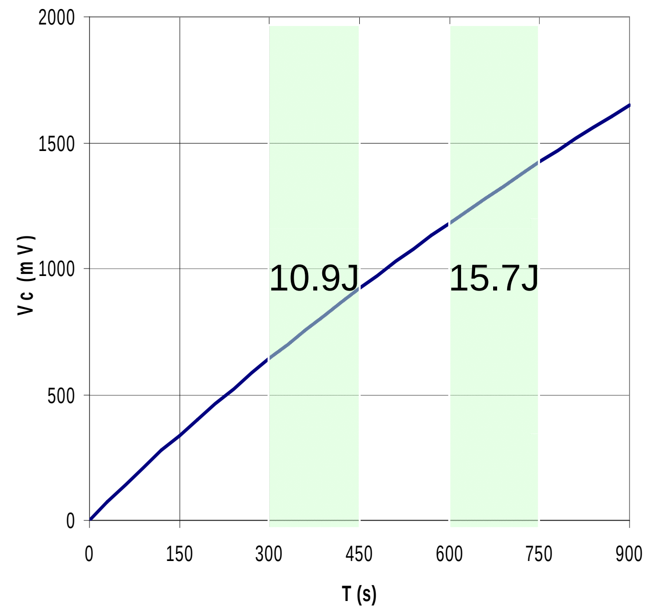
High-efficiency PV harvesting

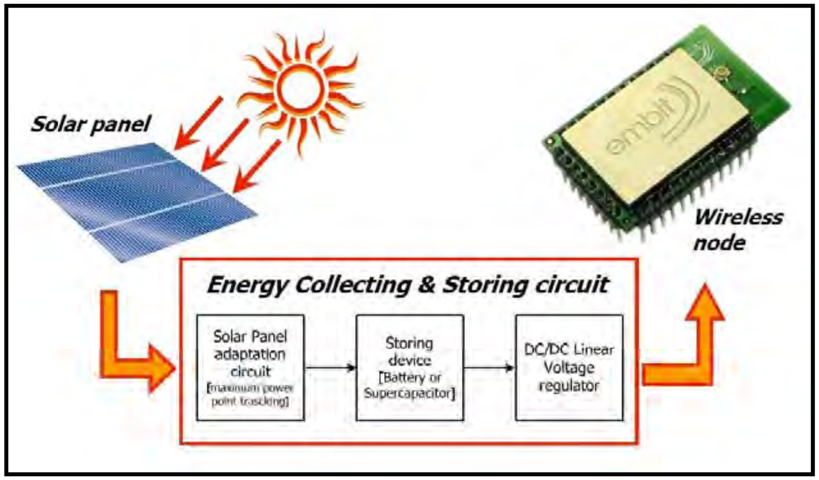
Problems:

- Maximum Power point (MPP)
- Tracking MPP (MPPT)
- *Low Power Budget (mW)*

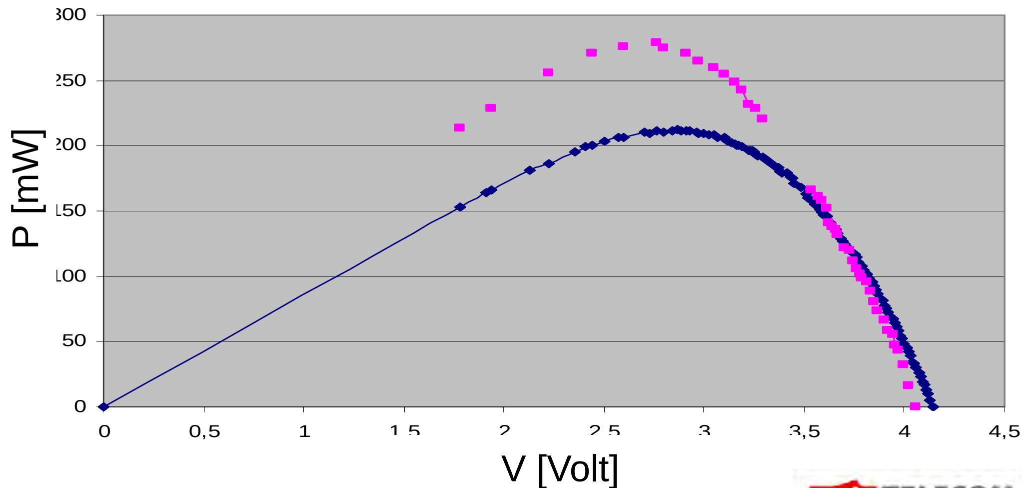
Goal:

