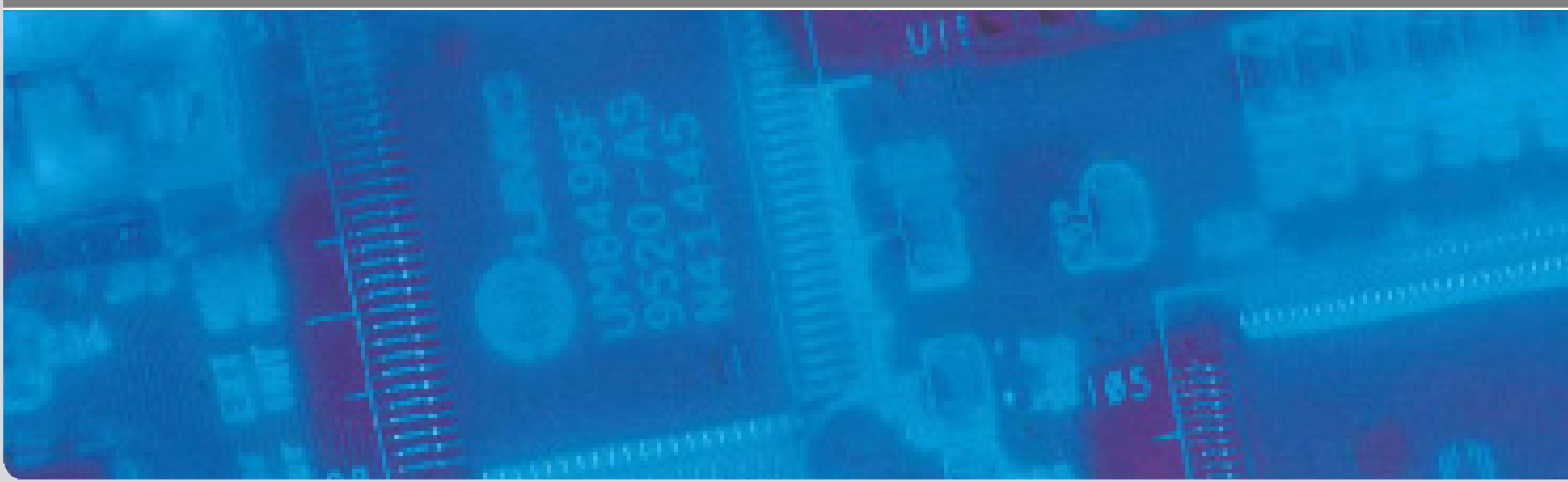
Karlsruhe Institute of Technology

Low Power Design

Volker Wenzel on behalf of Prof. Dr. Jörg Henkel
Summer Term 2016

CES – Chair for Embedded Systems



Organizational Issues

- Slides available online
  - **http://cesweb.itec.kit.edu/teaching/LPD/s16/slides/**
  - Username: student
  - Password: CES-Student
- Jabber/XMPP Conference Channel
  - ces-lowpower@conference.kit.edu
- Homework
  - practice reading of scientific papers
  - marked on the last slide
- Oral exam
  - make appointment with our secretary 6-8 weeks in advance
  - can be held in German/English
  - more information: **http://ces.itec.kit.edu/972.php**

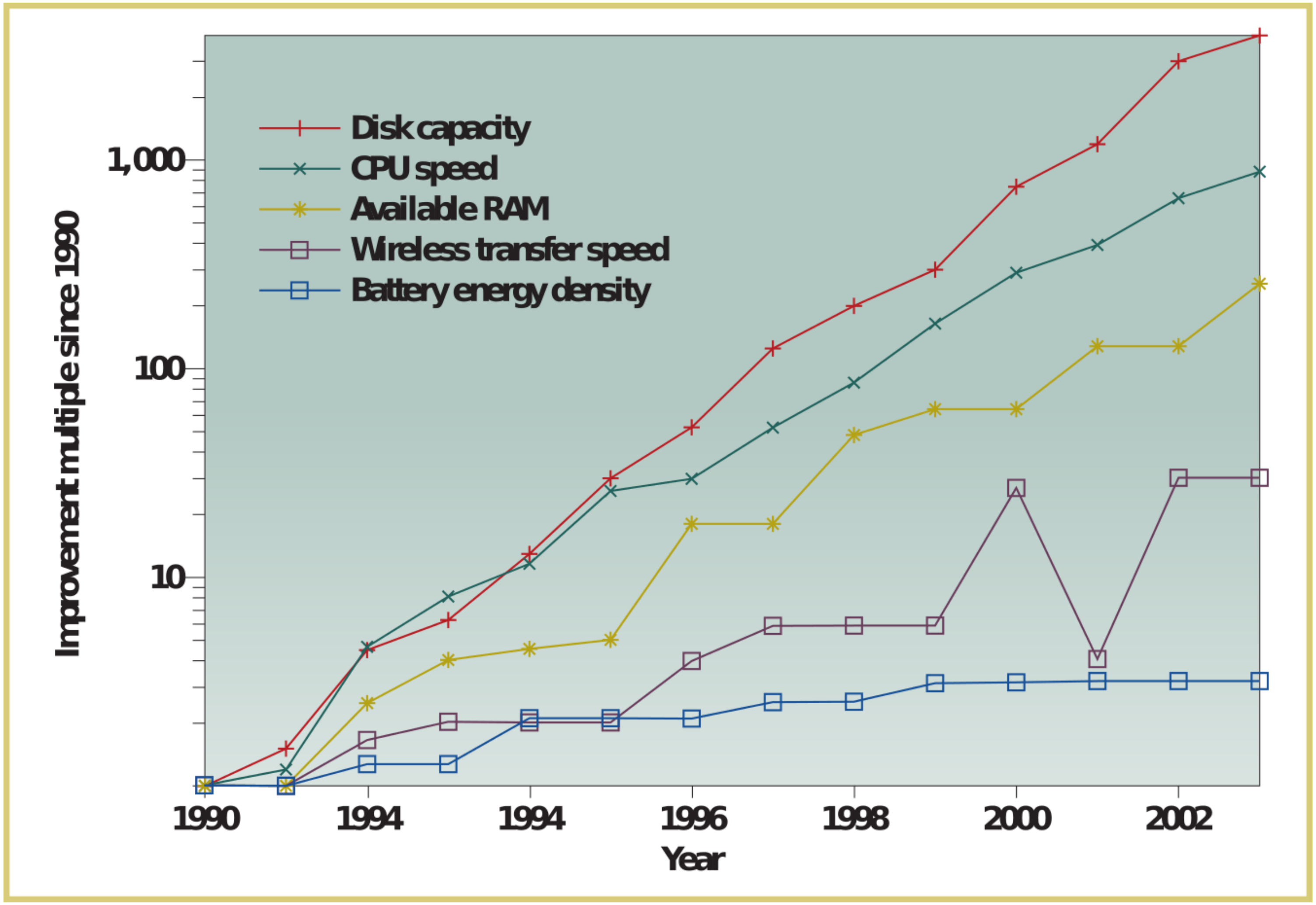
Overview Low Power Design Lecture

- Introduction and Energy/Power Sources (1)
- Energy/Power Sources(2): Solar Energy Harvesting
- Battery Modeling
- Hardware power optimization and estimation – Part 1
- Hardware power optimization and estimation – Part 2
- Hardware power optimization and estimation – Part 3
- Low Power Software and Compiler
- Thermal Management – Part 1
- Thermal Management – Part 2
- Aging Mechanisms in integrated circuits
- Lab Meeting

Overview for today

- Fuel Cells
- Human-generated Power for Portable Devices
- Solar Energy Harvesting
- Super Capacitors

Recap: Battery Gap



(src.: [Paradiso05])

