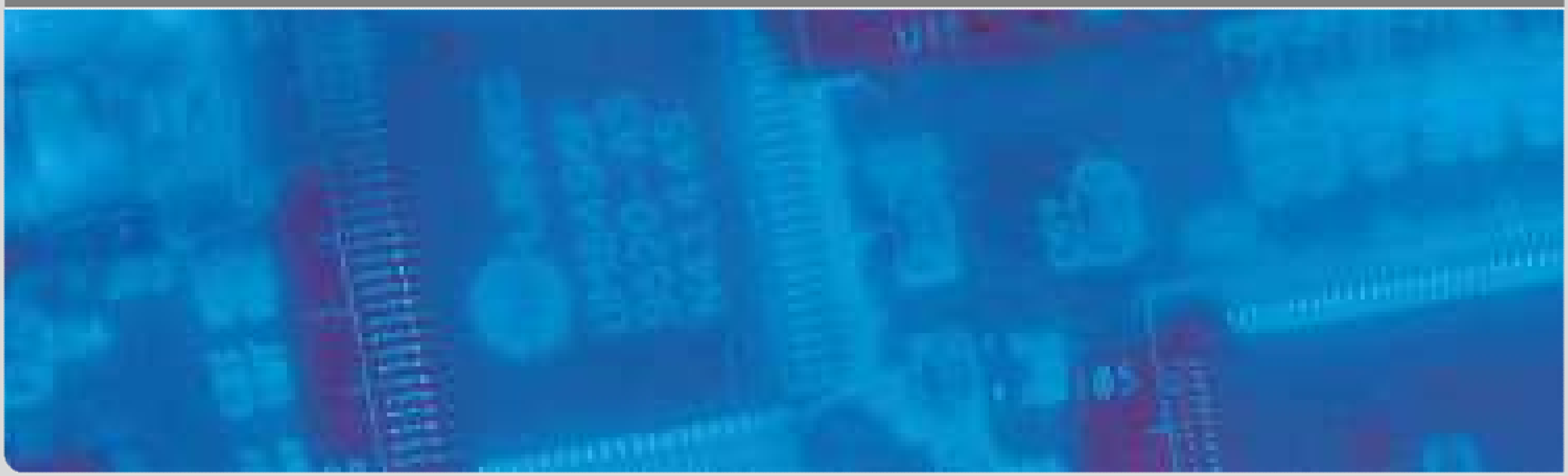
Lower Power Design

Lecture 1: Energy Sources

Anuj Pathania on behalf of Prof. Dr. Jörg Henkel

Summer Semester 2017

CES – Chair for Embedded Systems



Organizational Issues

- Slides available for download -
  - http://cesweb.itec.kit.edu/teaching/LPD/s17/slides/
  - Username: student
  - Password: CES-Student
- Homework
  - Read a relevant scientific paper.
  - Discussion next class.
- Oral Exam
  - Make appointment with KIT CES secretary 6-8 weeks in advance.
  - Exam will be in English (or German if told in advance).
  - More information: http://ces.itec.kit.edu/972.php

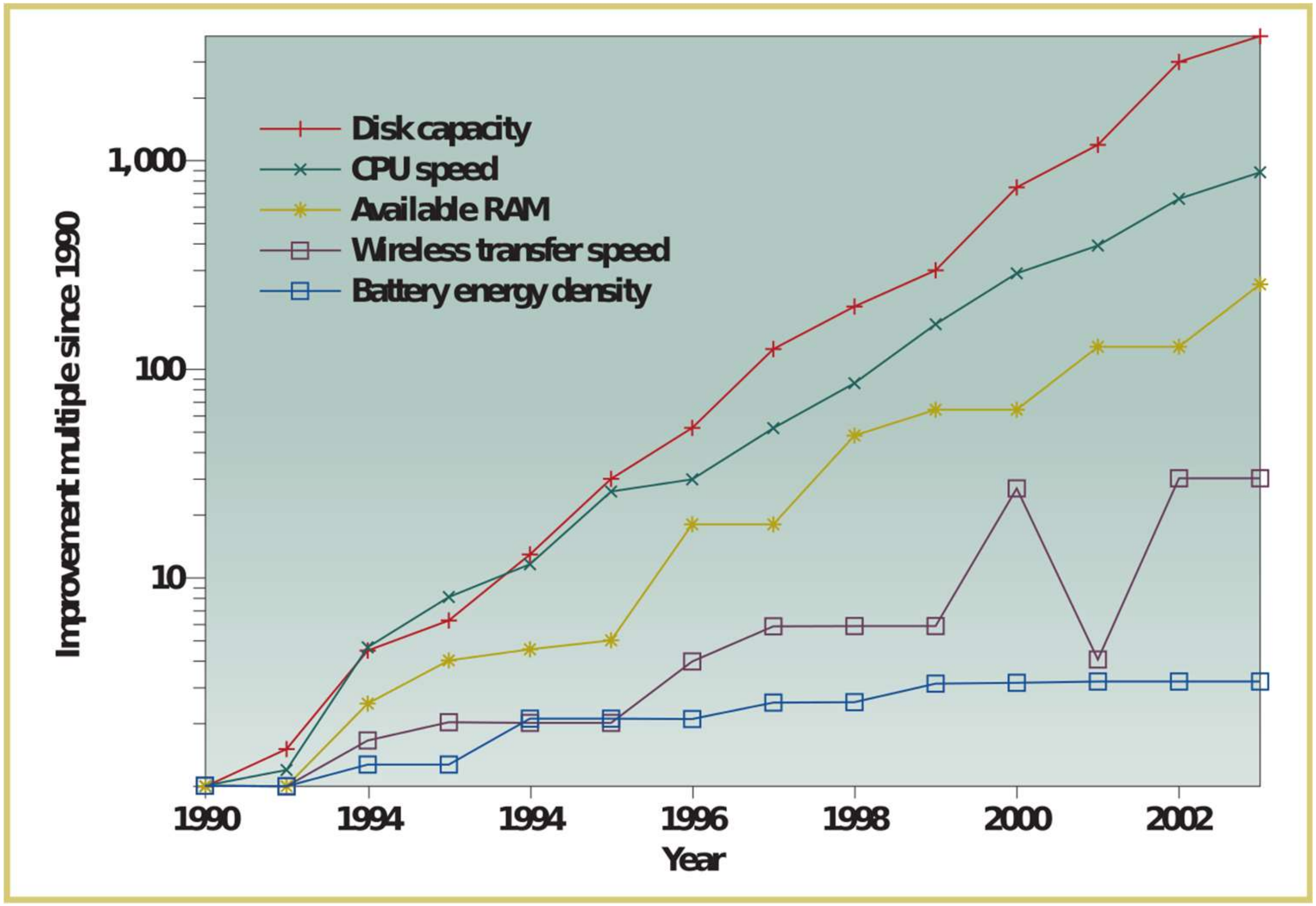
Lectures

- 27.04.2017 – ~~Lecture 0: Introduction~~
- 04.05.2017 – Lecture 1: Energy Sources
- 11.05.2017 – Lecture 2: Battery Modelling Part 1
- 18.05.2017 – Lecture 3: Battery Modelling Part 2
- 25.05.2017 – Ascension Day (Holiday)
- 01.06.2017 – TBA
- 08.06.2017 – TBA
- 15.06.2017 – Corpus Christi (Holiday)
- 22.06.2017 – TBA
- 29.06.2017 – TBA
- 06.07.2017 – TBA
- 13.07.2017 – TBA
- 20.07.2017 – TBA
- 27.07.2017 – TBA

Overview for Today

- Fuel Cells
- Human-Generated Power for Portable Devices
- Solar Energy Harvesting
- Super Capacitors
- Hybrid Electric Storage System

Battery Gap



Source: Paradiso [2005]