- reduce PV-cell size
- reduce storage device size
- increase the autonomy





P-V chart



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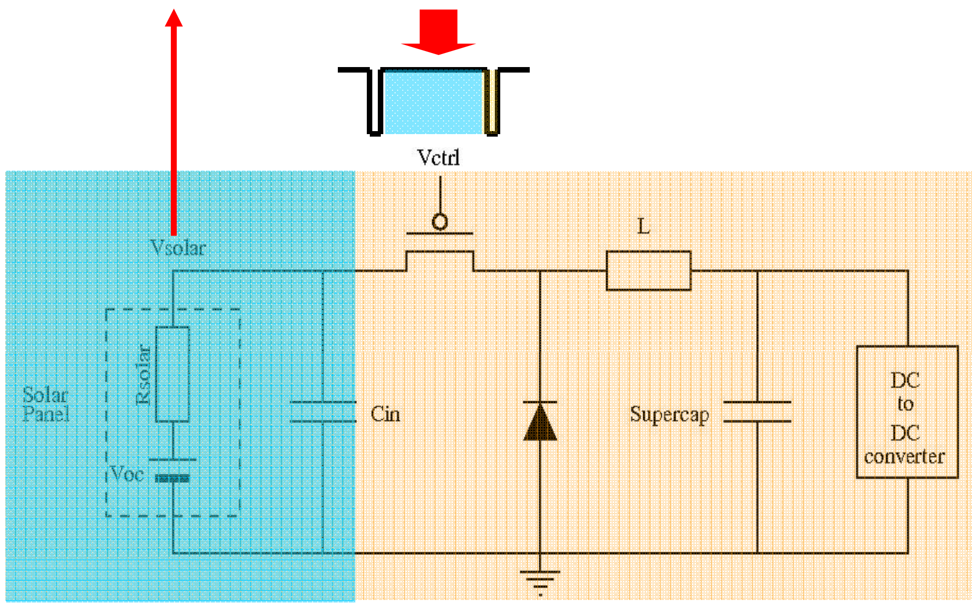
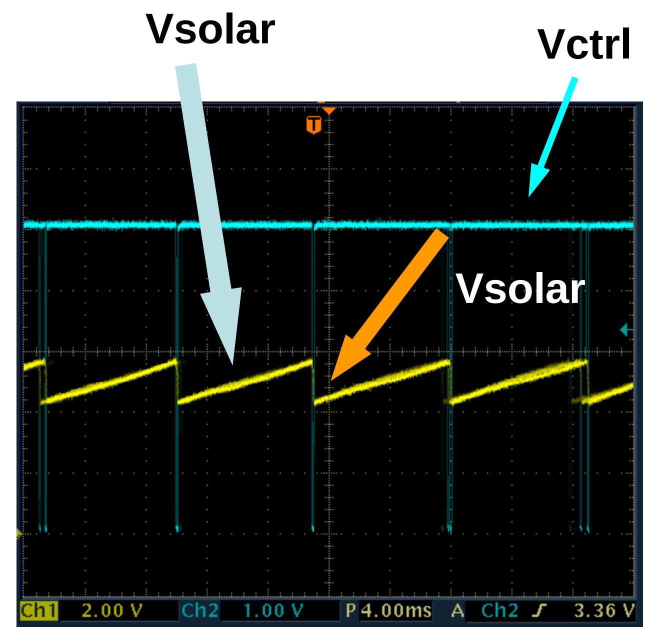
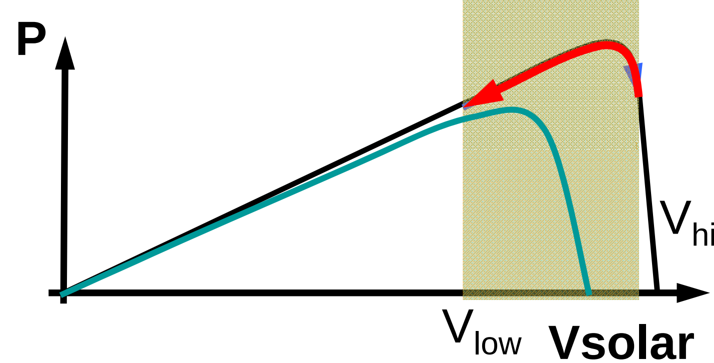
mW-Level MPP tracking

