NiPS Summer School 2011

Energy Harvesting at micro and nanoscale

Radiation Harvesting

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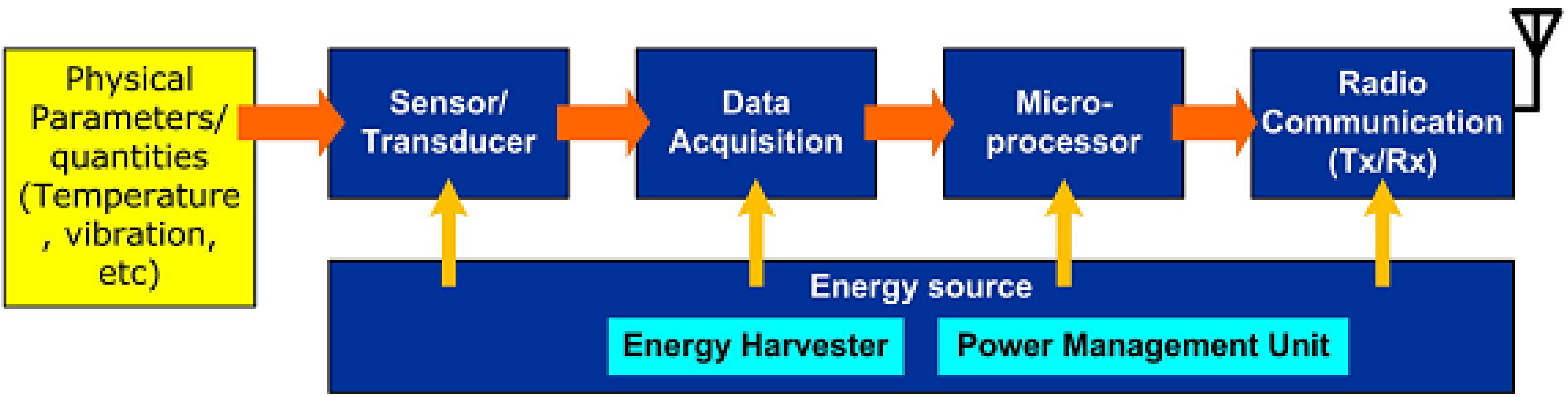
Outline

- Intro (usefulness, metrics, problems)
- LF EM Radiation Harvesting
- RF EM Radiation Harvesting
- Cockroft-Walton Voltage multipliers
- Solar Radiation, Photovoltaic
- Solar Radiation, nantenna

Intro

- Various forms of radiations may be collected and transduced into electric power
- Wireless sensor networks: energy harvesting may help increasing battery duration or even replace them entirely



Block diagram of energy-hungry wireless sensor node

Image source: [1]

Intro

- Wireless Sensor Networks: node power consumption

Component	Active (mA)	Idle (mA)	Inactive (μA)
MCU core (AT90S8535)	5	2	1
MCU pins	1.5	-	-
LED	4.6 each	-	-
Photocell	.3	-	-
Radio (RFM TR1000)	12 tx	-	5
Radio (RFM TR1000)	4.5 rx	-	5
Temp (AD7416)	1	0.6	1.5
Co-proc (AT90LS2343)	2.4	.5	1
EEPROM (24LC256)	3	-	1

Table 1: Current per hardware component of baseline networked sensor platform. Our prototype is powered by an Energizer CR2450 lithium battery rated at 575 mAh. At peak load, the system consumes 19.5 mA of current, or can run about 30 hours on a single battery. In the idle mode, the system can run for 200 hours. When switched into inactive mode, the system draws only 10 μA of current, and a single battery can run for over a year.

Typical state of the art MCU power consumption:
300-µA active current (1 MHz, 3 V)
0.5-µA standby current (LPM)

Intro

Wireless Sensor Networks: node power consumption

- WSNs operate with a *duty cycle* β.
- When active, node absorbs a power P_{ON}.
- In sleep mode, a power $P_{SLEEP} << P_{ON}$ is absorbed.
- In a time interval T, the average absorbed energy E_T is

$$E_T \cong \beta P_{ON} T + (1-\beta) P_{SLEEP} T = (\beta P_{ON} + (1-\beta) P_{SLEEP}) T$$