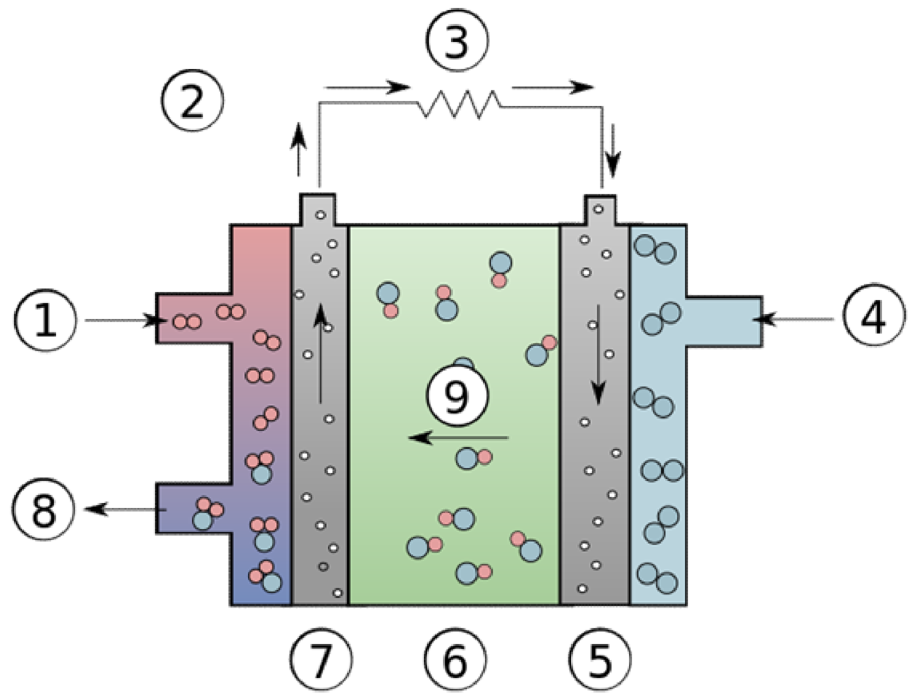
Fuel Cells 1

- 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.
- 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:
    - $H_2 + \frac{1}{2} O_2 \rightarrow H_2O \quad E_0 = 1.229V$

Source: Wikipedia

Fuel Cells 2: Alkaline Fuel Cell

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



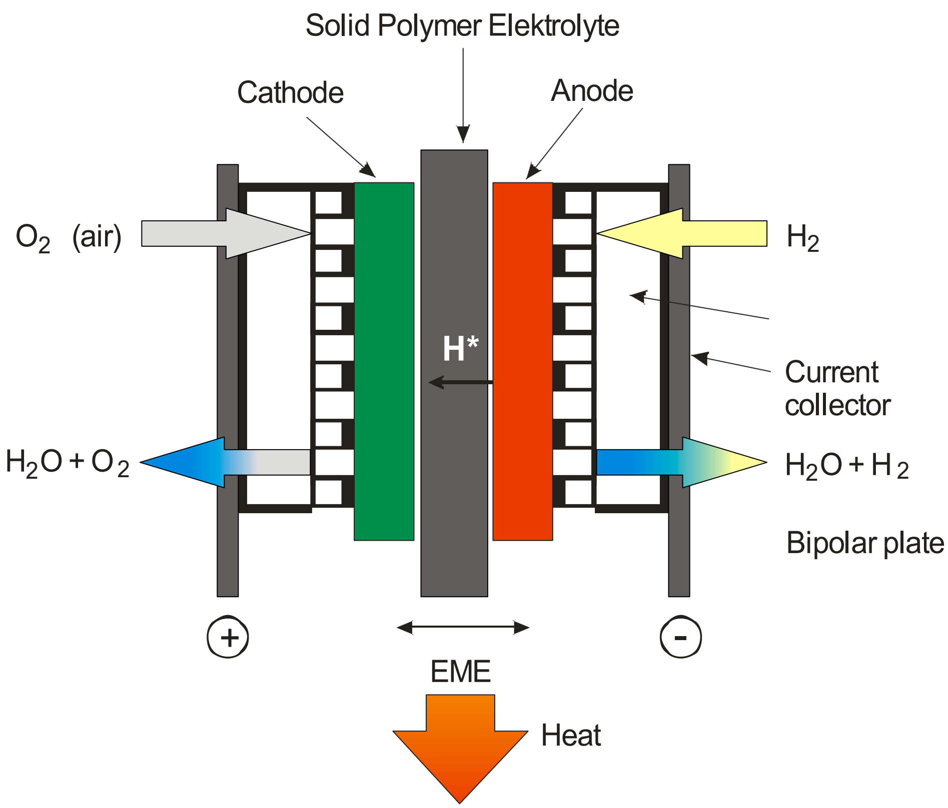
70% Efficiency

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$$
$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

Source: Wikipedia

Fuel Cells 3: Principle

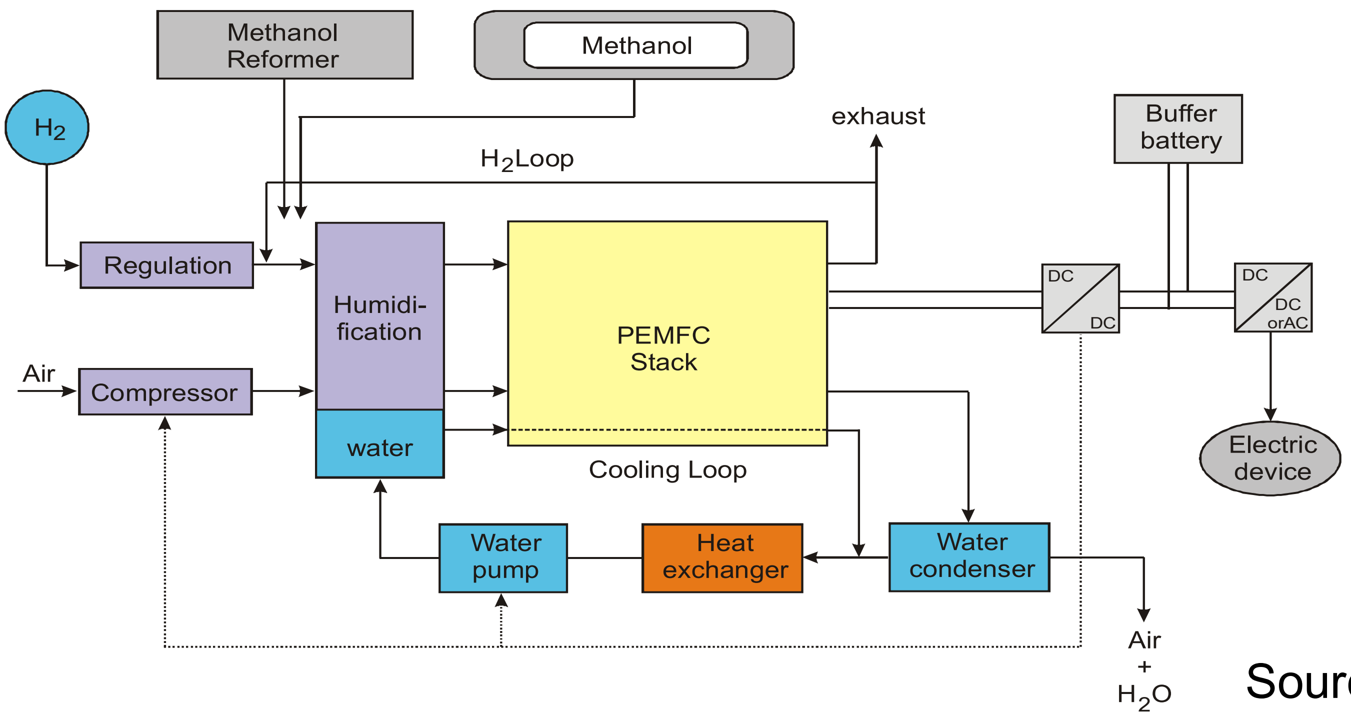
- Core parts
  - Two electrodes separated by an ion-conducting polymeric membrane (electrolyte).
  - Fuel (i.e. H_2) is transformed on catalytic sites at the negative electrode and form protons (H^+) which cross the membrane and electrons on the other hand which produce a current outside the cell.
  - Electrical energy is obtained when electrons recombine at the positive electrode with protons (H+) coming from the negative electrode and oxygen from the air.
    - Chemical reaction results in: electricity, water and heat.
    - A whole system is shown on the next page.