Vlow crossing → switch off
Vhigh crossing → switch on



Controlled variable
V_{low}, V_{high} → duty cycle



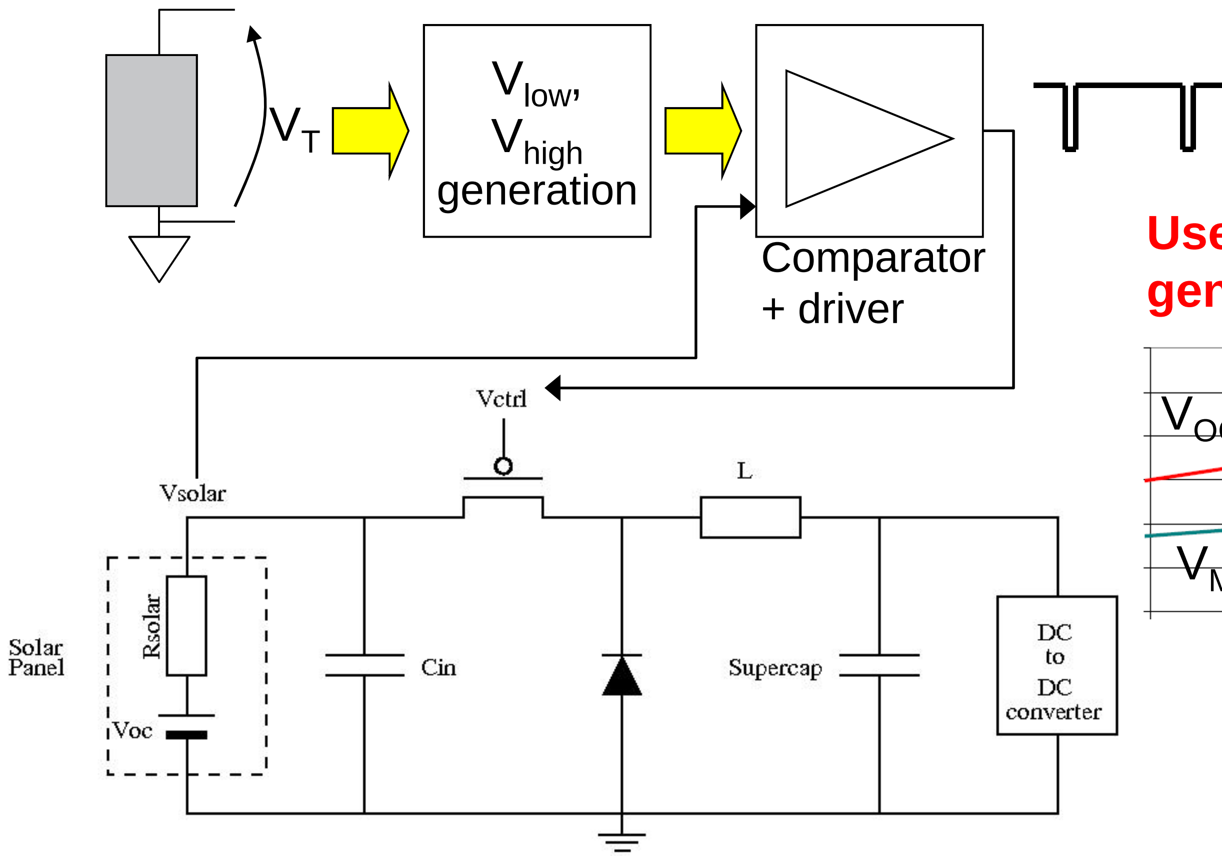


Online control for tracking PV curve variations with incident light, temperature

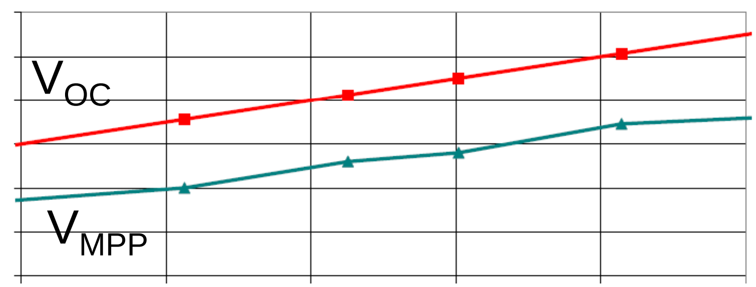
MPP tracking with a pilot PV cell

Fractional Open Circuit Voltage technique

$$V_{MPP}(T,L) \approx K_{FOCV}V_{OC}(T,L) \approx K_{FOCV}K_{T}V_{T}(T, L)$$



Use V_T from a micro PV cell to generate V_{low}, V_{high}

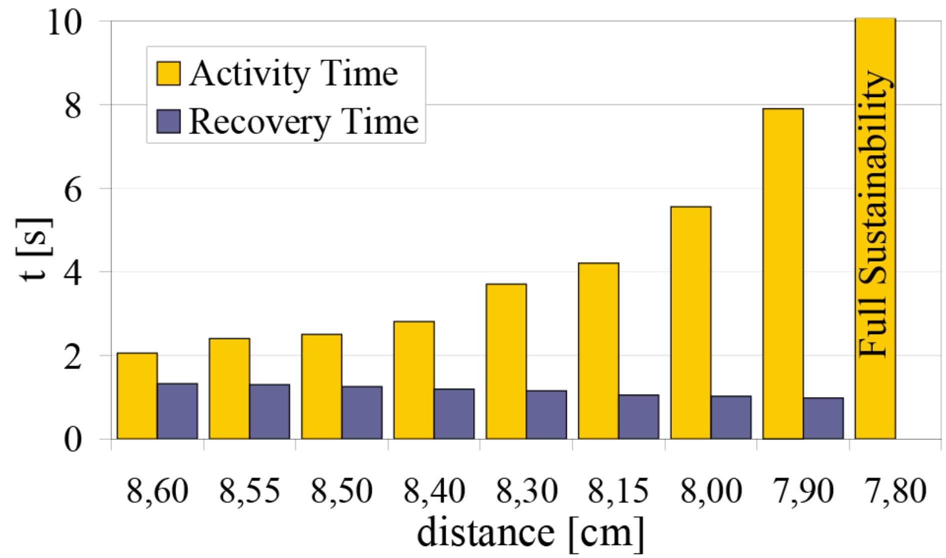


Minimize the cost of MPPT + tracker is unregulated
Highest efficiency reported (until 2008)

Sub-mW harvesting

- WSN HW support a wide voltage supply range (usually between 1V and 4V)

Tmote Sky	2,1 – 3,6 V
TinyNode 584	2,4 – 3,6 V
TI Node	1,8 – 3,6V



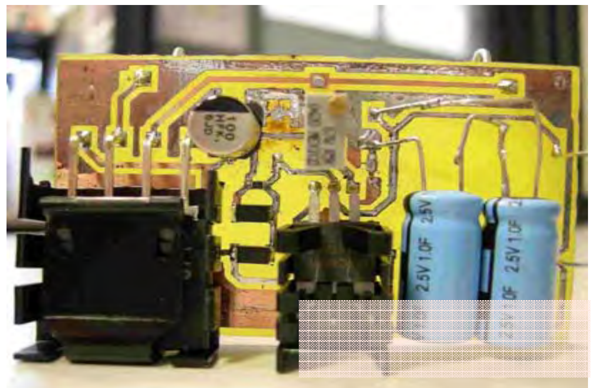
- Powering sensor nodes with unregulated and variable voltage supply from the solar cell → ***adaptive Active-Recovery DC***
  - Minimize the energy used for DC/DC or linear regulation
  - Automatically adapt duty-cycle with analog thresholds (comparators) on voltage supply
  - Optimize thresholds for MPP in low-lighting condition (no tracking at high lighting as energy is over-abundant)

Indoor PV powering is feasible!

Inductive Harvester

- Inductively powerered WSN Node

+



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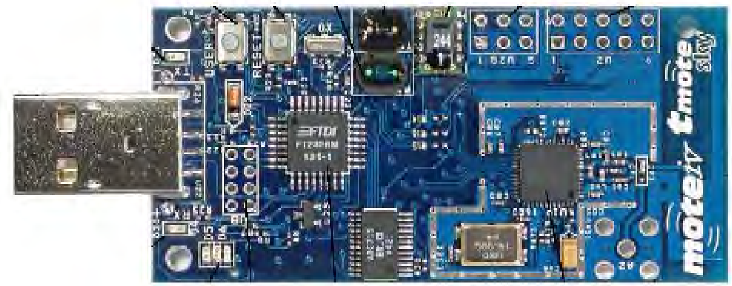

- Energy harvesting exploiting the EM field from AC electric current during idle (no measurement) times