Fuel Cells I

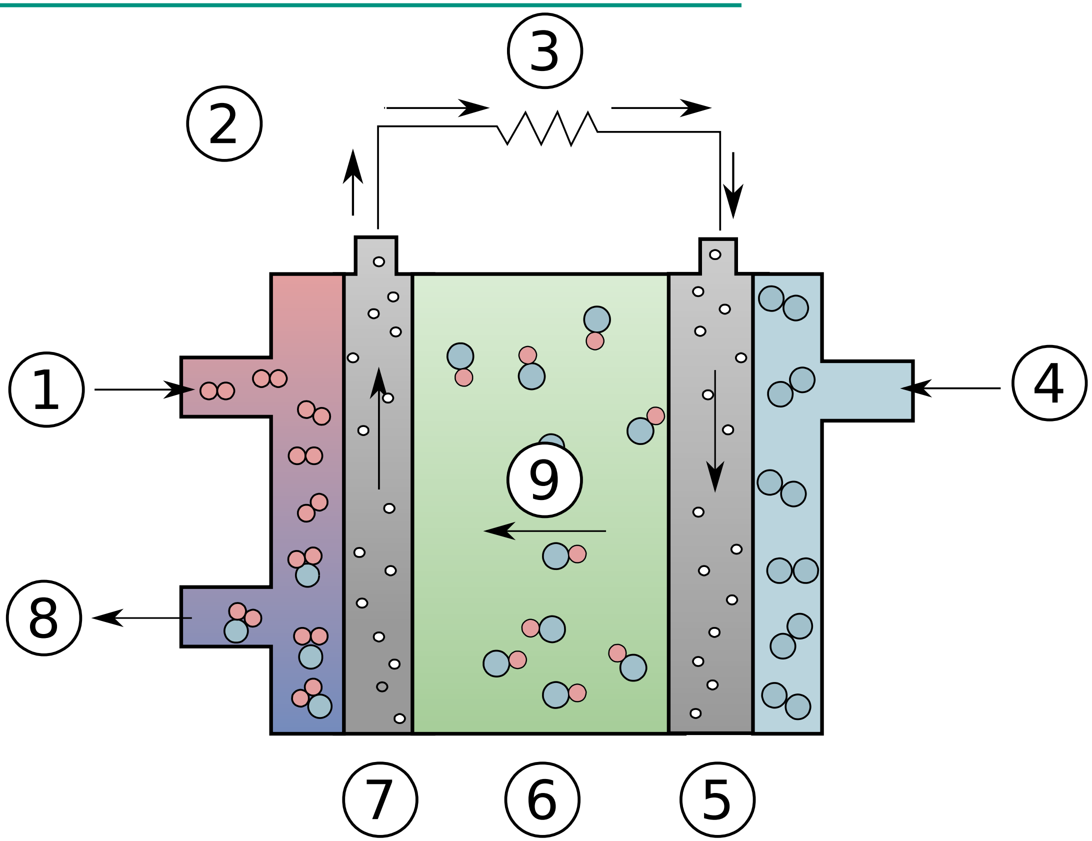
- direct conversion of fuel to electricity (direct current)
- high efficiency (~40-60%)
- different types of fuel cells exist beside Hydrogen-Oxygen fuel cell
- Hydrogen-Oxygen: environmentally (mostly) clean; byproduct is water
- not yet mass-produced

(src.: en.wikipedia.org)

- Solid oxide fuel cells (SOFC):
  - Needs 800-850°C
- Proton Exchange Membrane (PEM)
  - Reaction positive electrode:
    - $\frac{1}{2} O_2 + 2\ H_3O^+ + 2e^- \rightarrow 3\ H_2O$
  - Reaction negative electrode:
    - $H_2 + 2\ H_2O \rightarrow 2H_3O^+ + 2\ e^-$
  - Overall reaction:
    - $H_2 + \frac{1}{2} O_2 \rightarrow H_2O \quad E_0 = 1.229V$

Fuel Cells II – Alkaline fuel cell

1) Hydrogen
2) Electron Flow
3) Load
4) Oxygen
5) Cathode
6) Electrolyte
7) Anode
8) Water
9) Hydroxyl Ion



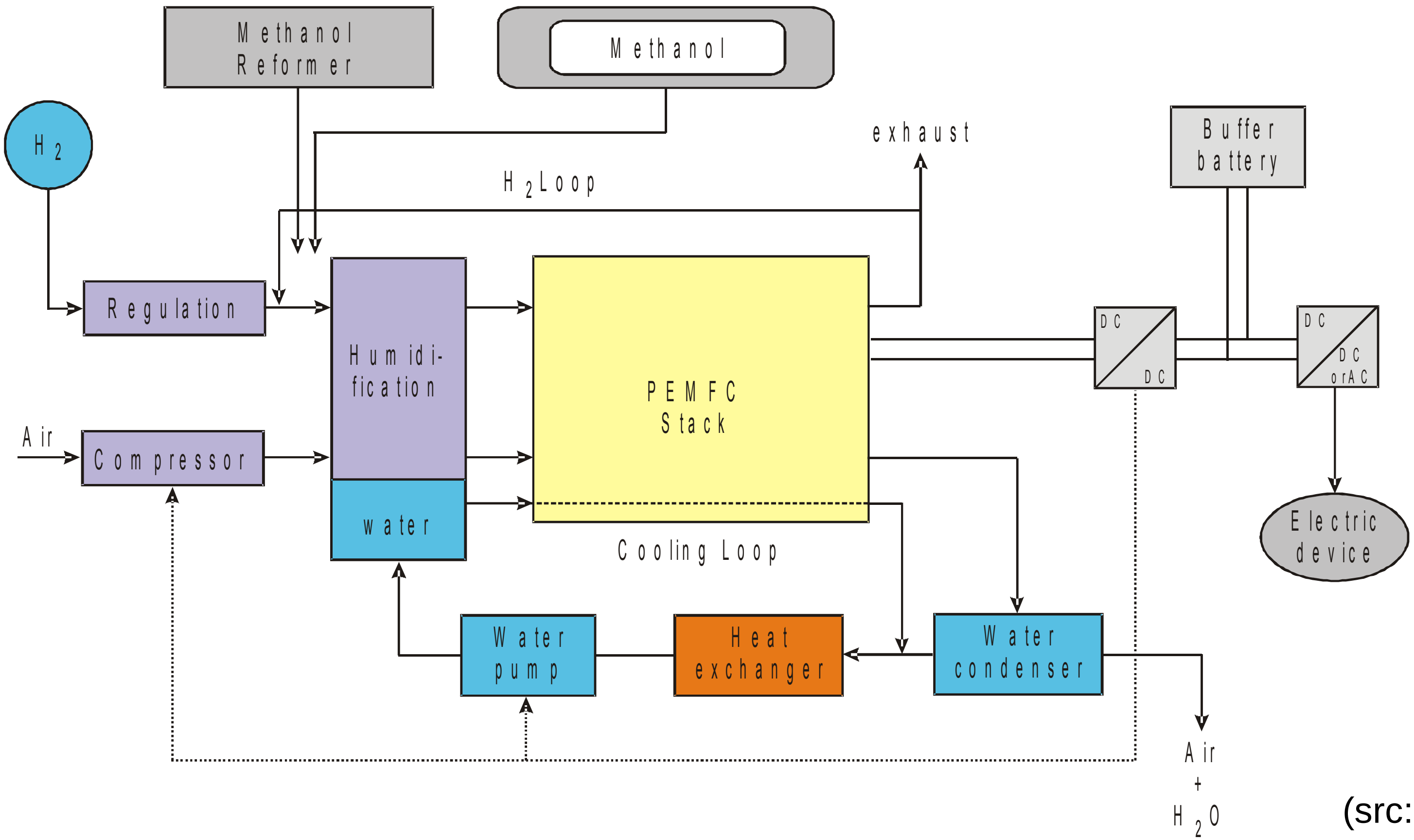
$$2H_2 + 4OH^- \longrightarrow 4H_2O + 4e^-$$

$$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$$

(src.:en.wikipedia.org)

A whole fuel cell system

Whole system contains besides the core (stack): a) electrical, b) thermal, c) and fluidic management systems



(src: [Blo04])

Miniature Fuel Cells

- application domain: portable electronic devices (smartphone, cameras, etc.)
- two approaches:
  - a) “bipolar” technology
    - Built with bipolar plates forming the fuel cell stack
    - Typically 20-500W
    - Smaller stacks seem not to be competitive with Lithium-Ion batteries
    - sfc.com and many others
  - b) Various approaches with new concepts e.g. micro fabrication techniques
    - Typically 0.1-25W
    - substrate (thin-film)-based

Silicon Fuel Cells

- Silicon wafer; grown and treated with lithographic techniques

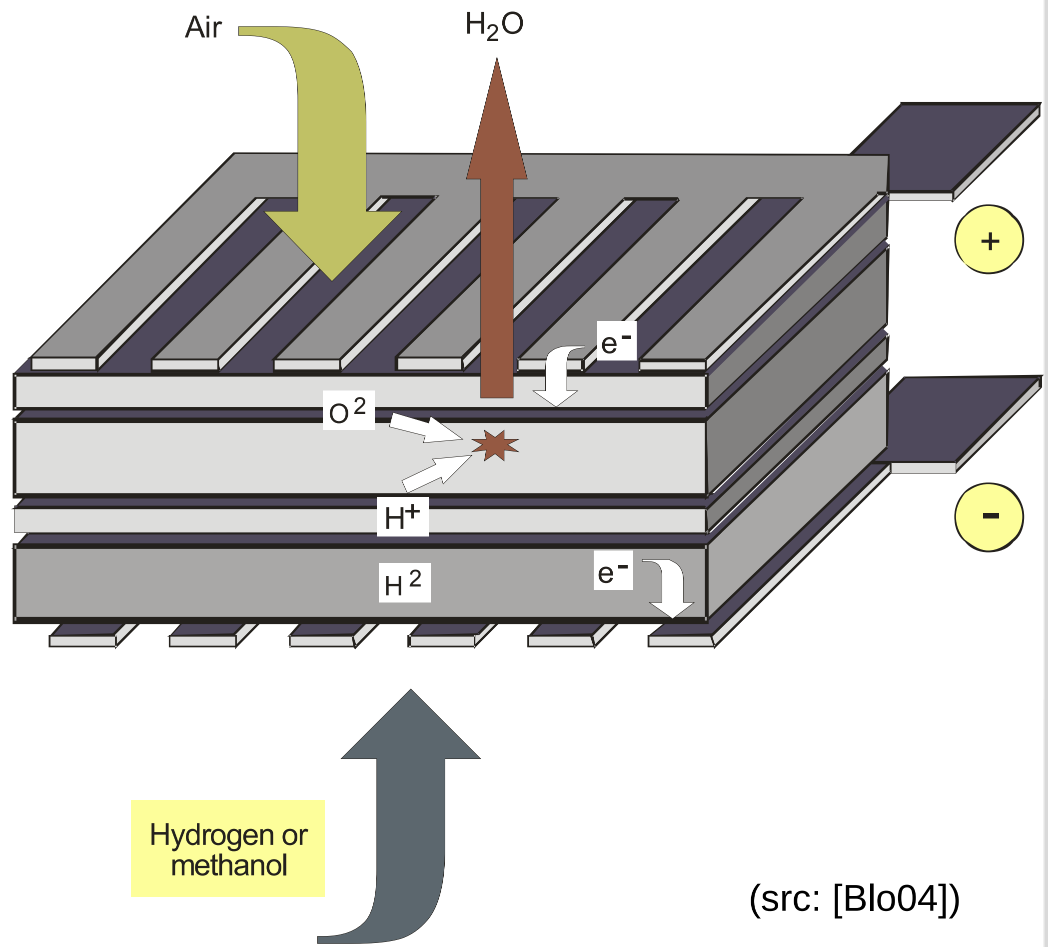
  Often less than a centimeter wide

- By various companies/institutions like: *Neah Power;*

  Integrated Fuel Cell Technologies,

- *French Atomic Energy Commission,*

  Case Western University



(src: [Blo04])

- Can energy for portable electronic devices be harvested from humans?