Source: Bloch [2004]

Fuel Cells 4: Whole System

- Whole system contains besides the core (stack):
  - electrical management systems.
  - thermal management systems.
  - fluidic management systems.



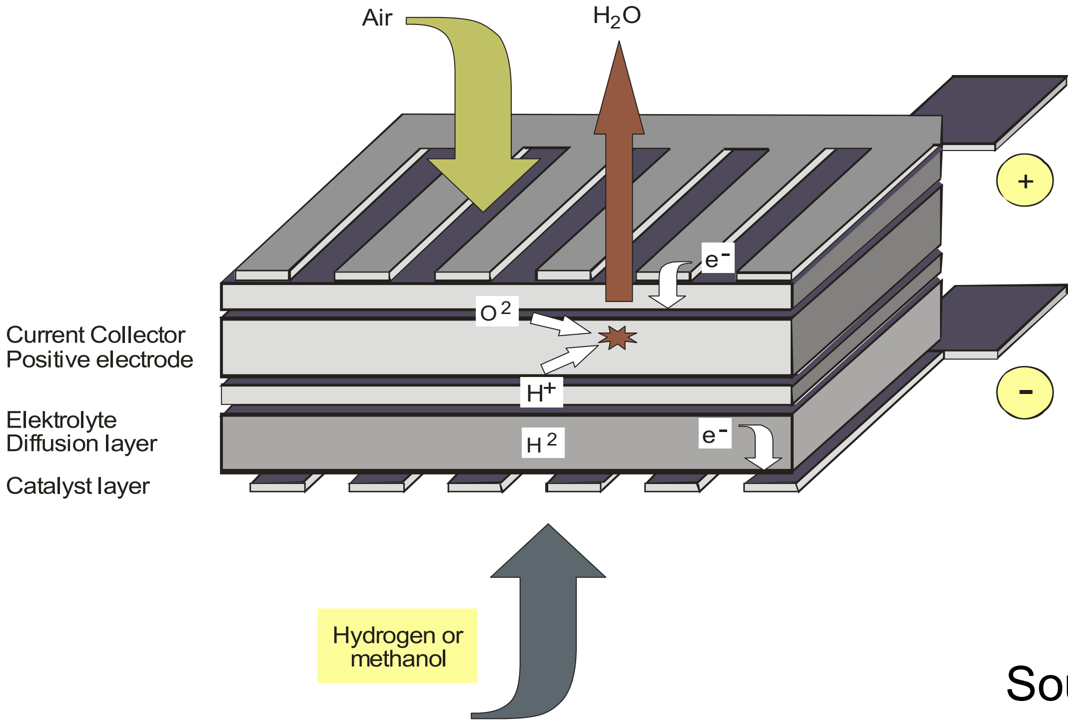
Source: Bloch [2004]

Miniature Fuel Cells

- Application domain: portable electronic devices (smartphone, etc.)
- Two approaches.
  - "Bipolar" Technology
    - Built with bipolar plates forming the fuel cell stack.
    - Typically 20-500 W.
    - Smaller stacks seem not to be competitive with Lithium-Ion batteries.
    - Example: SFC Energy fuel cells (sfc.com).
  - Various approaches with new concepts e.g. micro-fabrication techniques.
    - Typically 0.1 – 25 W.
    - Substrate (thin-film)-based.

Silicon Fuel Cells

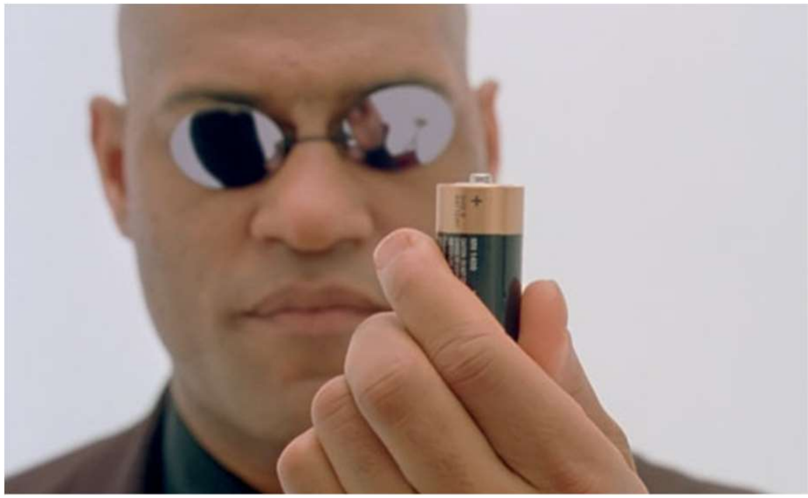
- Silicon Fuel Cells
  - Silicon wafer; grown and treated with lithographic techniques.
  - Often less than a centimeter wide.
  - Available from various companies: *Neah Power*, *Integrated Fuel Cell Technologies*.



Source: Bloch [2004]

Human-Generated Power for Portable Devices

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



1 gram of Fat = 37,700J of Energy

68 kg Human (with 15% fat) = 384 MJ !!!

Source: WarnerBros and ExtremeTech

Human Power Consumption for Various Activities

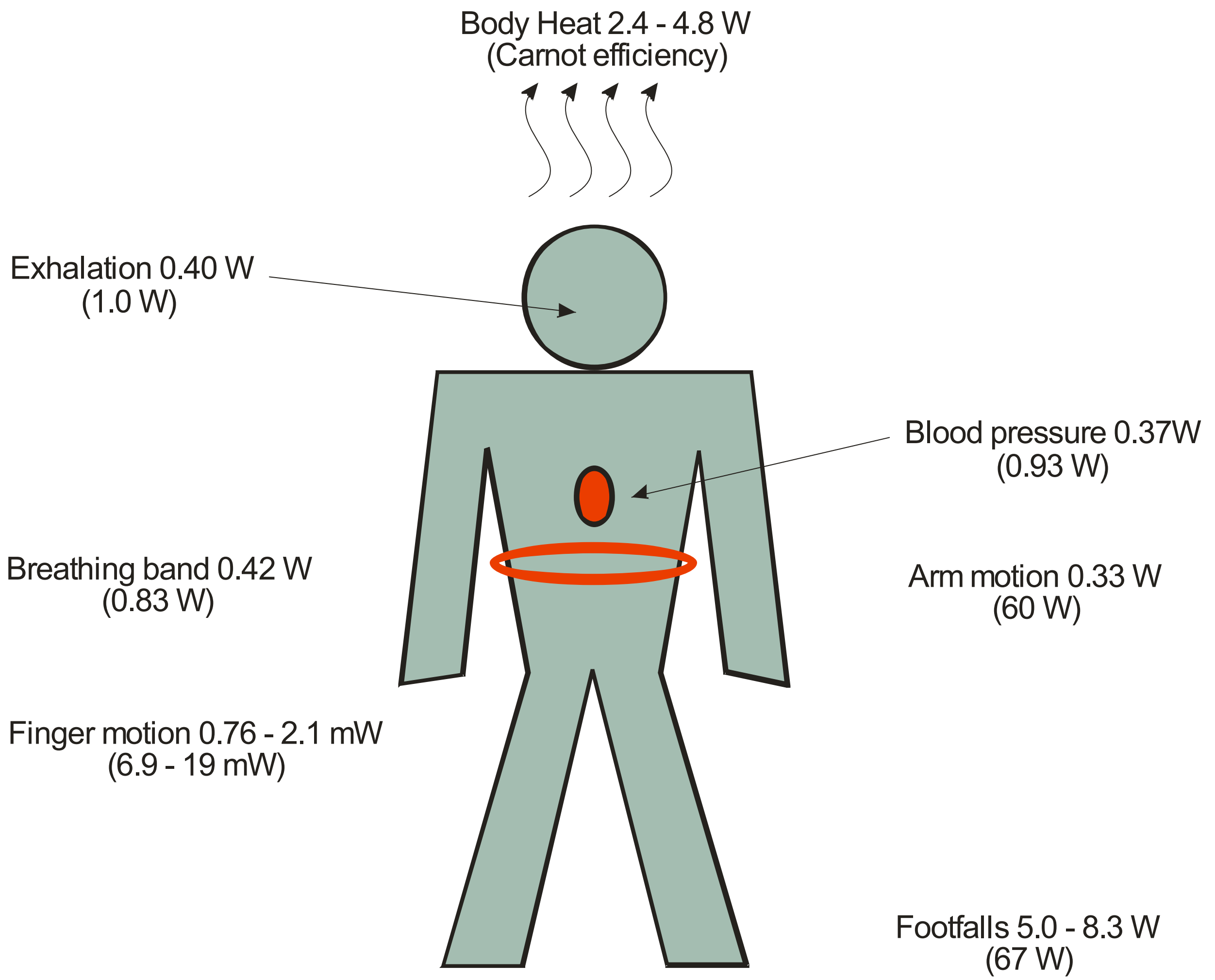
- A span of ~20x!
- Difficult to harvest.
- Need to be converted to DC/AC.
- Must be non-intrusive.