Fully energy-neutral solution

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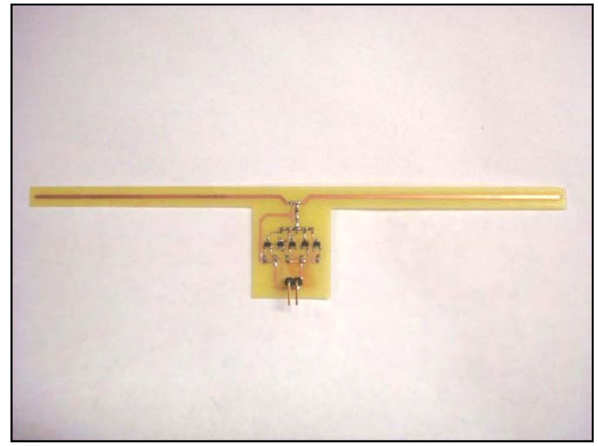
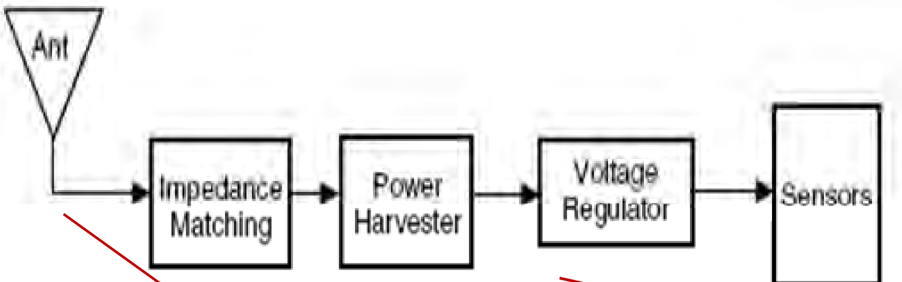
Radio Frequency “Harvester”

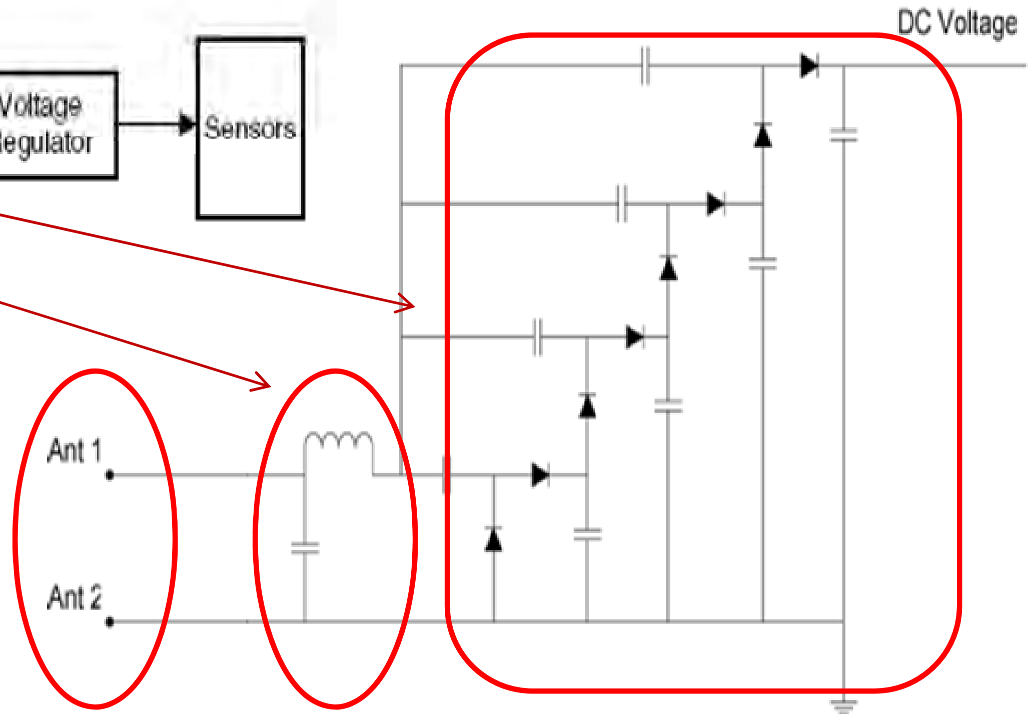
- Energy harvested from RF waves, generated by a transmitter (wireless power transmission)
- Store the energy with supercapacitor like energy buffer