(src.: http://www.extremetech.com/)

(src.: www.warnerbros.com)

Human power consumption for various activities

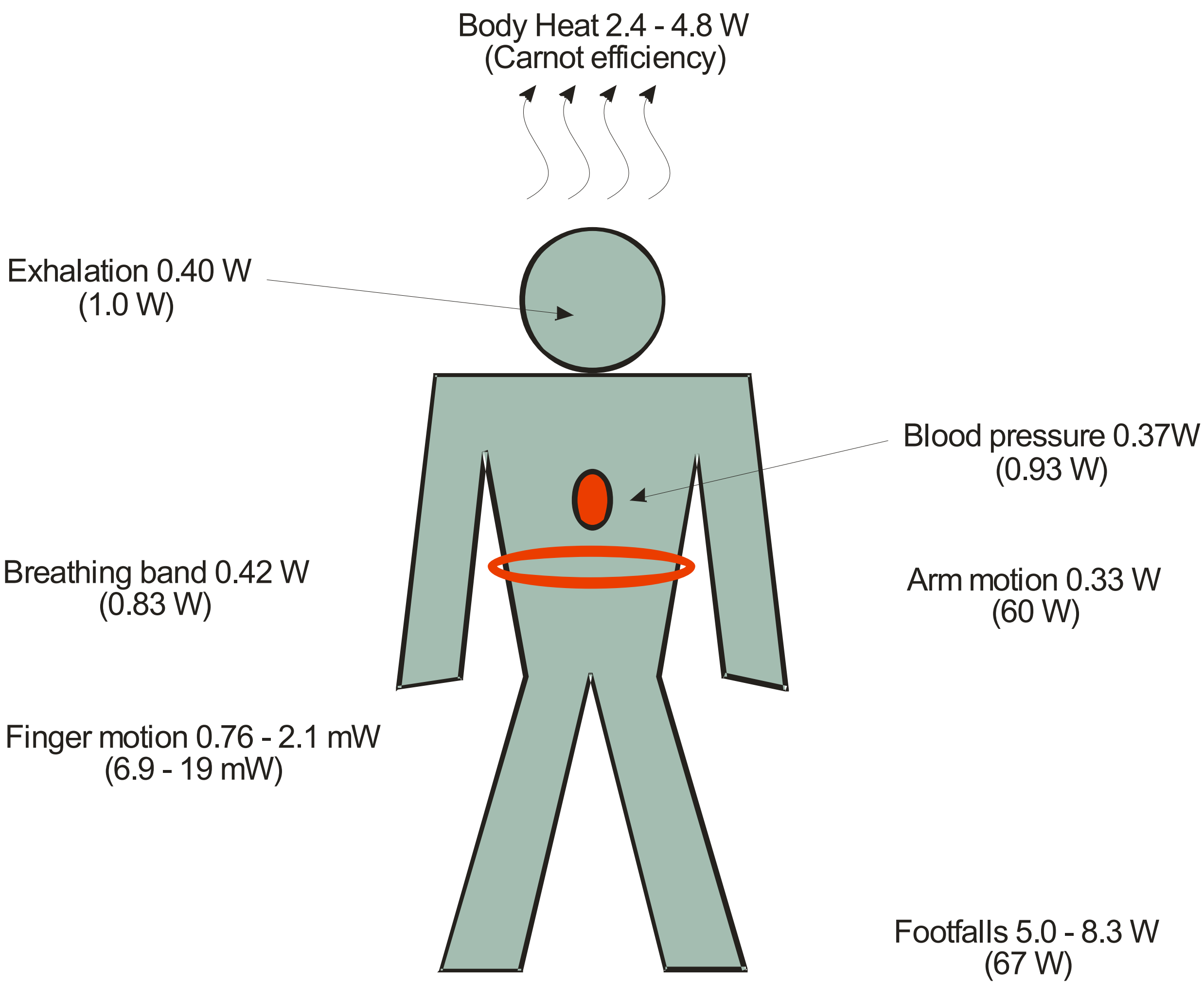
- A span of ~20x !
- However: power may not be easily harvested
- But even then: for usage the power/energy stored, converted (DC/DC, impedance, etc)
- For acceptance, harvesting needs to be completely non-obtrusive

Human Energy Expenditures for Selected Activities

Activity	Kilocal/hr	Watts
Sleeping	70	81
Lying quietly	80	93
Sitting	100	116
Standing at case	110	128
Conversation	110	128
Eating a meal	110	128
Strolling	140	163
Driving a car	140	163
Playing the 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	1048
Sprinting	1400	1630

Source: Derived from D. Morton. Human Locomotion and Body Form. Williams & Wilkens, Baltimore, MD.1952

Power/energy from humans



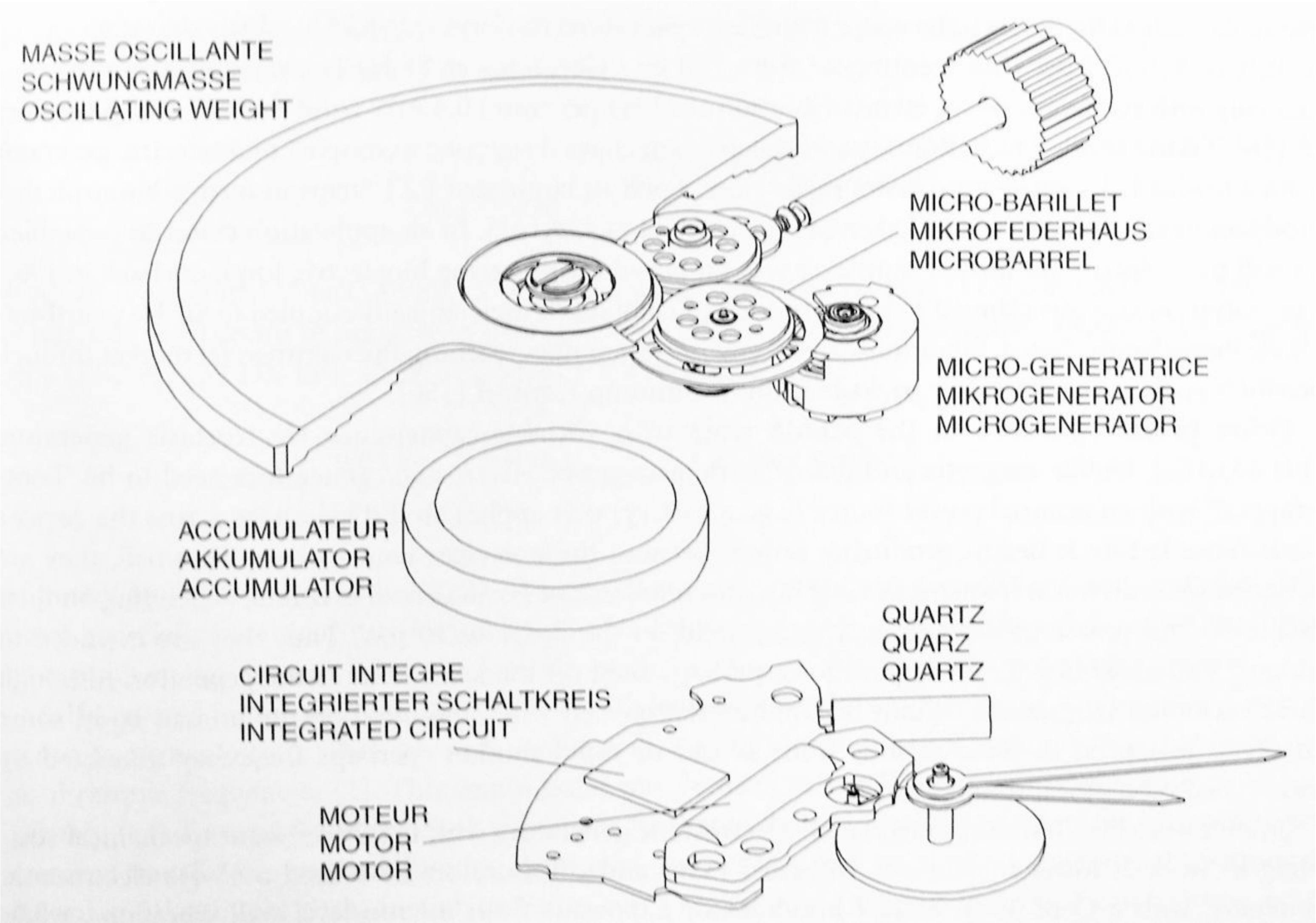
Human power sources

- body heat:
  - (T_body-T_ambient)/T_body = 310K-293K)/310K = 5.5%
  - not very efficient
- from breath:
  - Principle: uses diff. in from breath pressure and atmospheric pressure → only 2% efficiency
- From blood pressure
- Capturing energy from vibrations, motion etc.