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: Morton [1952]

Human Power Consumption for Various Activities



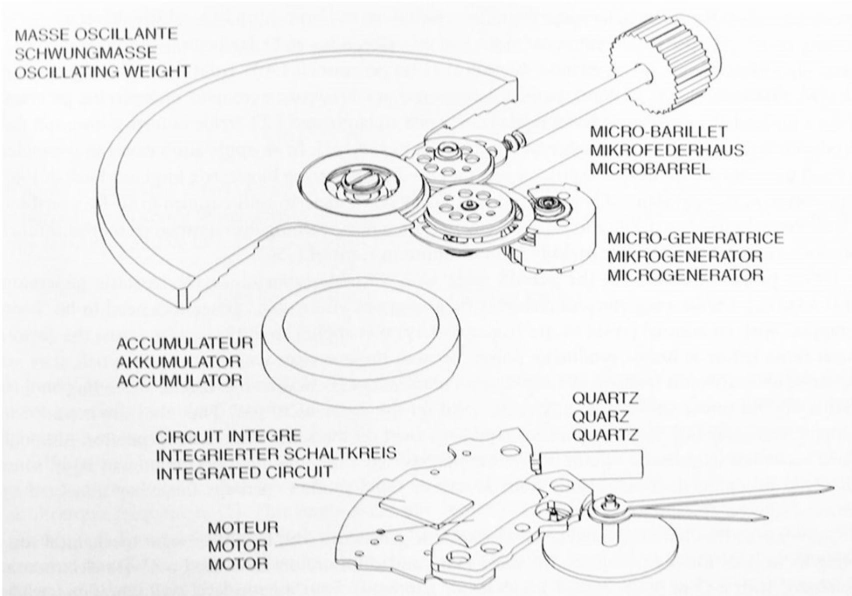
Source: Morton [1952]

Human Power Sources 1

- Body Heat.
  - (T_Body – T_Ambient)/T_body = (310K – 293K)/310K = 5.5% [Carnot Efficiency]
  - Not very efficient (even theoretically); real-world only 0.8% efficient at best.
- Breathing.
  - Exploit difference breathing pressure and atmospheric pressure.
  - Only 2% difference.
- Blood Pressure.
- Vibrations from motion.

Human Power Sources 2

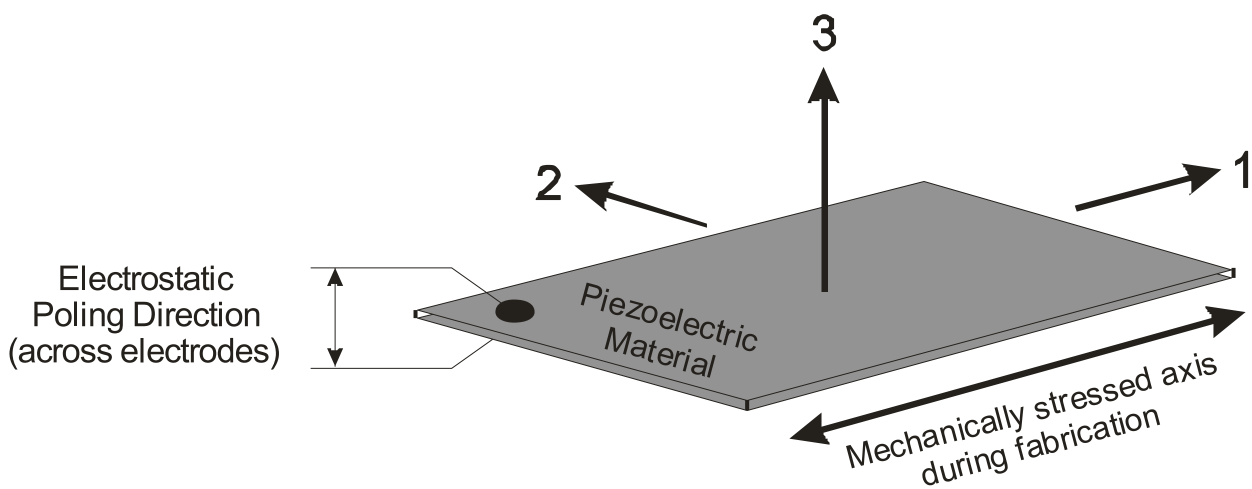
- Power from typing
  - Ex: 50 g key pressure, depress by 0.5 cm.
  - .05 kg/stroke * 9.8 m/s^2 * .005 m * 7.5 strokes/sec = 19 mW (too less).
  - User is not continuously typing.
  - Can at least power the keyboard (if not whole system).
- Inertial micro systems
  - Used for hundred of years in watches
- Electrical version
  - The mass winds a spring.
  - Drive a generator at 15000 rpm.
  - Yield 6 mA and 16 V for 50 ms.



Source: Paradiso [2004]

Human Power Sources 3: Walking

- Walking (68 kg Human, 5.6 km/h) cost 324 Watts of power.
  - Most of this power is used to move legs.
- Power through the fall of the heel:
  - 68 kg * 9.8 m/s^2 * 0.05 m * 2 steps/sec = 67 Watts.
  - This power cannot be converted into electrical power w/o significant intrusion.
  - Use piezoelectric device like Quartz.

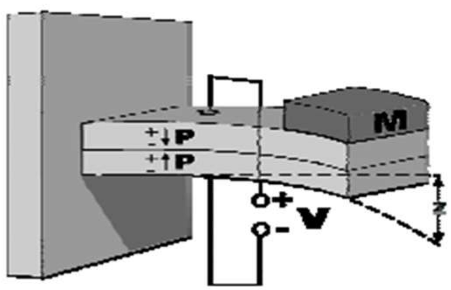


Source: Paradiso [2004]

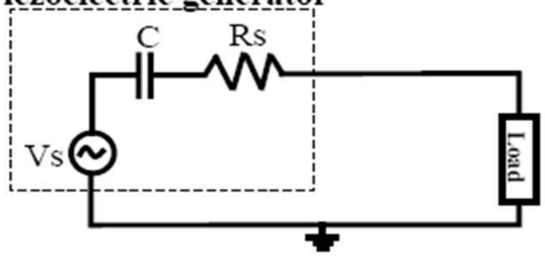
Vibrations into Electricity

Piezoelectric

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

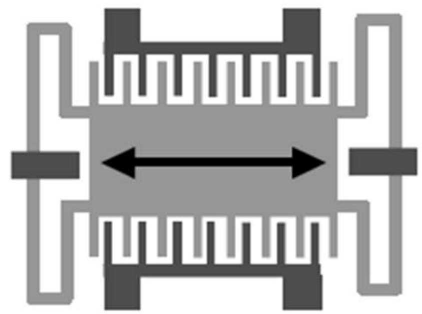


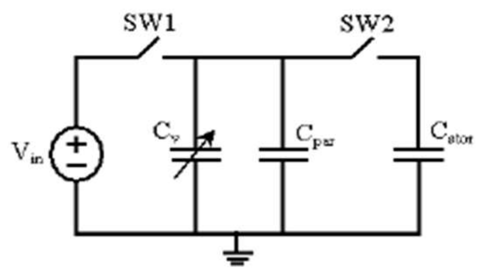
Piezoelectric generator



Capacitive

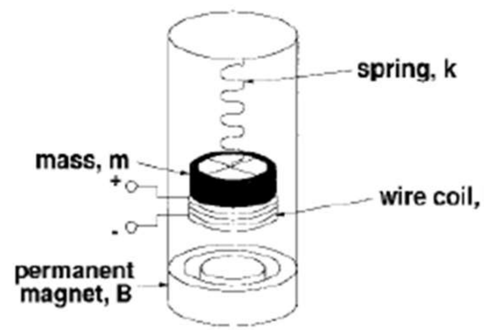
Change in capacitance causes either voltage or charge increase.