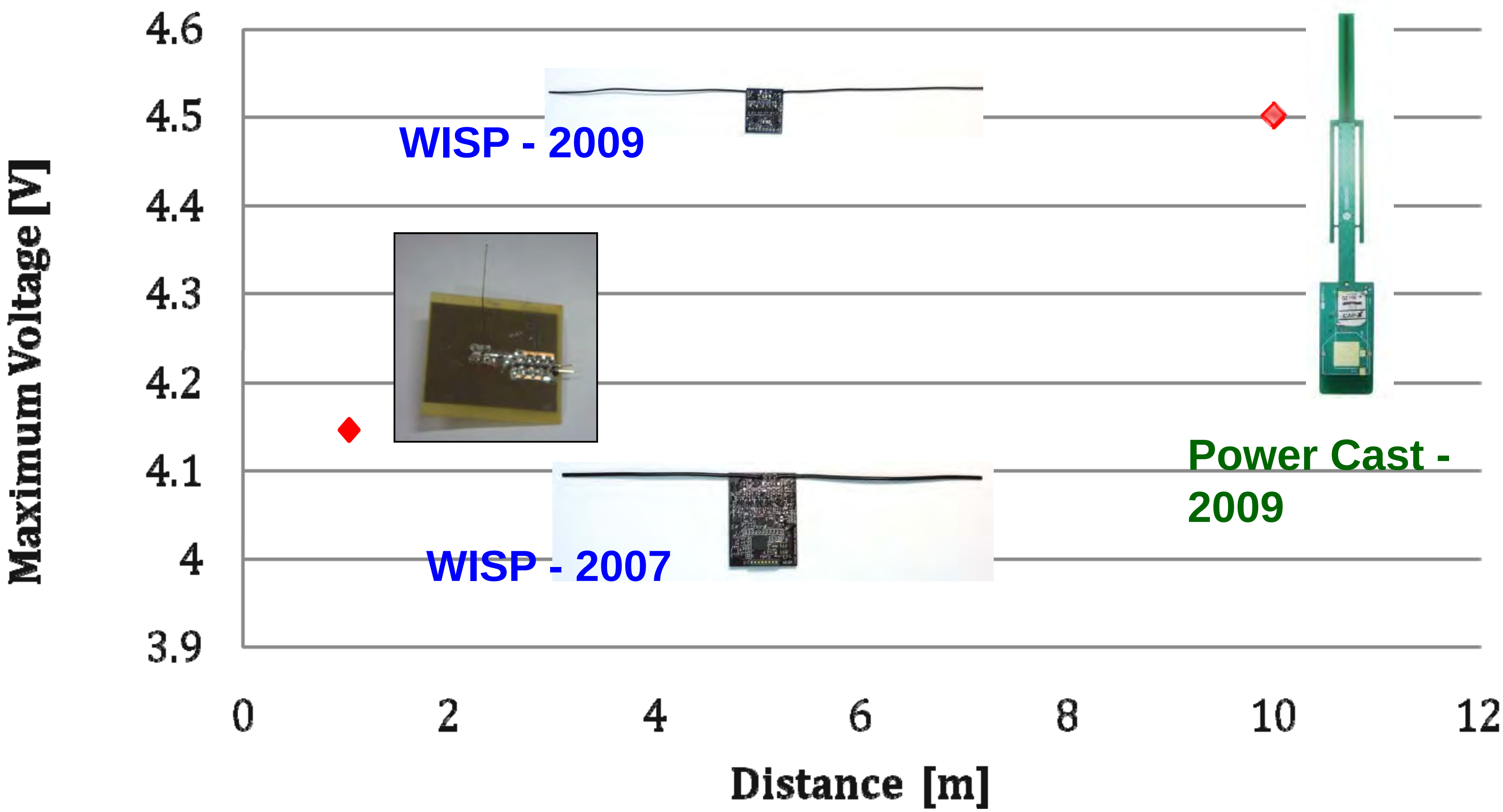


RFID transmitter

868 MHz



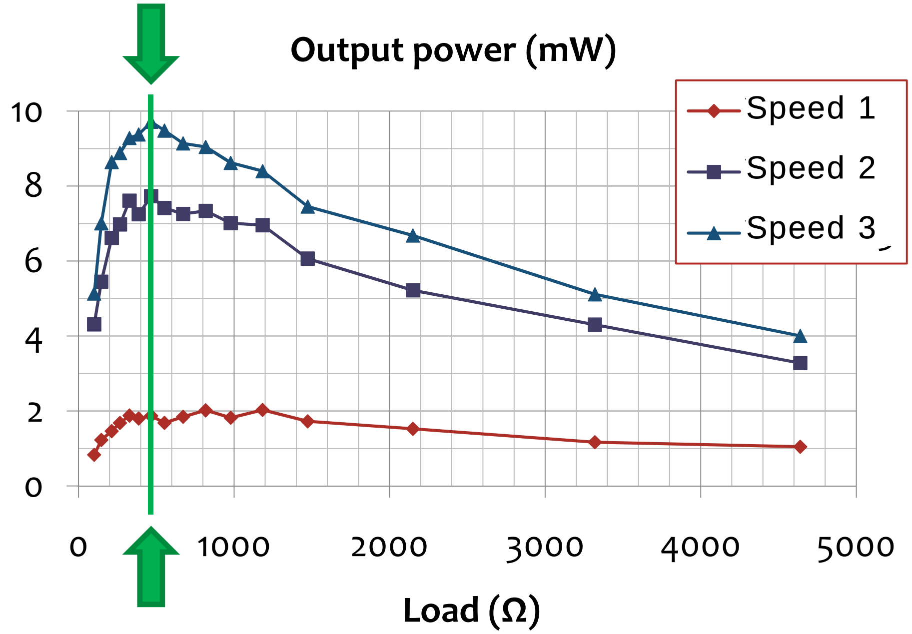
Power Transfer Efficiency

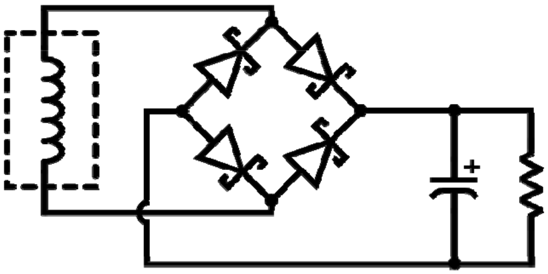


Lessons Learned:
Power levels are low (tens of µW)
Advanced RF & Antenna design is needed

Windmill Harvester

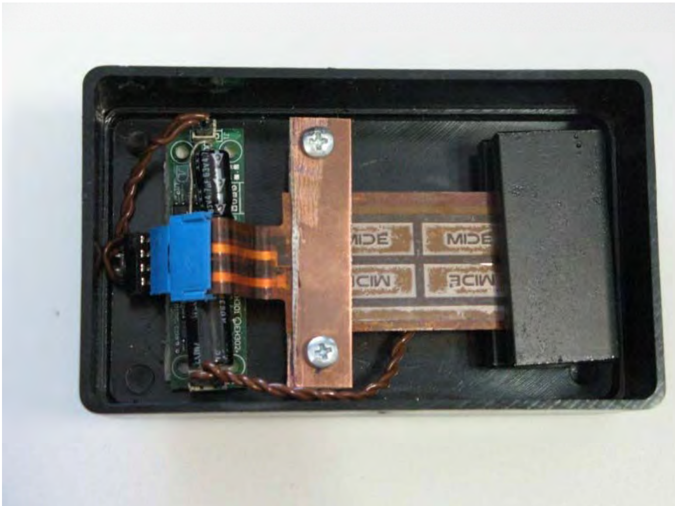
- In-runner brushless
- higher number of turns → higher output voltage
- Up to 10mW output Power





MPPT with constant load at any wind speed.