Human power sources (cont'd)

- Power from typing
  - Ex: 50g key pressure, depress by 0.5cm
  - (0.05kg/key-stroke) * ($9.8m/s^2$) * 0.005m * (7.5 key-strokes / sec) =
  - = 19 mW -> too less to power a whole portable system; plus, user is not continuously typing
  - Idea: keyboard can at least announce its character to the rest of the system through own energy
- Inertial micro systems
  - Used for hundred of years in watches
- Electrical version (next slide)
  - Functionality:
    - the mass winds a spring
    - when enough mech. (spring) energy is accumulated, a micro generator is driven at 15,000 rpm (rotations per minute)
    - yields 6mA and 16V for 50ms

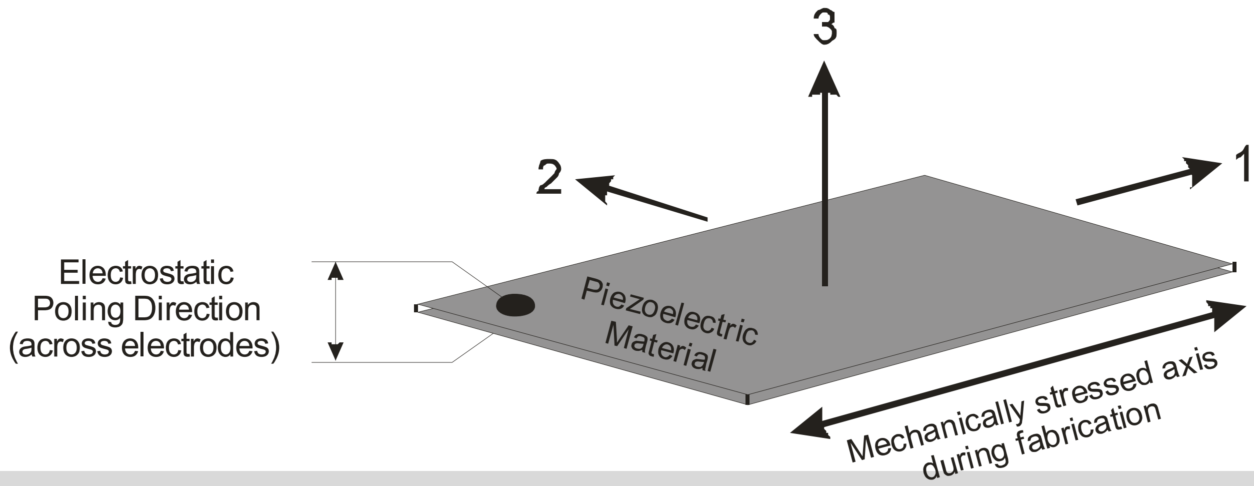
Self-winding electric watch



(src.: [StaPa04])

Human power sources: walking

- Walking (68kg human, 5.6km/h) costs ~324Watt of power
  - Most of this power is used to move legs
- Power through the fall of the heel:
  - 68kg * (9.8m/sec^2) * 0.05m * (2 steps/sec) = 67W
  - This power cannot simply be converted in electrical power w/o significant intrusion
  - Converting to electrical power: e.g. via piezoelectric device (e.g. Quartz)

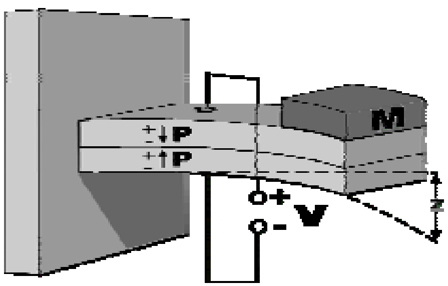


Vibration → Electricity

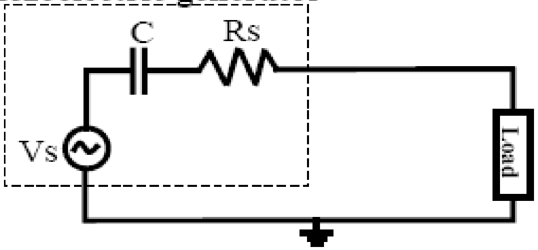
(src: Hande, Dallas)

Piezoelectric

Strain in piezoelectric material causes a charge separation (voltage across capacitor)

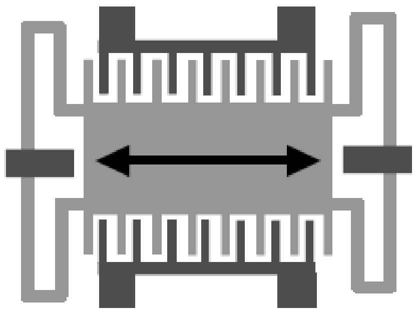


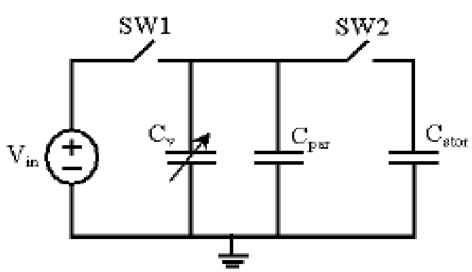
Piezoelectric generator



Capacitive

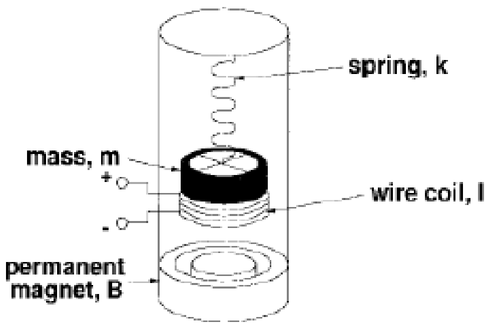
Change in capacitance causes either voltage or charge increase.





Inductive

Coil moves through magnetic field causing current in wire.



Amirtharajah et. al., 1998

Other power/energy sources

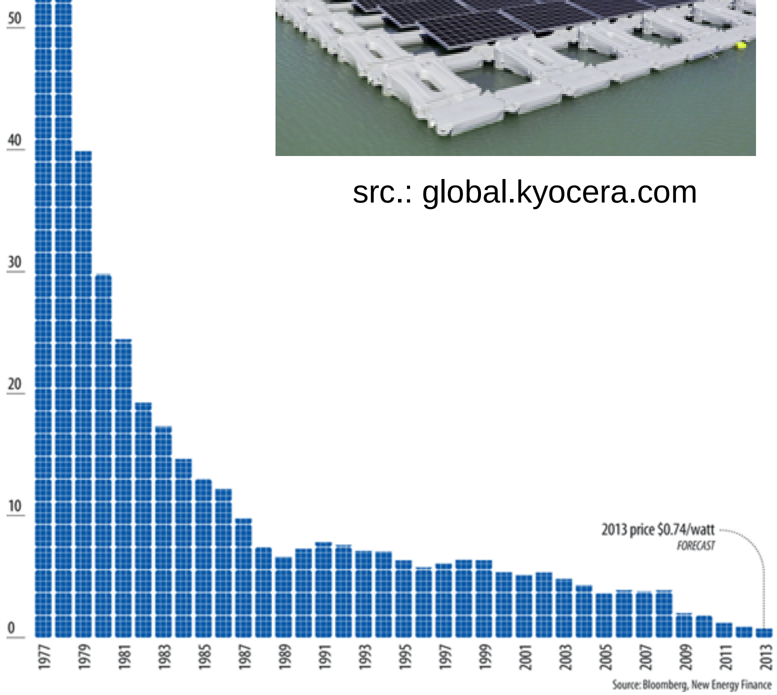
Energy Source	Power/Energy Density
Batteries (Zinc-Air, primary)	1050-1560 mWh/cm^3
Batteries (Li, rechargeable)	300 mWh/cm^3
Solar (outdoors)	15 mW/cm^2 (direct sun) 1 mW/cm^2 (24 hour avg)
Solar (indoors)	0.006 mW/cm^2 (office desk) 0.57mW/cm^2 (<60W desk lamp)
Vibrations	0.01-0.1 mW/cm^3
Acoustic (noise)	3 e-6 mW/cm^2 @ 75dB 9.6 e-4 mW/cm^2 @ 100dB
Miniature Fuel cells	0.1-500W

(derived from: A. Raghunathan, NEC)

Solar Energy

- eg. floating solar plant in Japan
- output power: 2.9MW
- expected annual power generation: 3,300MWh/year