- The average absorbed power P_{MEAN} is:

$$P_{MEAN} \cong \beta P_{ON} + (1-\beta) P_{SLEEP}$$

- Typical values for β: $[10^{-3}, 10^{-2}]$

Intro

Wireless Sensor Networks: node power consumption

- 1.5 V AA alcaline battery (3000 mAh).

$$E_T = 1.5\,\text{V} \cdot 3000\ \text{mA} \cdot 3600\ \text{s} \cong 16200\ \text{J}$$

- When active, node absorbs 20 mA DC (P_{ON}=30 mW)
- In sleep mode, node absorbs 10 nA DC (P_{SLEEP}=15 nW).
- With β=0.01 the average absorbed power P_{MEAN} is:

$$P_{MEAN} \cong \beta P_{ON} + (1-\beta) P_{SLEEP} \cong 300\,\mu\text{W}$$

- With β=0.01 the battery duration is:

$$T = \frac{E_T}{\left(\beta P_{ON} + (1-\beta) P_{SLEEP}\right)} = \frac{16.2\ \text{kJ}}{300\,\mu\text{W}} = 5.4 \cdot 10^7\ \text{s} \cong 625\ \text{days}$$

Intro

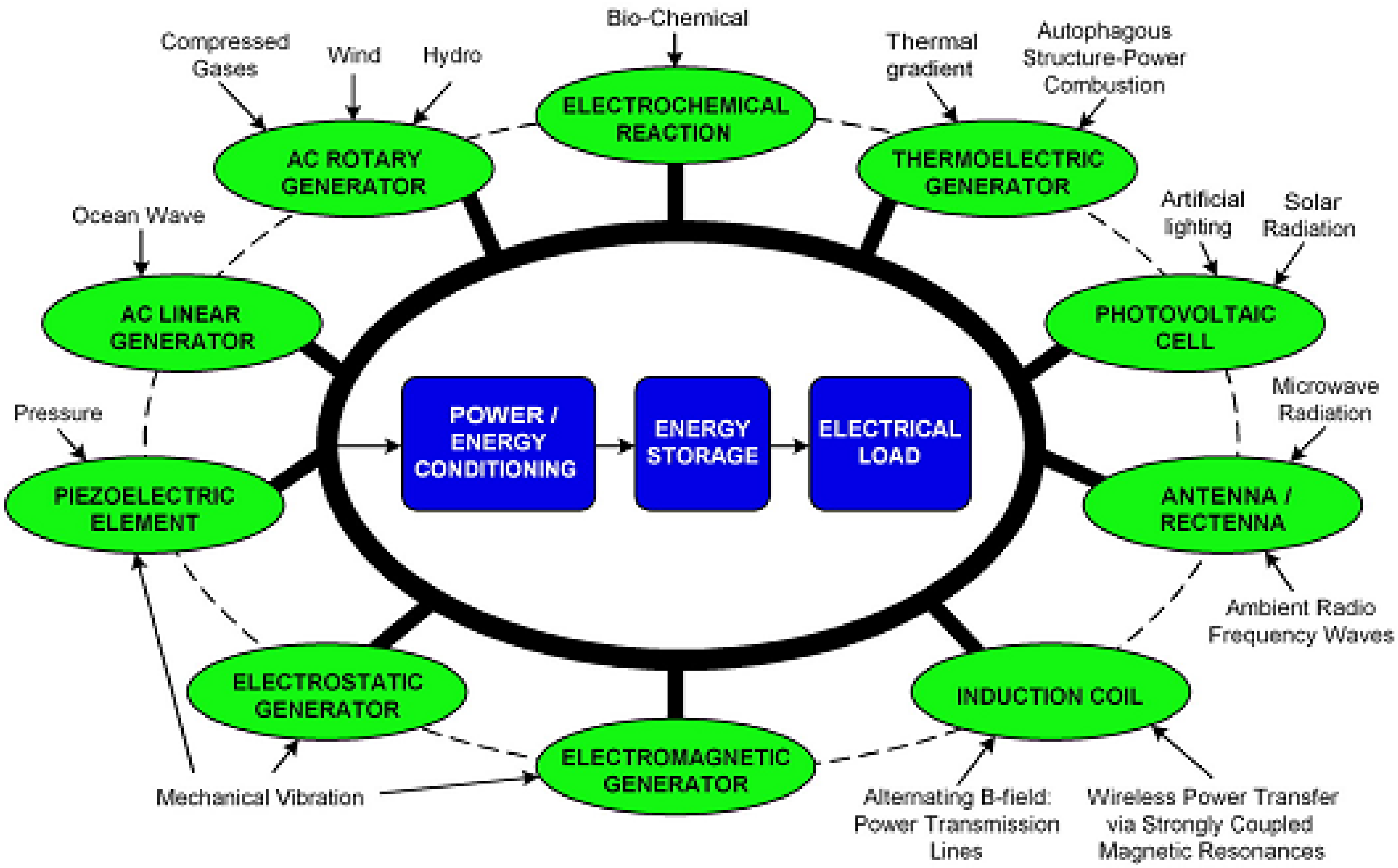


Fig. 7. Energy sources and respective transducers to power autonomous sensor nodes. Adapted from Thomas (2006) with additional power sources.