Inductive

Coil moves through magnetic field causing current in wire.



Amirtharajah et. al., 1998

Source: Hande [2007]

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

Source: Hande [2007]

Solar Energy

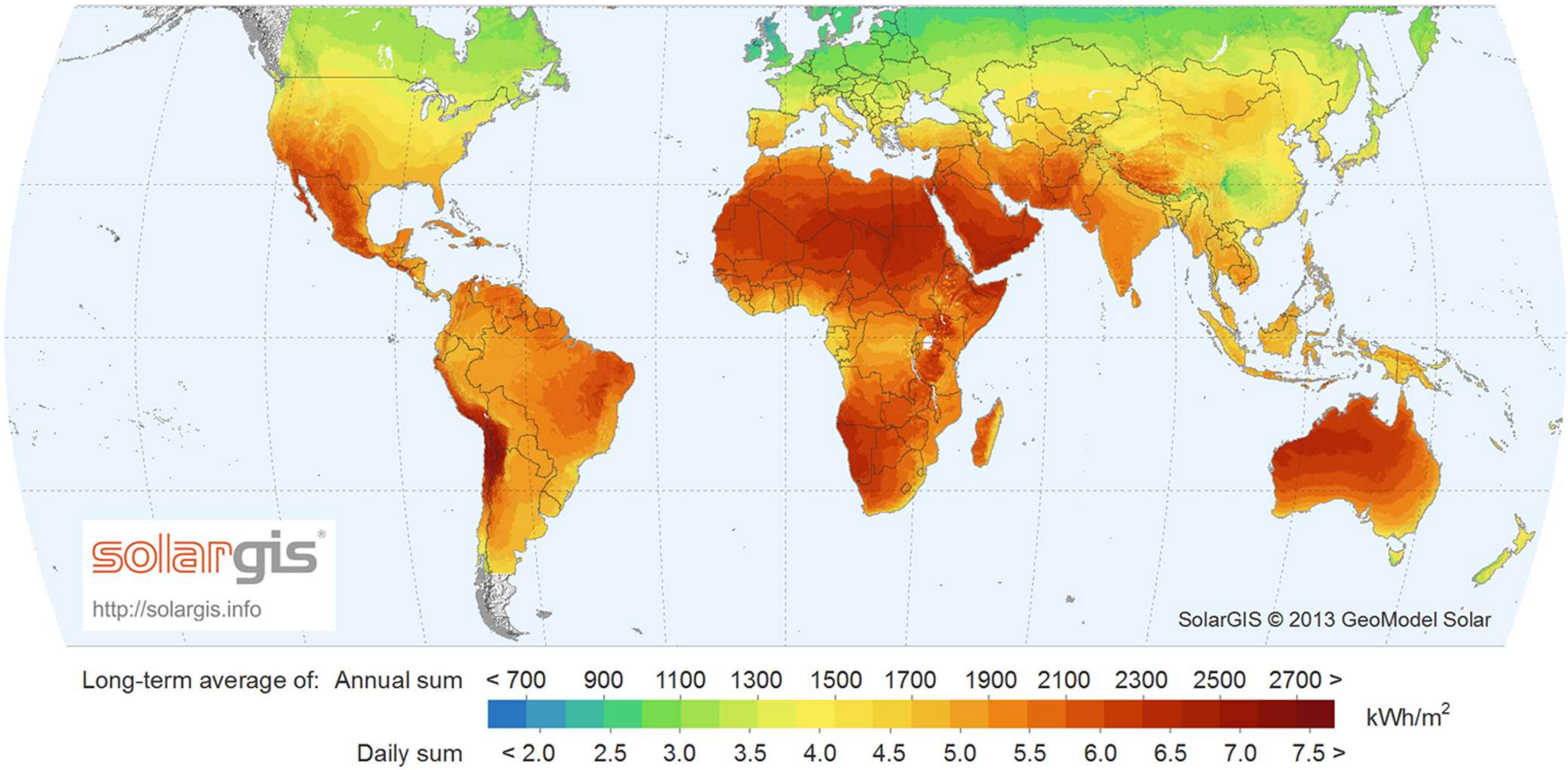
- Energy from almighty Sun.

Floating Solar Power Plant in Japan (2.9 MW)

Canal Top Power Plant in India (10 MW)

Source: Kyocera and SSND Ltd.

Solar Energy Distribution

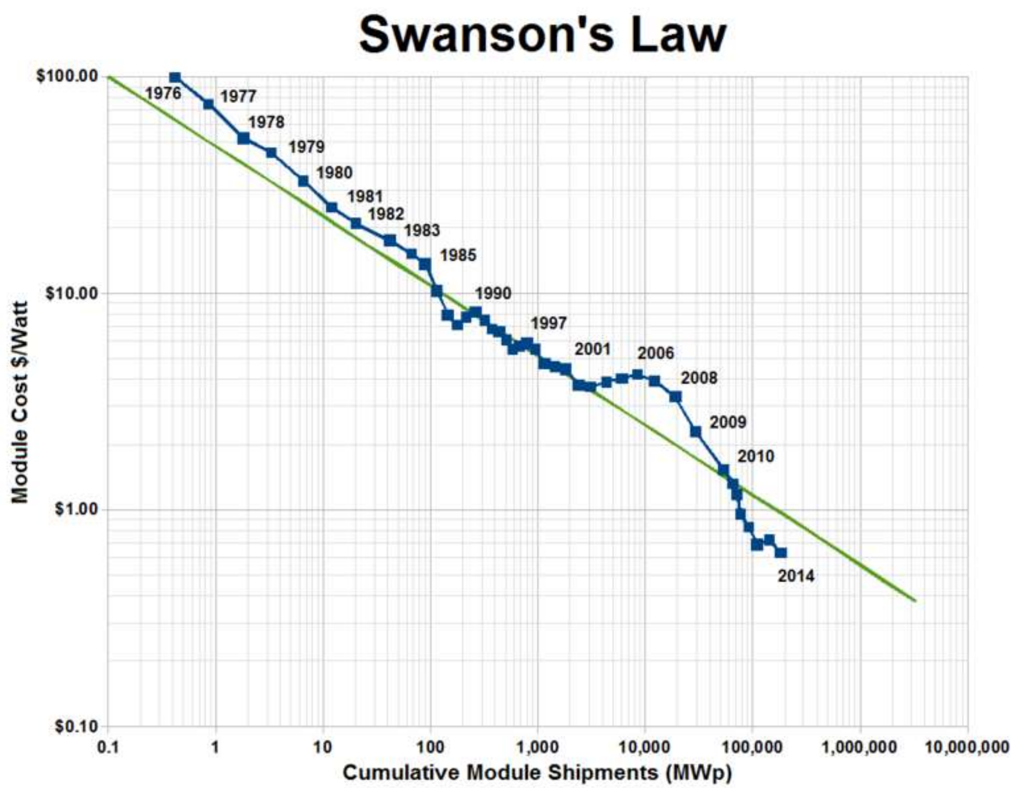


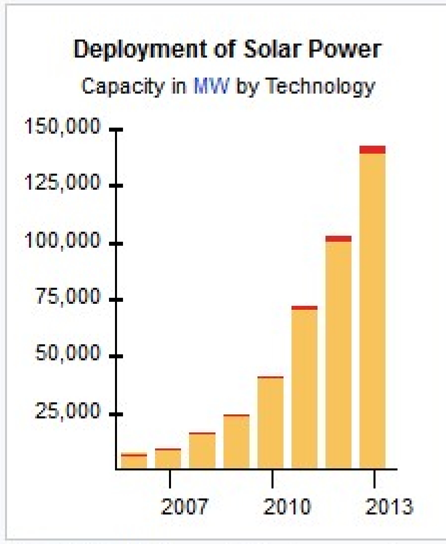
Outside Earth: Constant 1353 W/m^2

Source: Wikipedia

Swanson's Law

- Solar cell price drop 20% for doubling of cumulative cells shipped.
  - Half every ten years at current speed.