(src.: global.kyocera.com)



src.: global.kyocera.com

src.: economist.com

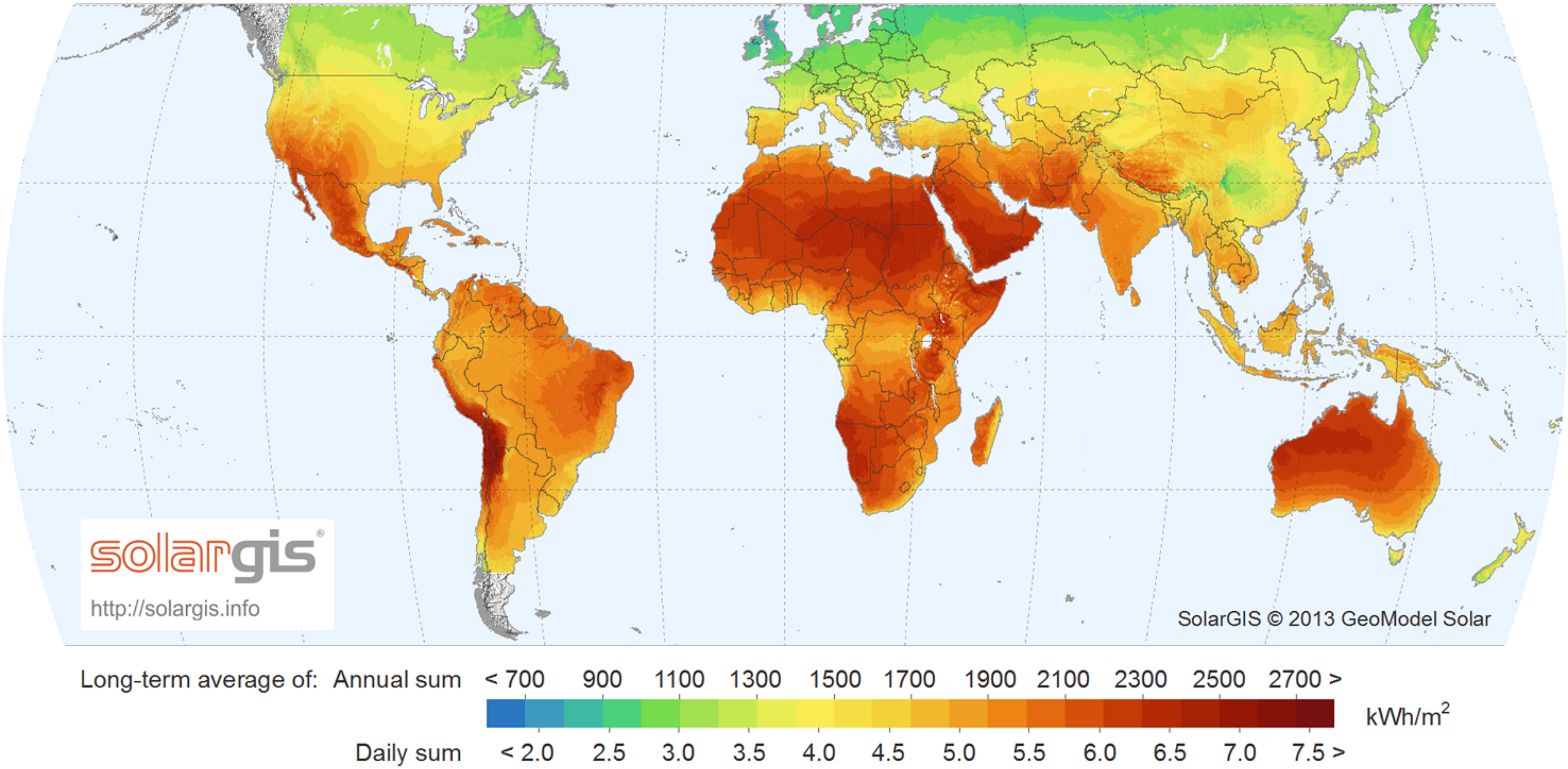
Solar Energy

- Energy harvesting through photo-voltaic conversion provides high power density
- Good for embedded systems that need some mW power
- But: characteristics of solar cells need to be taken into consideration for system design

Harvesting technology	Power density
Solar cells (outdoors at noon)	$15mW/cm^2$
Piezoelectric (shoe inserts)	$330\mu W/cm^3$
Vibration	$116\mu W/cm^3$
Thermoelectric (10^oC gradient)	$40\mu W/cm^3$
Acoustic noise (100dB)	$960nW/cm^3$

(src: VRagh05)