Image source: [1]

Intro

Main metrics for renewable power generation/storage technologies:

- Power density (peak power), energy density, per mass/volume unit (Photovoltaic: 100 $\mu W/cm^3$-100 mW/cm^3, other non radiant sources are in the tens of $\mu W/cm^3$ range)
- Conversion/Transfer Efficiency

LF Radiation Harvesting

- Basics: LF harvesting often relies on inductive powering (Es: rechargeable tootbrushes, RFID)
- Magnetic coupling between a primary and a secondary coil
- Safe technology (Galvanic insulation)

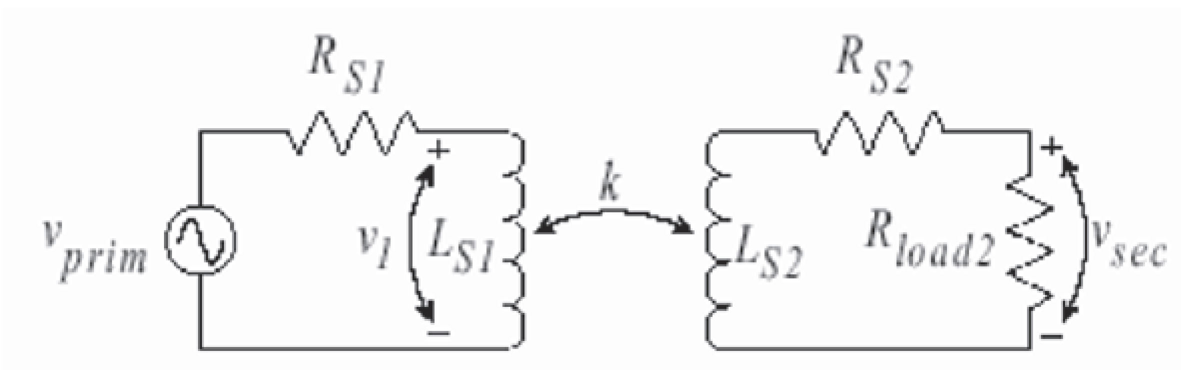


Image source: [3]

LF Radiation Harvesting

$$Q_1 = \frac{\omega L_{S1}}{R_{S1}}, \qquad Q_2 = \frac{\omega L_{S2}}{R_{S2}}$$

$$\eta = \frac{k^2 Q_1 Q_2}{2 + k^2 Q_1 Q_2 + 2\sqrt{1 + Q_1^2 + k^2 Q_1 Q_2}}$$

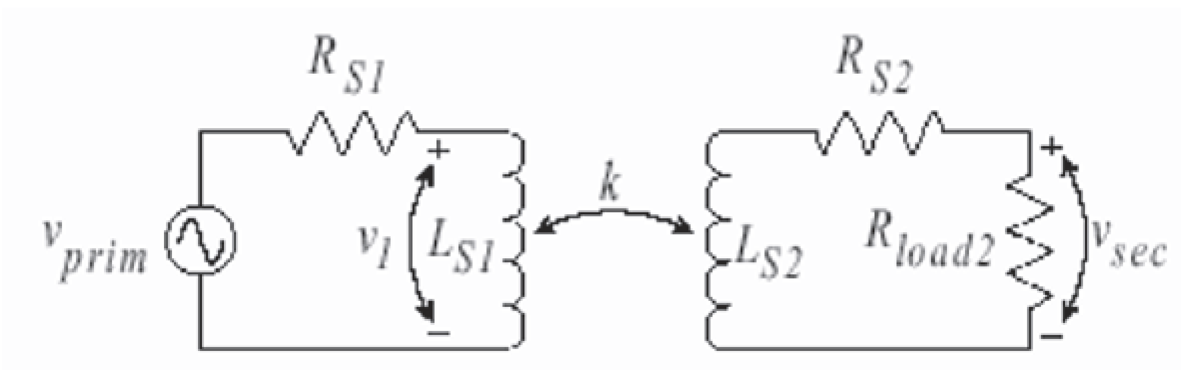


Image source: [3]