Worldwide deployment of solar power by technology since 2006[22]

Solar PV CSP - Solar thermal

Source: Wikipedia

Solar Energy

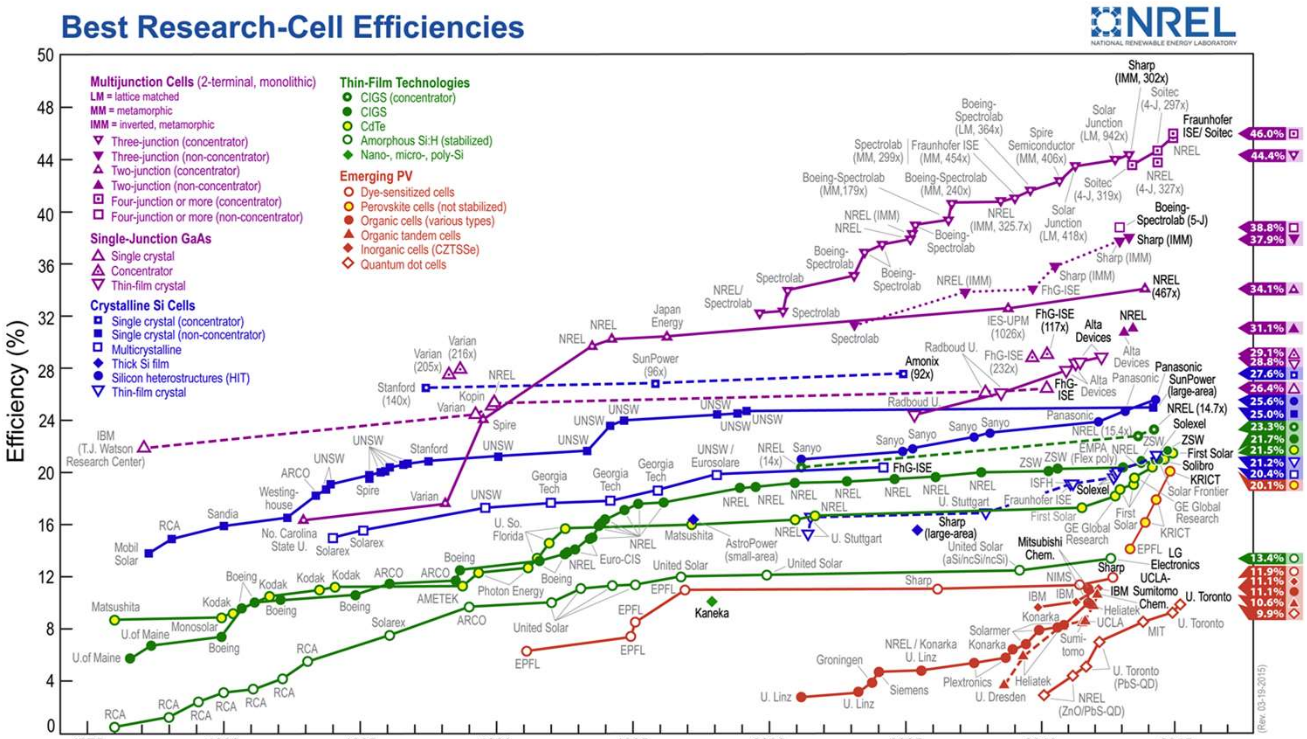
- Energy harvesting through photo-voltaic conversion provides high power density.
  - Good for embedded systems that need some mW power.
  - Characteristics of solar cells need to be taken into consideration for system design.

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)	$960nW/cm^3$

Source: Raghunathan [2005]

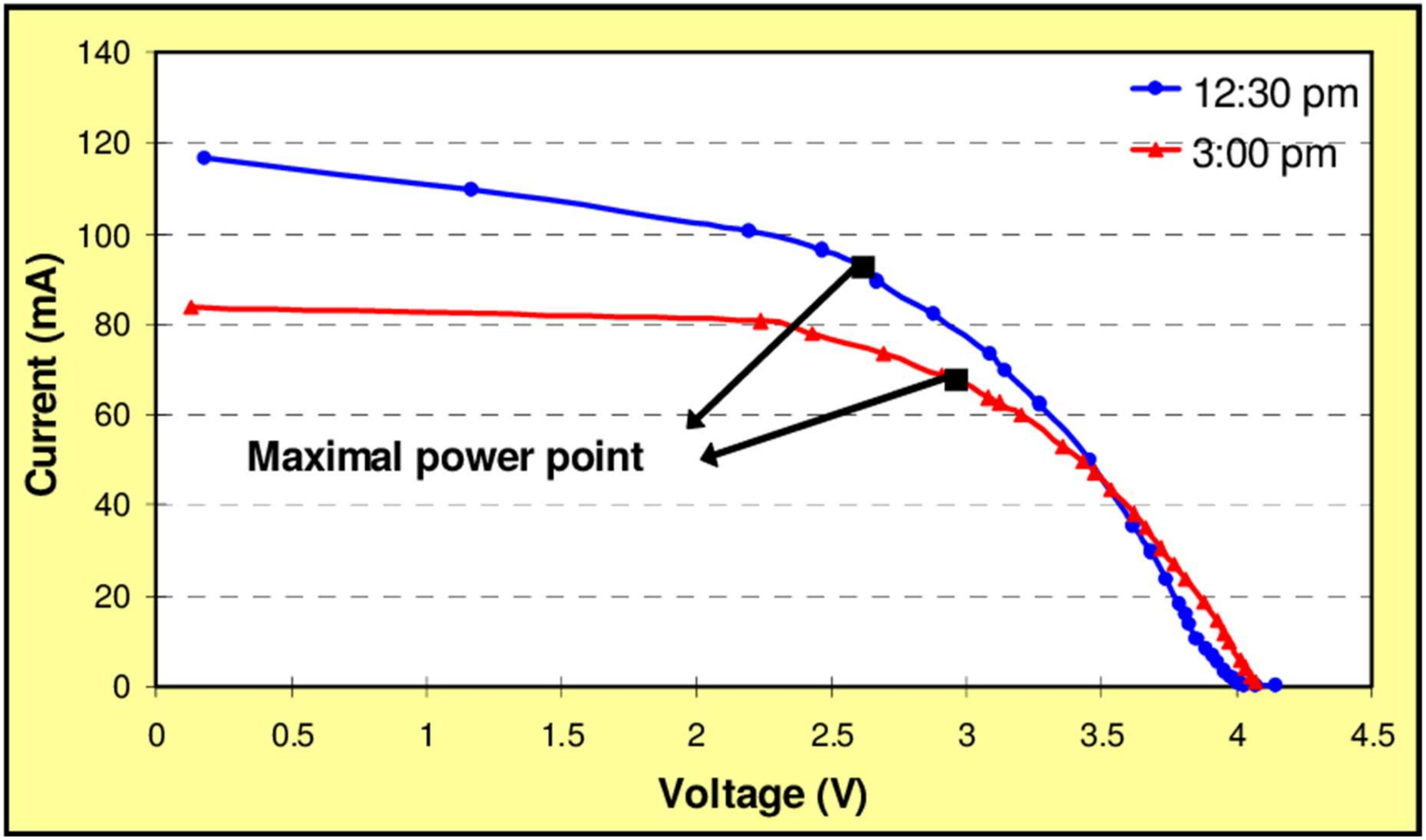
Shockley-Queisser Limit

- Solar cell efficiency has a theoretical upper limit.
  - Single-Layer: 33.7%
  - Multi-Layer: 86.8%