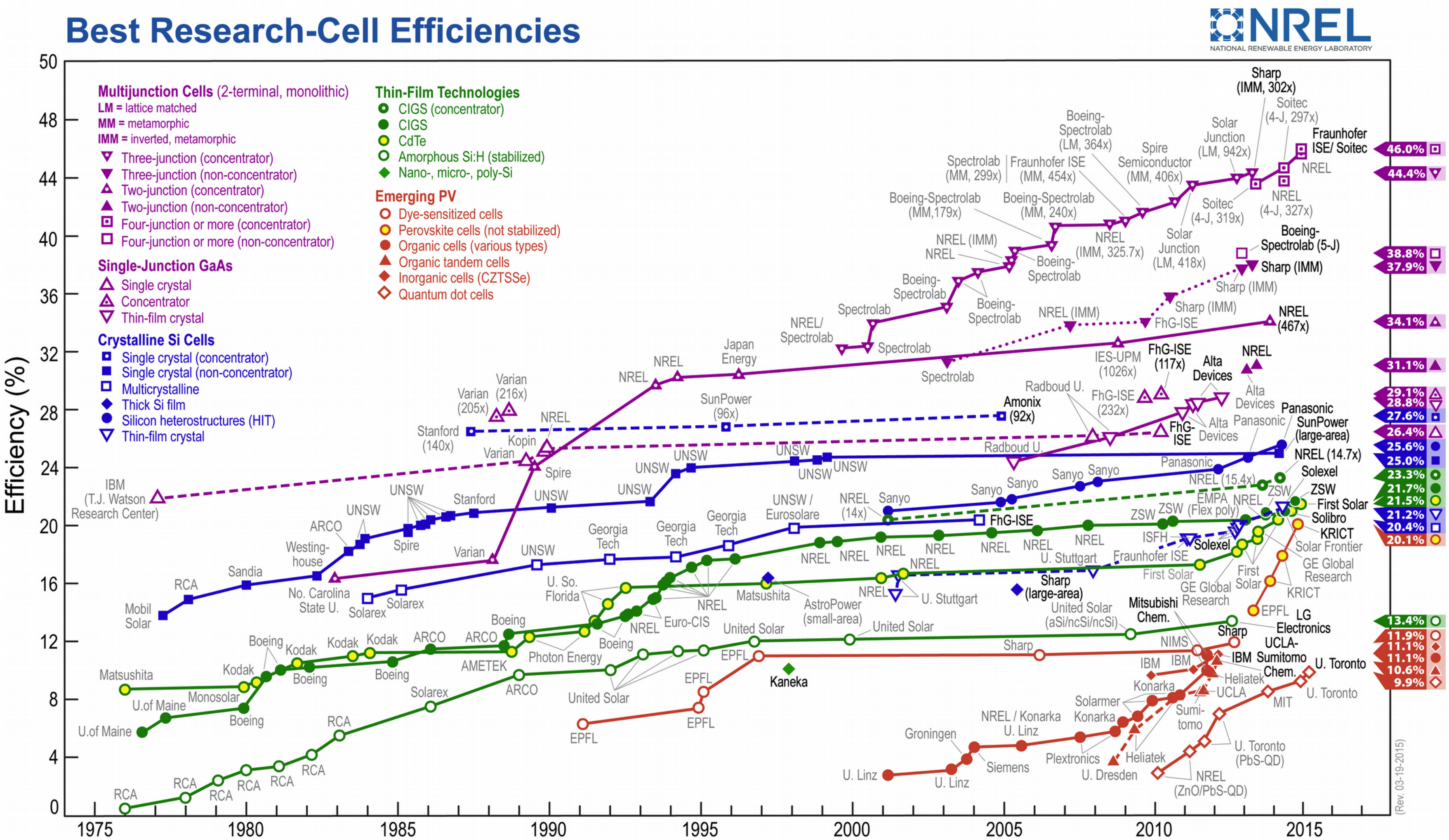
Solar Energy



src.: en.wikipedia.org

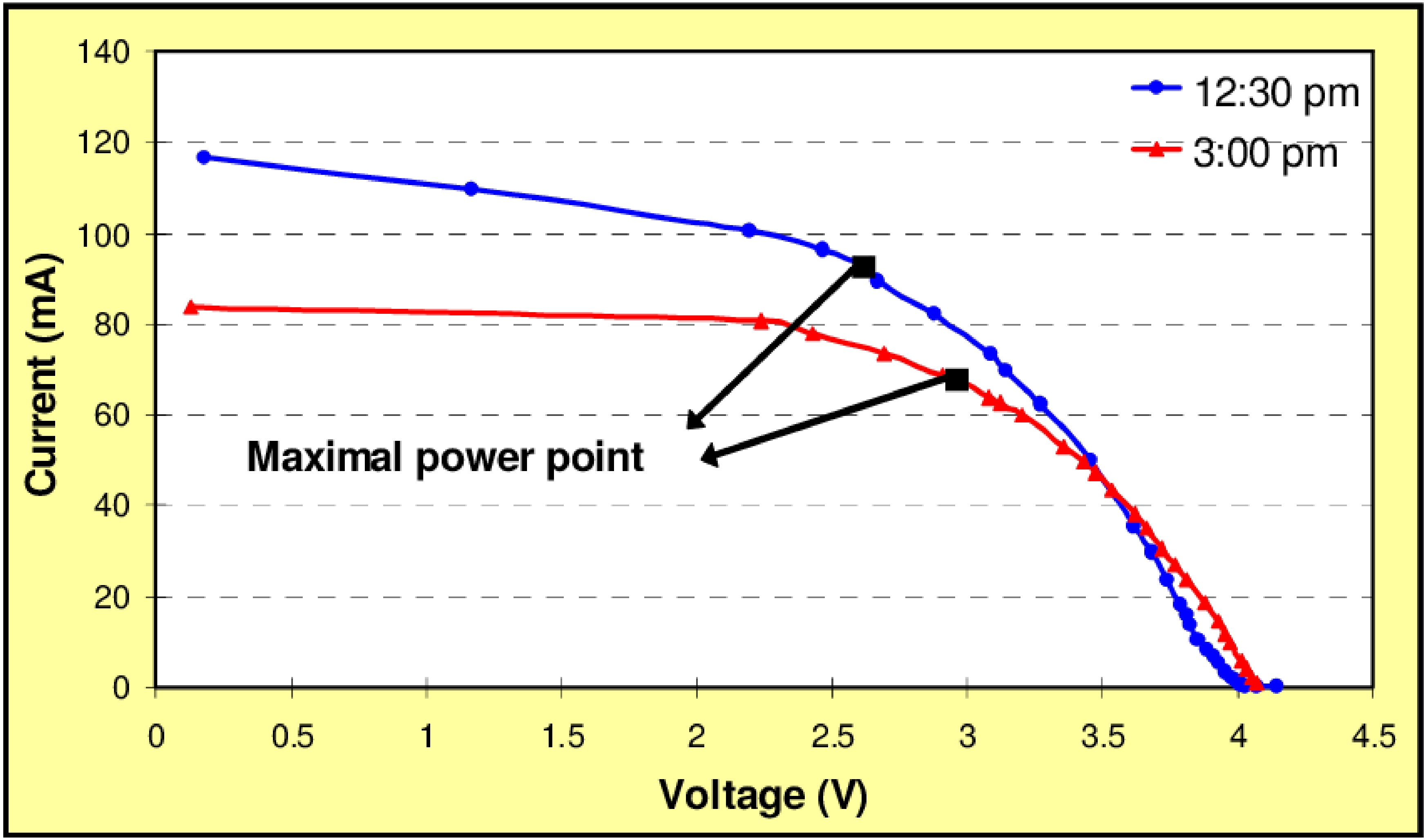
Outside earth's atmosphere: solar constant 1353 W/m²

Solar Panels



src.: en.wikipedia.org

Solar Panels



Measured V-I characteristics of the Solar World 4-4.0-100 solar panel(src.: VRagh05)

Solar Panels

- Characteristics:
  - a) Solar panel behaves as a voltage limited current source

    ie. current rather constant,

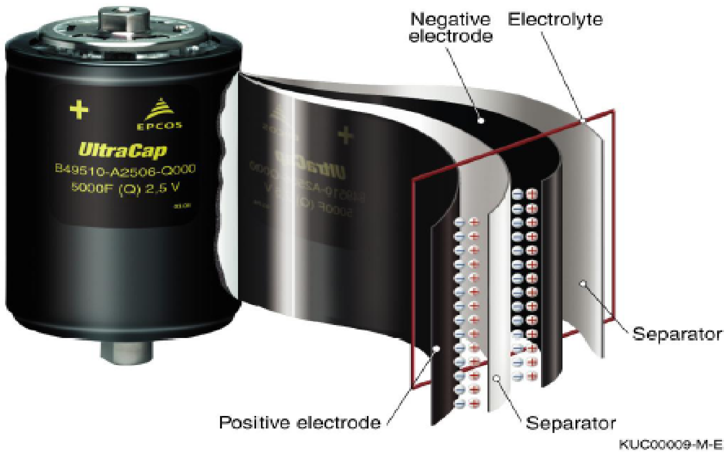
    voltage varying in wide range

    Remember: battery is a voltage source)
  - b) There is an optimum operation point for maximum power extraction
  - c) When solar radiation decreases (increases) => I_sc also decreases (increases); V_oc is almost constant
- Since it behaves like a current source (supply voltage depends on varying load) => energy storage element i.e. battery is necessary (could store harvested energy)

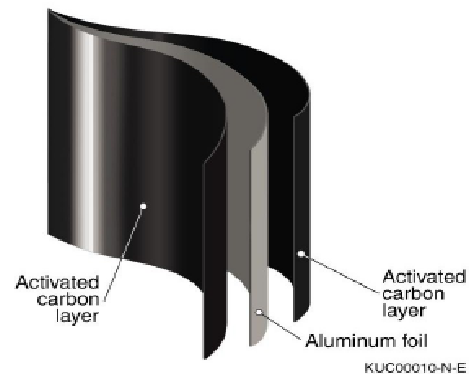
(src.: VRagh05)

Super Capacitors

(src: VRagh05)



UltraCap layer structure



Electrode structure

- Have lower energy density compared to batteries
  - e.g. 5.1 Wh/kg (src: Maxwell Boostcap series)
  - e.g. 6.2 Wh/l (src: Maxwell Boostcap series)
- But:
  - Higher power density
  - Higher life time (charge/discharge cycles: > 500,000 cycles)

Super Capacitors

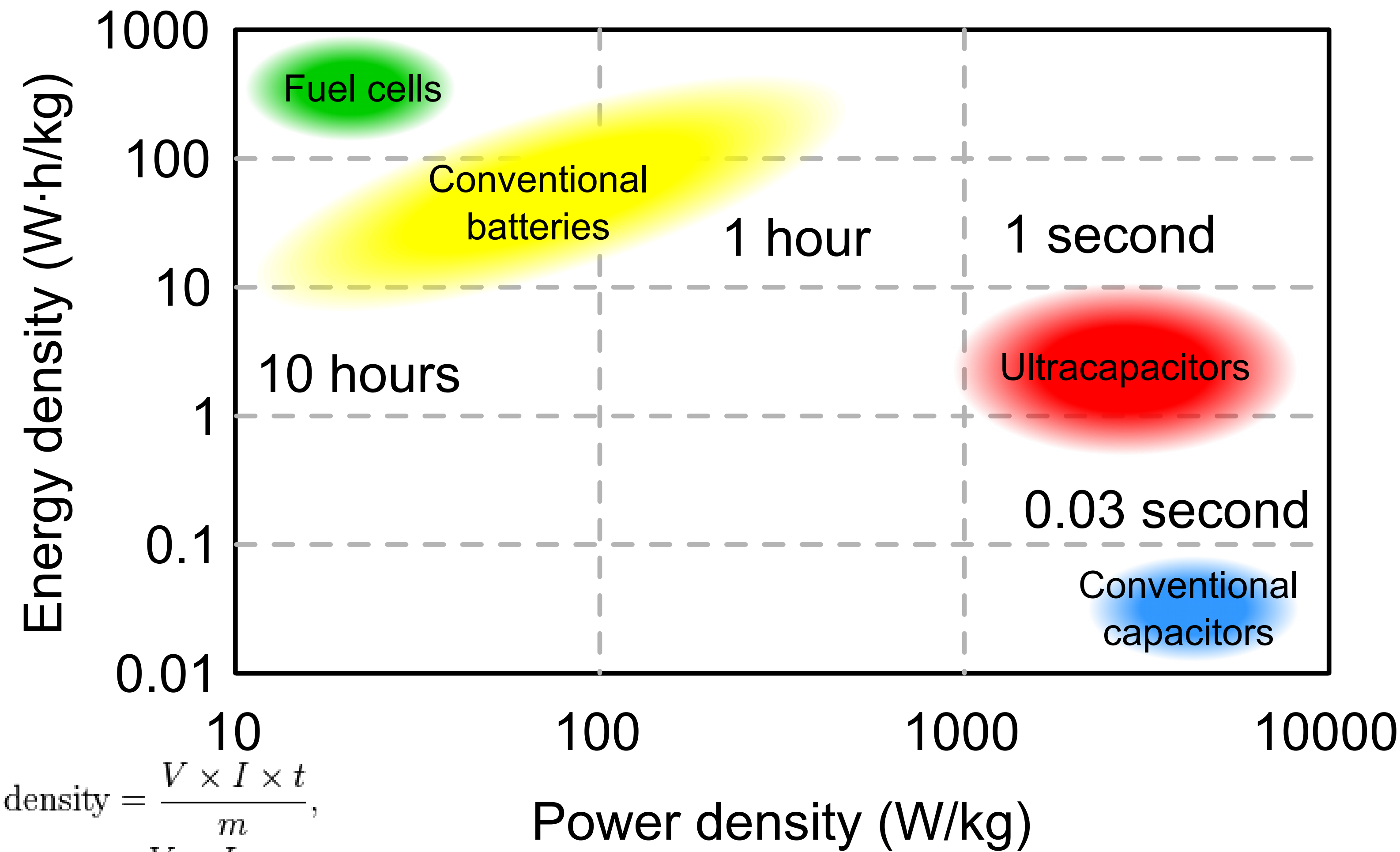
Parameter	aluminium electrolytic capactors	double-layer capacitors for memory backup	super-capacitors for power applications	pseudo and hybrid capacitors (Li-Ion capacitors)	lithium-ion batteries
temperature range (°C)	-40 to 125	-20 to +70	-20 to +70	-20 to +70	-20 to +60
cell voltage (V)	4 to 550	1.2 to 3.3	2.2 to 3.3	2.2 to 3.8	2.5 to 4.2
charge/discharge cycles	unlimited	10^5 to 10^6	10^5 to 10^6	$2*10^4$ to 10^5	500 to 104
capacitance range (F)	≤1	0.1 to 470	100 to 12000	300 to 3300	
energy density (Wh/kg)	0.01 to 0.3	1.5 to 3.9	4 to 9	10 to 15	100 to 265
power density (kW/kg)	> 100	2 to 10	3 to 10	3 to 14	0.3 to 1.5
self discharge time at room temperature	short (days)	middle (weeks)	middle (weeks)	long (month)	long (month)
efficiency (%)	99	95	95	90	90
life time at room temperature (years)	> 20	5 to 10	5 to 10	5 to 10	3 to 5