Kinetic Harvesters

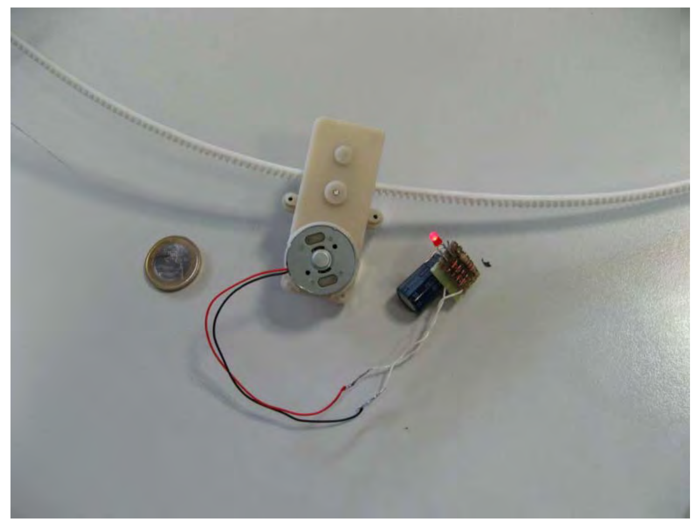


Piezoelectric

Size	**9,8 x 5,7 x 3 cm**
Weight	**~120 g**
Energy buffer	**4,7 µF**
Mean power (benchmark 2 Hz)	**18 µW**
Energy (1 min.)	**1,1 mJ**

Electromechanical

Size	**6,5 x 2,5 x 2,5 cm**
Weight	**~80 g**
Energy buffer	**4700 µF**
Mean power (benchmark 2 Hz)	**206 µW**
Energy (1 min.)	**12,4 mJ**



Motion frequency spectrum is a key design parameter!

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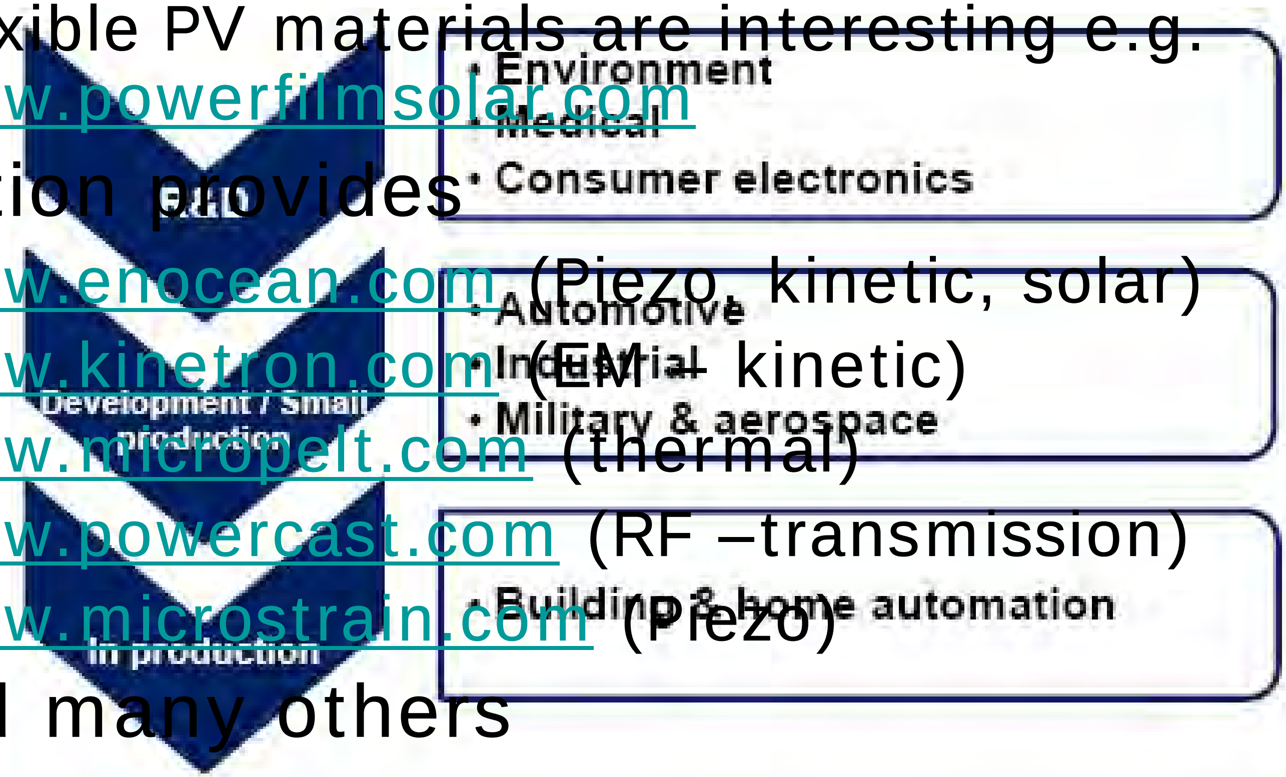
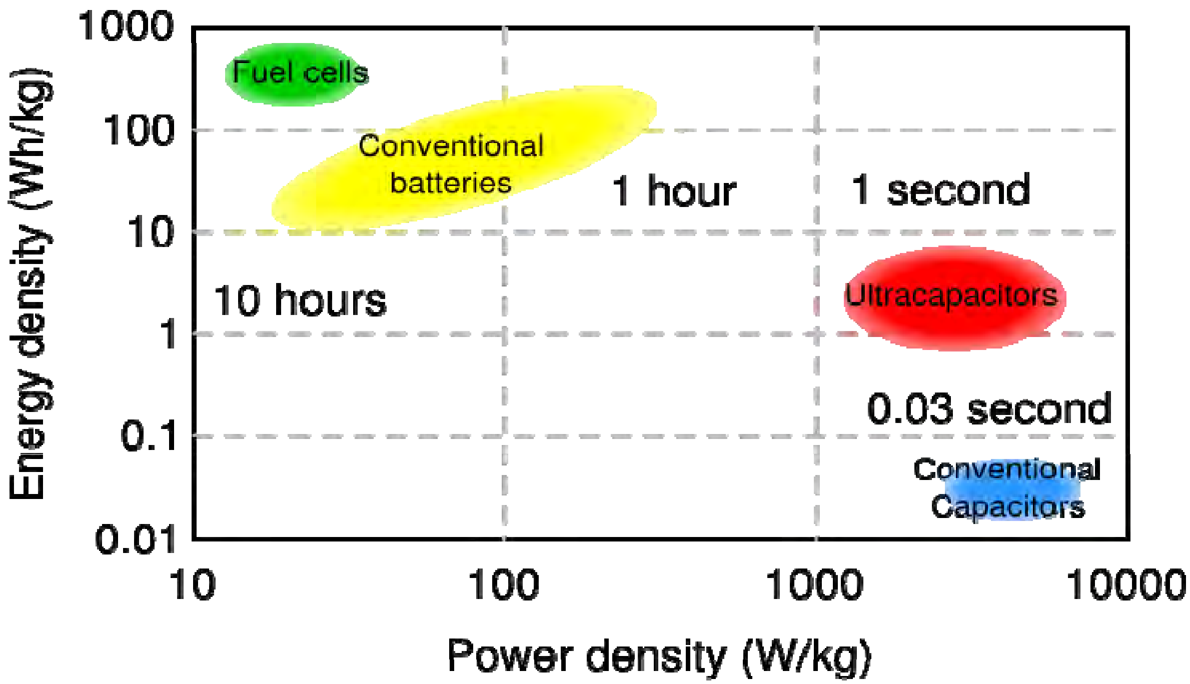
Market Outlook