Source: Wikipedia

Solar Panels 2



Source: Raghunathan [2005]

Solar Panels 3

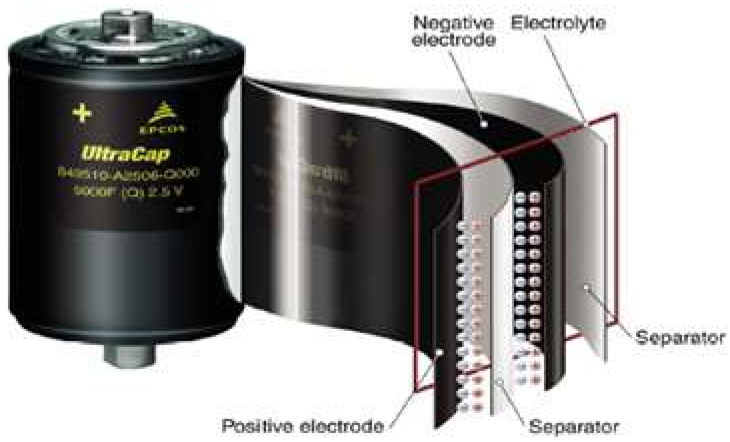
- Characteristics:
  - Solar panel behaves as a voltage limited current source.
    - Current tend be to constant, voltage vary over a wide range.
    - Remember: Battery is a voltage source.
  - There is an optimum operation point for maximum power extraction.

- Since it behaves like a current source (supply voltage depends on varying load), an energy storage element like a battery is necessary.

Source: Raghunathan [2005]

Super Capacitors (Ultra Capacitors)

- Capacitors with very high capacitance (10x - 100x normal capacitor).
- Bridge gap between normal capacitors and rechargeable batteries.
- Advantages
  - High power density.
  - Very long life (10 – 12 Years); charge/discharge cycles > 500,000 cycles.
  - No danger of overcharge.
- Disadvantage
  - Low energy density.
  - Relatively expensive.
  - High self-discharge (20% per Day).



Source: Raghunathan [2005]

Super Capacitors 2

Parameter	Aluminum Electrolytic Capacitors	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

Source: Wikipedia

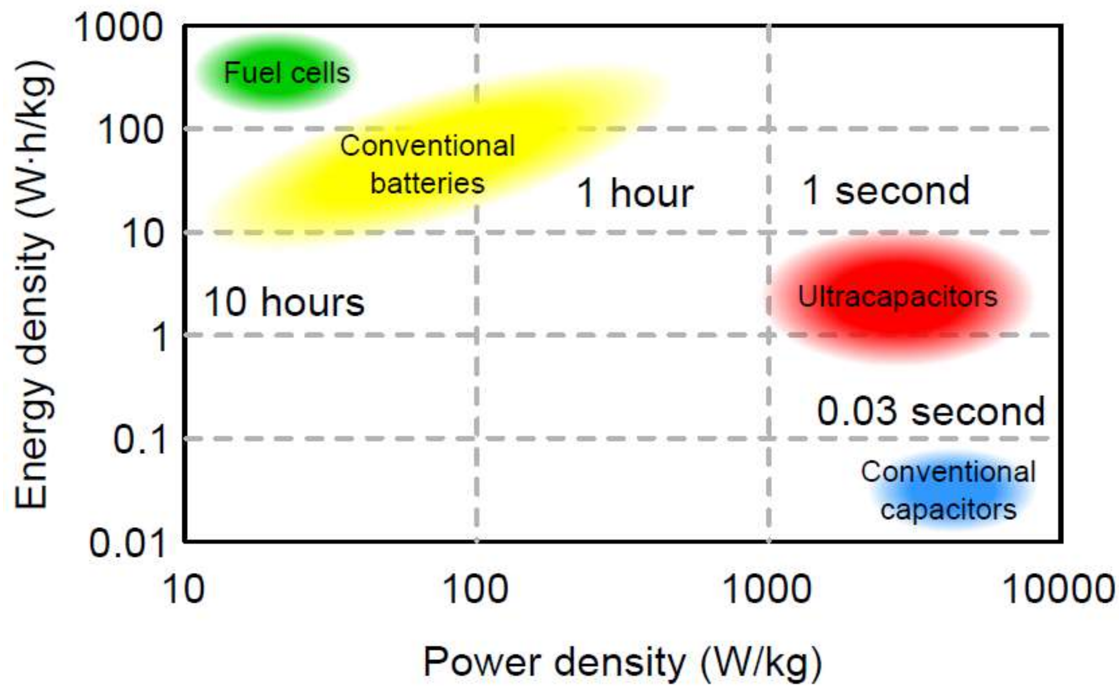
Super Capacitors 3

- Type: Storage Capacitor
- Execution: Gold-Cap
- Material: Cadmium Free
- Capacity: 22 Faraday
- Tension DC: 2.3 Volts
- Dimensions: 18.00 mm
- Price: 5.60 Euros

Source: reichelt.de

Ragone Chart

- Performance comparison of various energy-storage devices.