src.: en.wikipedia.org

Super Capacitors

- Typ: Speicherkondensator
- Ausführung: Gold-Cap
- Material: cadmiumfrei
- Kapazität 22 F
- Spannung DC 2,3 V
- Maße
- Ø 18,0 mm
- Preis 5,70€ (www.reichelt.de, April 2016)

Batteries vs. Capacitors (Ragone Chart)



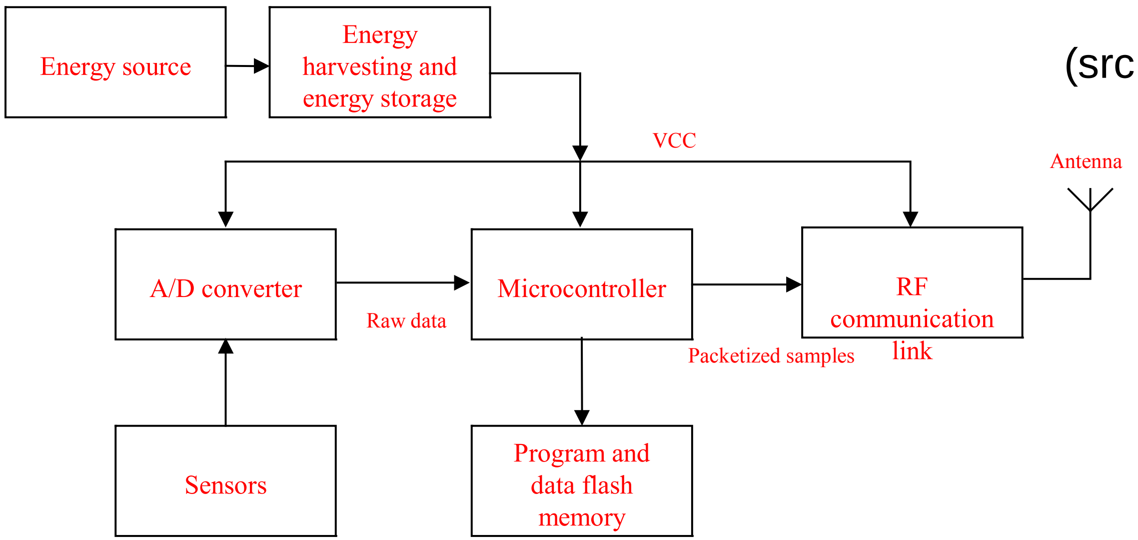
$$\text{Energy density} = \frac{V \times I \times t}{m},$$

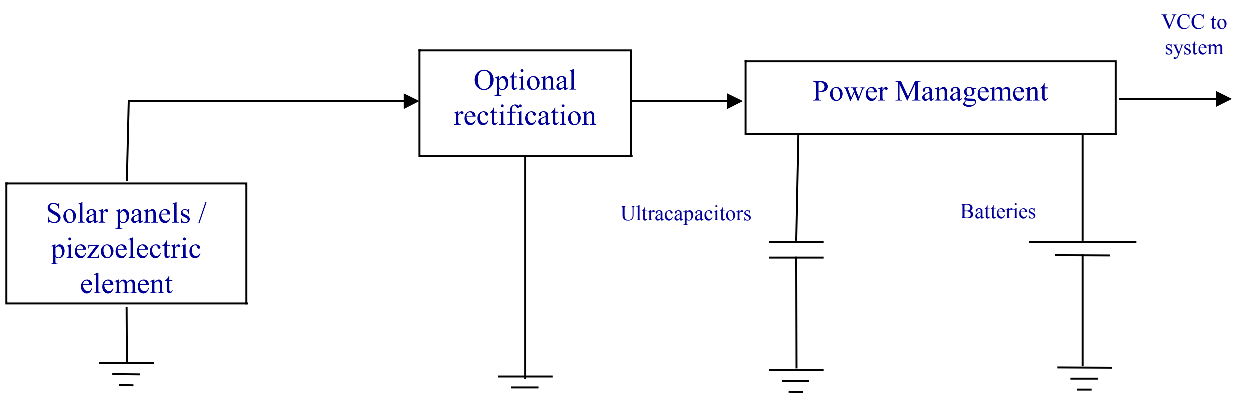
$$\text{Power density} = \frac{V \times I}{m},$$

(src.: en.wikipedia.org)

Energy harvesting for wireless sensor nodes

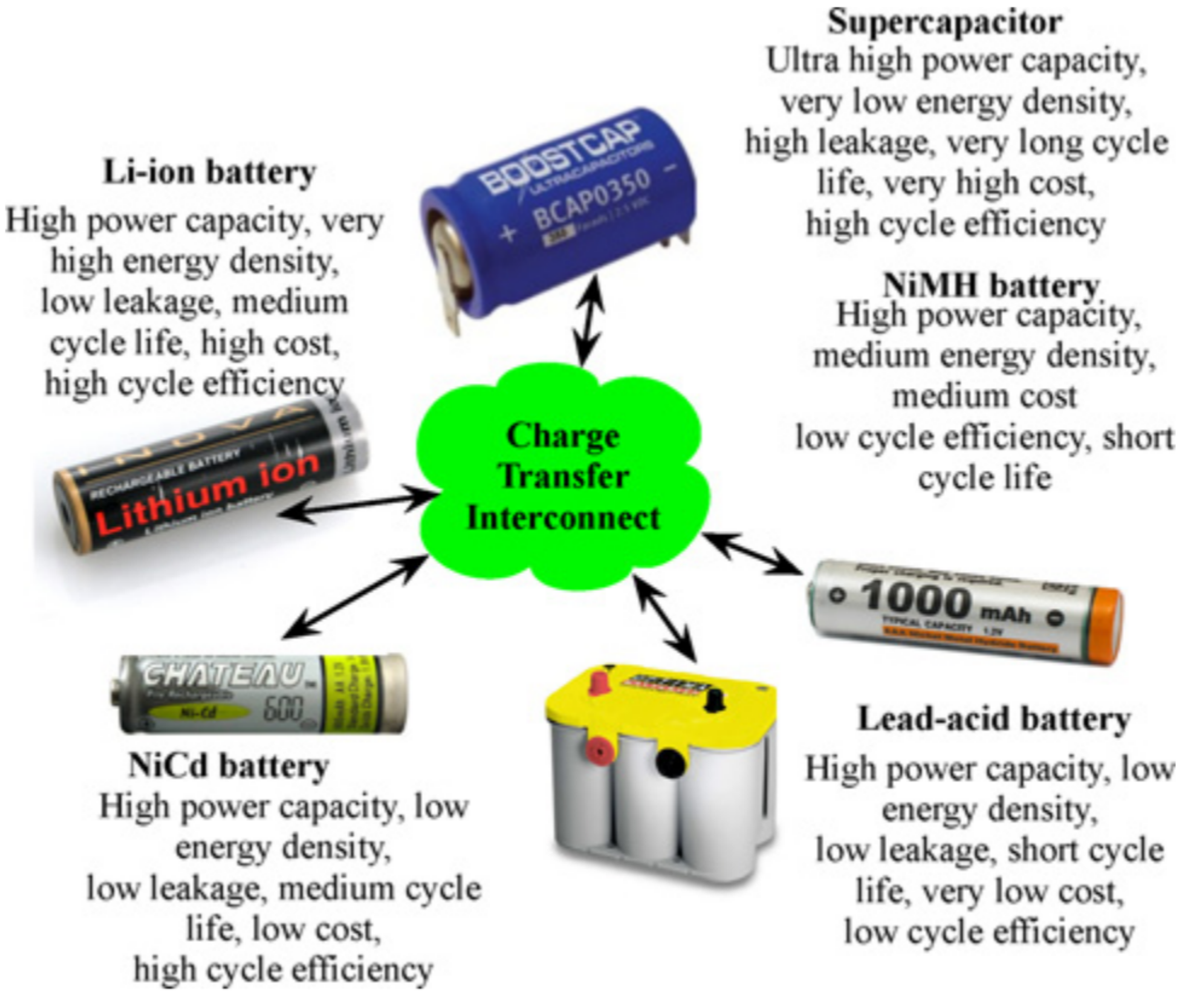
(src.: [Hande07])