- PV: quite mature, with many products
  - Flexible PV materials are interesting e.g. www.powerfilmsolar.com
- Solution provides
  - www.enocean.com (Piezo, kinetic, solar)
  - www.kinetron.com (EM – kinetic)
  - www.micropelt.com (thermal)
  - www.powercast.com (RF –transmission)
  - www.microstrain.com (Piezo)
- ...and many others



[Yole 09]

Energy Storage Technologies

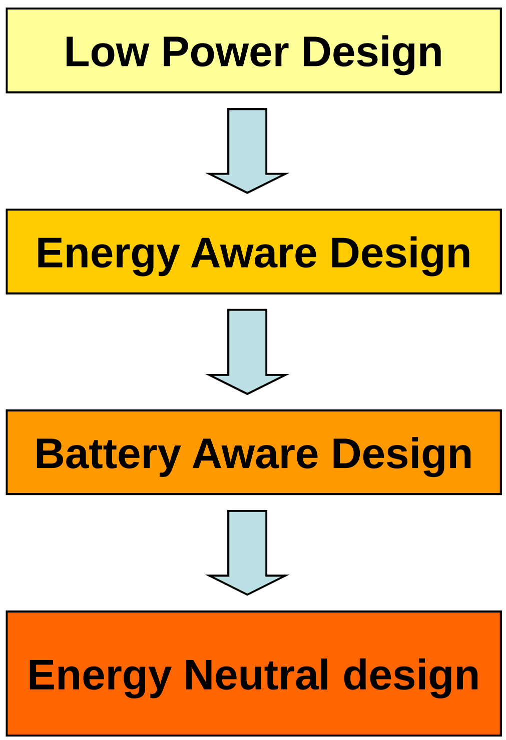


- Options
  - Secondary batteries
  - Capacitors
  - Flywheels
  - Fuel cell…
- Tradeoffs
  - Batteries
    - Mature technology, high energy density, less efficient, limited to few **hundred full recharging cycles** (significantly more shallow cycles)
  - Ultracapacitors (up to hundreds of Farads)
    - **Virtually infinite recharge cycles**, higher leakage current (goes up with size)