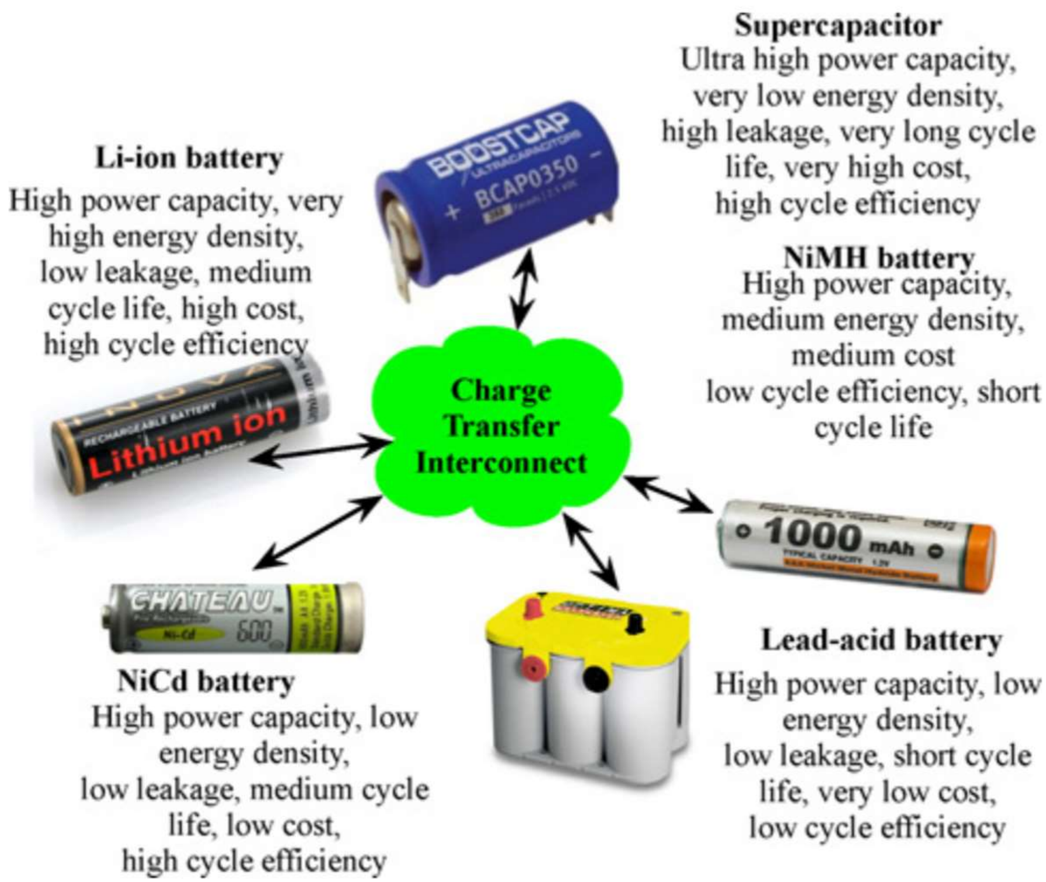


$$\text{Energy density} = \frac{V \times I \times t}{m},$$

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

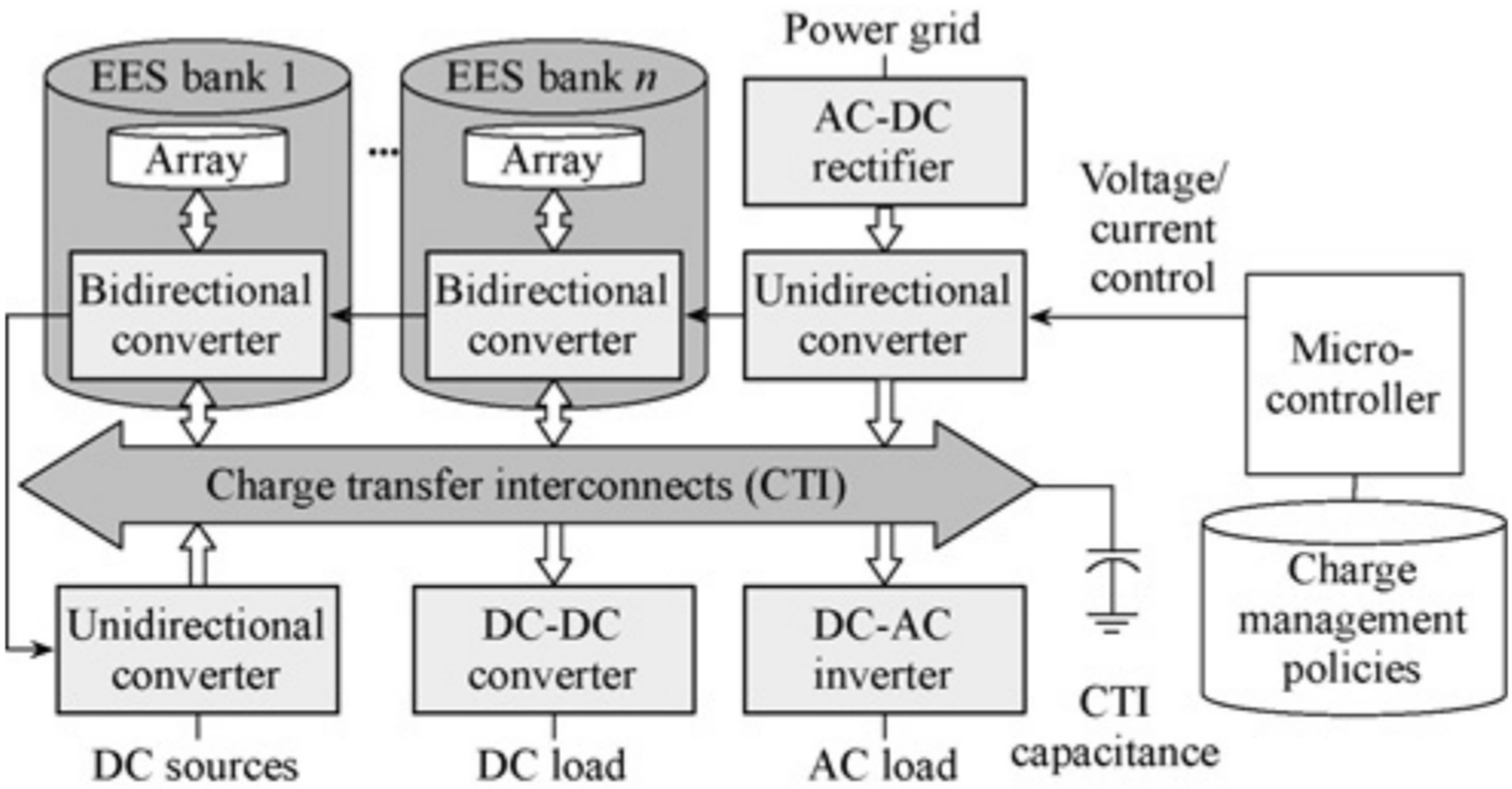
Source: Wikipedia

Hybrid Electric Storage System



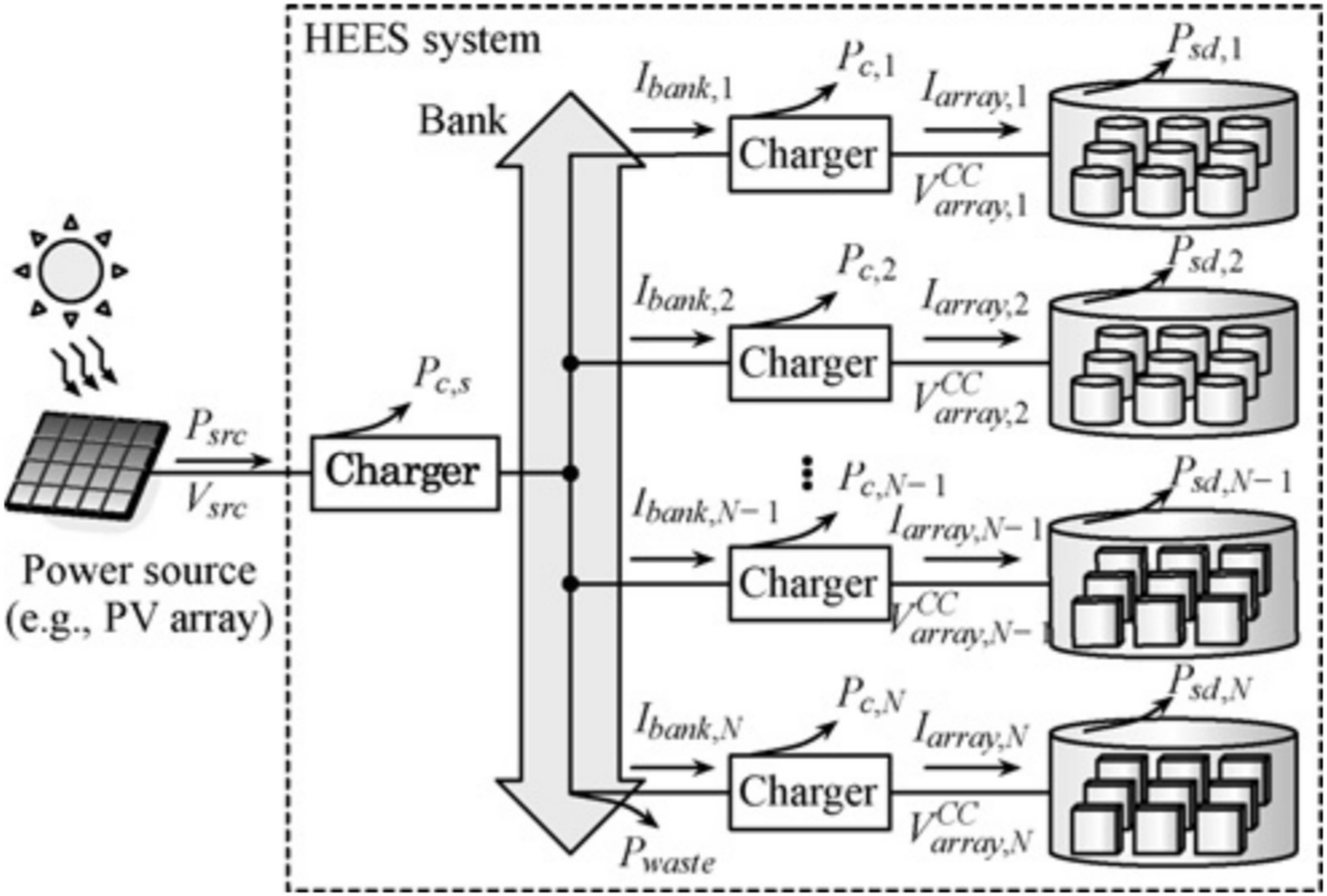
Source: Xie [2013]

Hybrid Electric Storage System 2: Design



Source: Xie [2013]

Hybrid Electric Storage System 3: Process



Source: Xie [2013]

Source

- Homework >> Paradiso, Joseph A., and Thad Starner. "Energy scavenging for mobile and wireless electronics." *IEEE Pervasive computing* 4.1 (2005): 18-27.
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