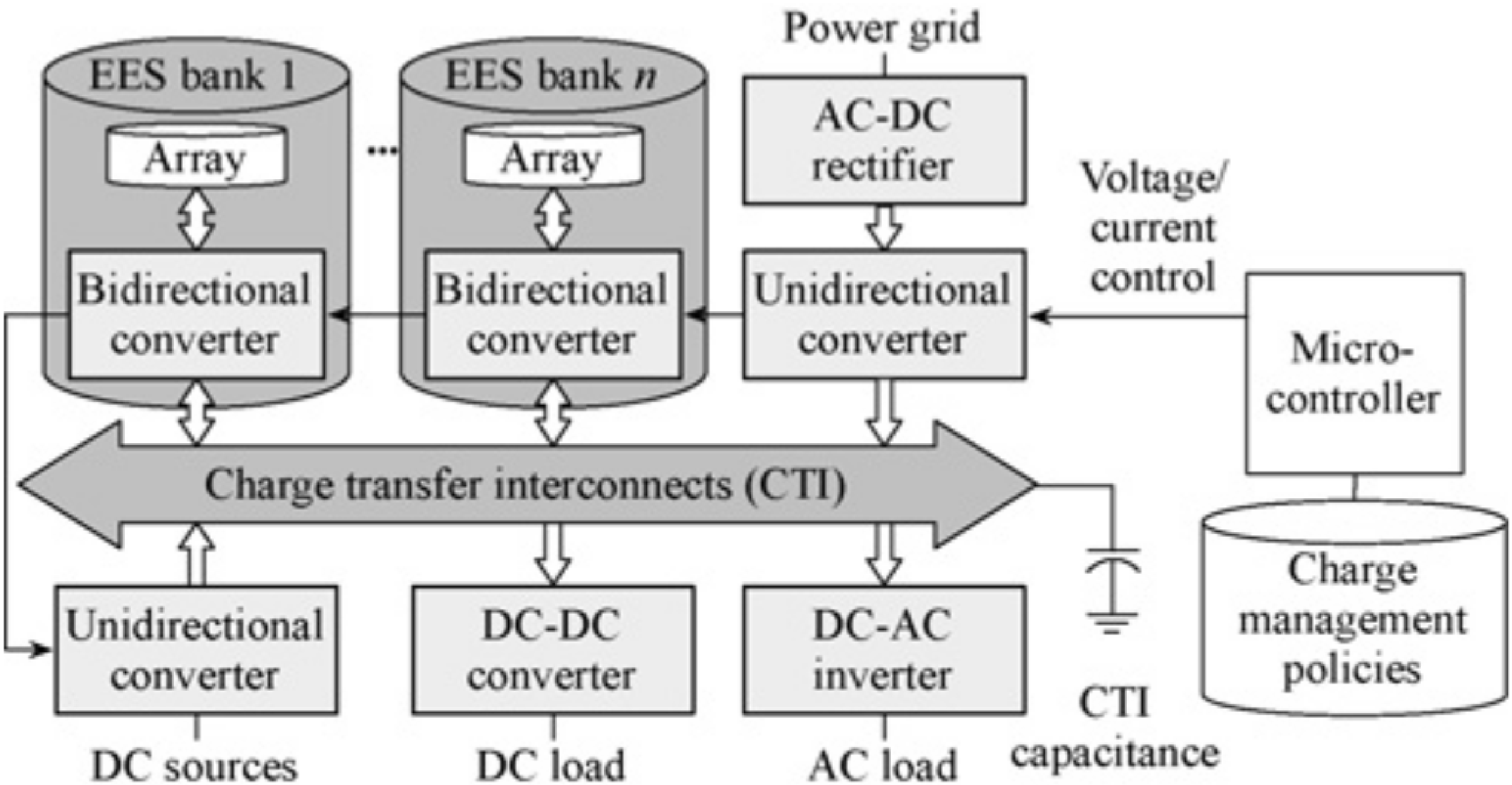
Power management:
- Charge storage
- Monitor energy level
- Low power converter

Homework: Hybrid Electrical Energy Storage Systems



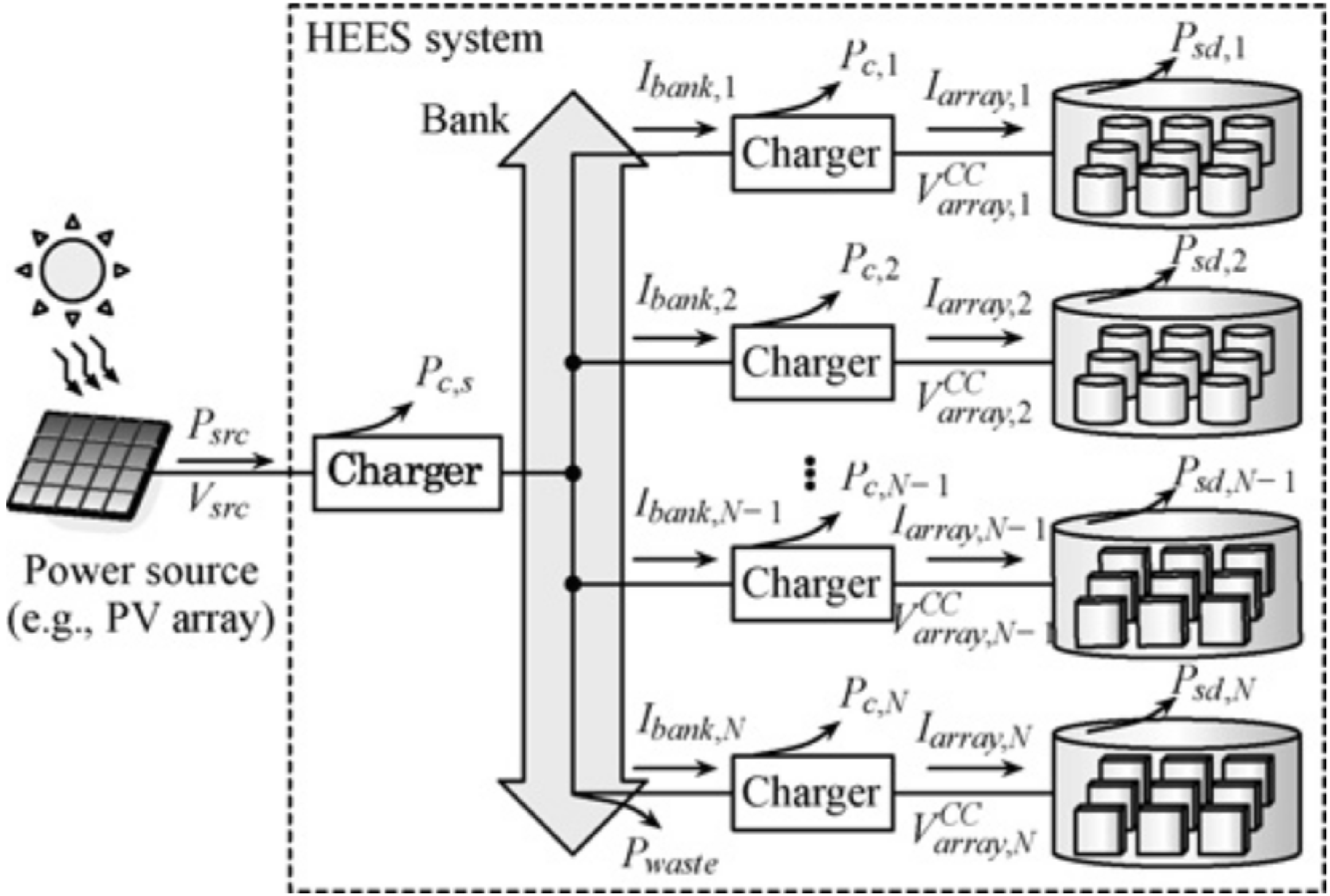
Concept diagram of the HEES systems (src.:[Xie])

Homework: Hybrid Electrical Energy Storage Systems (cont'd)



Architecture of the proposed HEES system (src. [Xie])

Homework: Hybrid Electrical Energy Storage Systems (cont'd)



Schematic of the charge allocation process in a HEES system (src. [Xie])

Sources

[Paradiso05] Paradiso, J.A.; Starner, T., "Energy scavenging for mobile and wireless electronics," Pervasive Computing, IEEE , vol.4, no.1, pp.18,27, Jan.-March 2005

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[Raghunathan] A. Raghunathan, Tutorial on low power design, held at various CAD conferences

[Hande07] Abhiman Hande and Todd Polk and William Walker and Dinesh Bhatia „Indoor solar energy harvesting for sensor network router nodes“ Special Issue on Sensor Systems Microprocessors and Microsystems 2007

[VRagh05] V. Raghunathan, A. Kansal, J. Hsu, J. Friedman, M. Srivastava, “Design Considerations for solar energy harvesting wireless embedded systems”, Fourth IEEE/ACM International Conference on Information Processing in Sensor Networks (IPSN) - Special Track on Platform Tools and Design Methods for Network Embedded Sensors (SPOTS), April 2005.

[Xie] Q. Xie, Y. Wang, Y. Kim, M. Pedram and N. Chang, "Charge Allocation in Hybrid Electrical Energy Storage Systems," in IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, vol. 32, no. 7, pp. 1003-1016, July 2013.doi: 10.1109/TCAD.2013.2250583