- Configurations: Battery-only, Capacitor-only, Tiered Capacitor+Battery

Energy Neutral System Design

Evolution of design techniques and tools



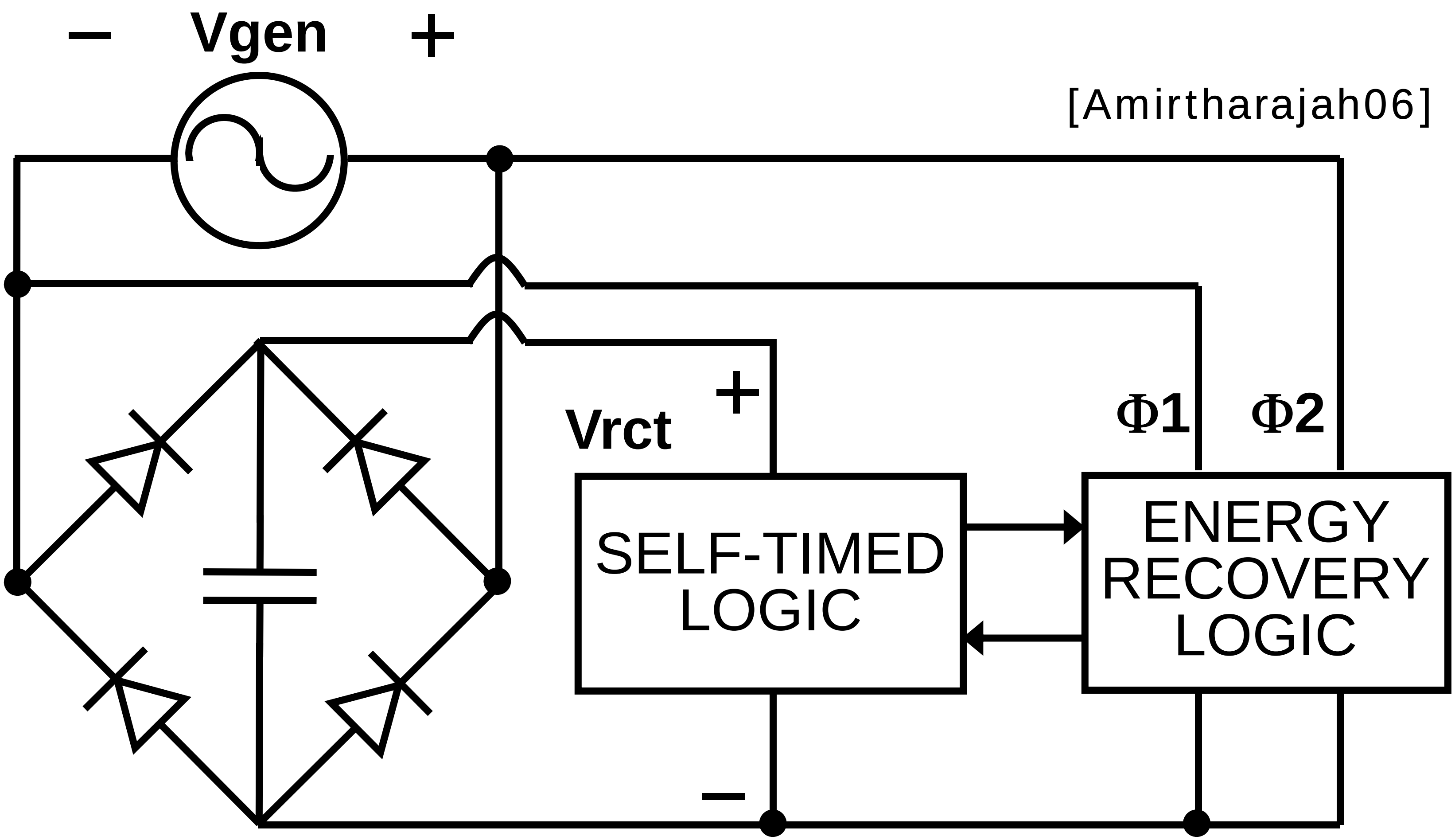
Hardware Design

- Conversion efficiency
- Impedance Matching
- Maximum power transferred
- ...

Software Design

- Scheduling algorithm
- Adaptive duty cycle
- Energy prediction algorithm
- ...

Harvester-friendly Circuits

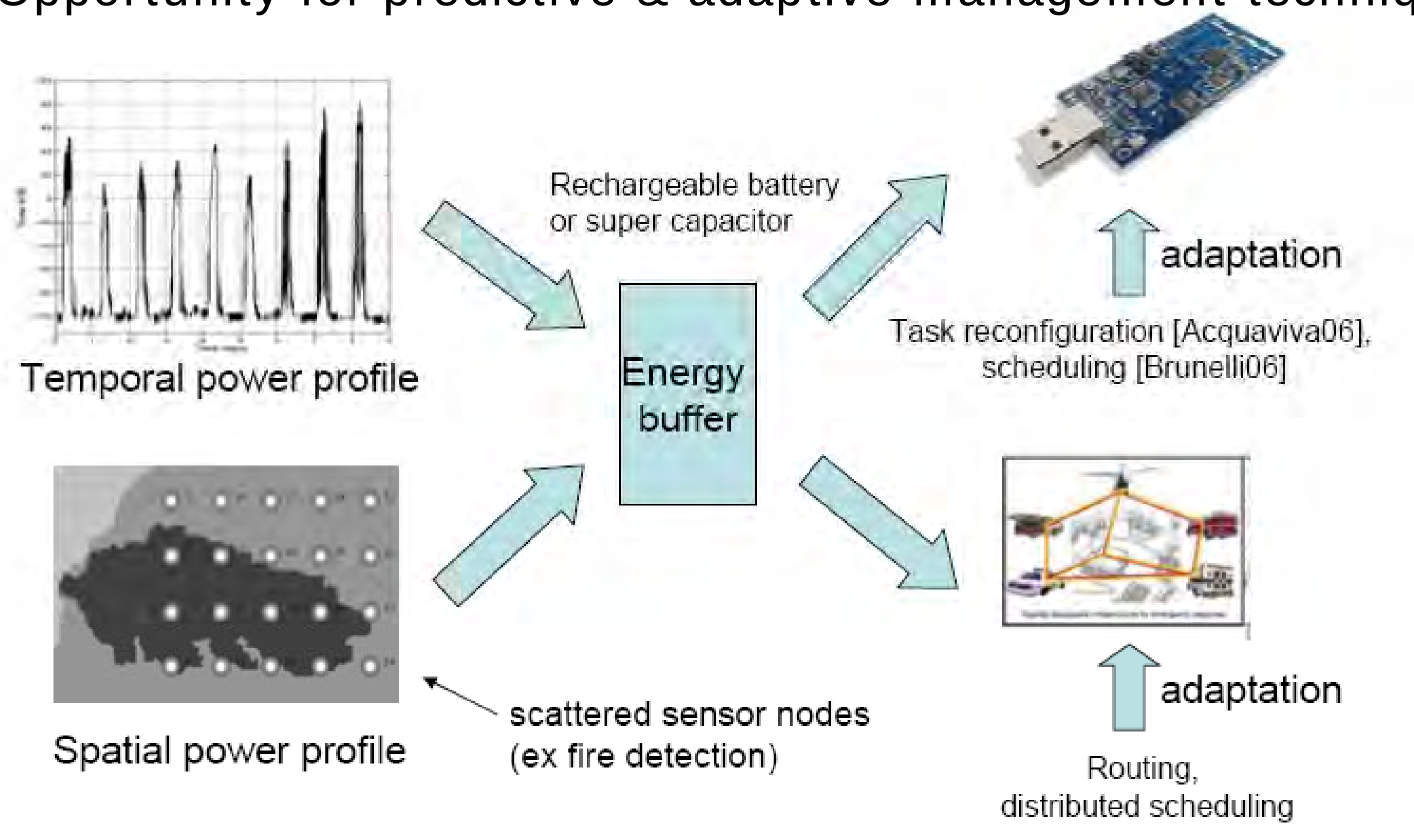


- Logic styles for AC power supplies: self-timed circuits and energy recovery
- ULP CMOS to avoid charge pumps

Managing Harvested Energy

It is **different** from battery energy

- Supply varies in time
  - Sometimes is scarce, sometime over-abundant
- Supply varies in space
  - Different nodes get different energy: need (dynamic) load migration
- Supply is repetitive (does not die out) & predictable
  - Opportunity for predictive & adaptive management techniques



Summary

- Energy neutral sensors (actuators) are promising for many smart & efficient energy applications
- Energy Harvesting and power storage devices are key enablers
- All system components need to be considered: not only a HW design challenge
- Distributed energy management is the frontier of system research