LF Radiation Harvesting

- Efficiency grows with Q factor of both coils (can exceed 80%) and with mutual coupling k
- May require high currents in the primary
- Short range (near field), using resonant circuits helps increasing efficiency and range

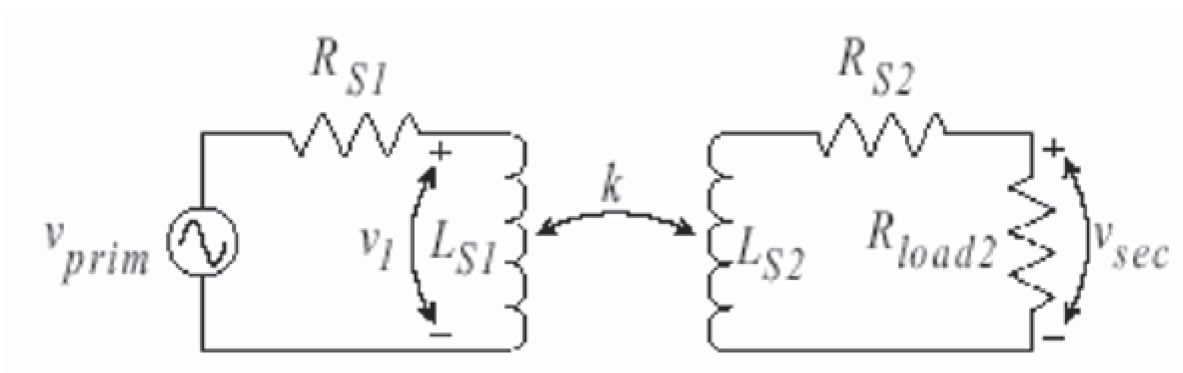


Image source: [3]

RF Radiation Harvesting

- Basics
- Rectenna
- Cockroft-Walton multiplier

Basics

- Main idea: collect energy from RF waves.
- “Ad Hoc” RF sources (Es: RFID, military applications, satellite based power source).
- “Unintentional” sources (Radio or TV broadcasting, Cell phone base stations, solar radiation…).
- Italy: FM Radio, 98-108 MHz

Rectenna

- Rectifying Antenna (rectenna): conceived by W. C. Brown at Raytheon, 1960's.
- Idea: a dipole antenna connected to a low barrier diode (typically Schottky)
- Note: Old AM receivers are precursors of rectennas (Antenna+rectifying diode+headphone)
- Usually Narrowband, omnidirectional (typically dipoles or half dipoles)
- Experiments since 60's, 2.4 GHz ISM band preferred.

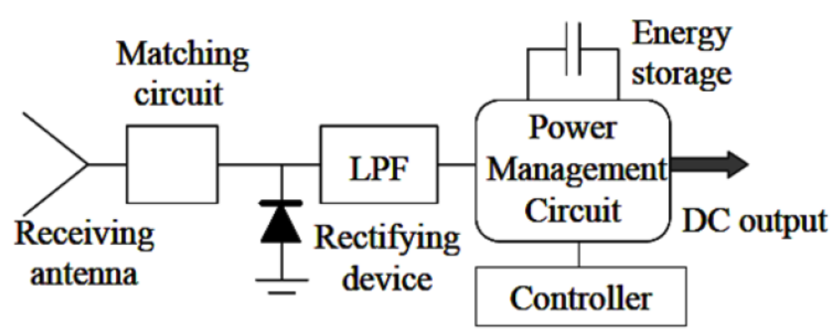


Image source: [4]

Rectenna

- High power density directive powering @microwave frequencies.
- Both linear and circular polarization of the receiving antennas may be used, demonstrating efficiencies ranging from around 85-90% at lower microwave frequencies to around 60% at X-band (8-12 GHz) and around 40% at Ka-band (26.5-40 GHz) [4].

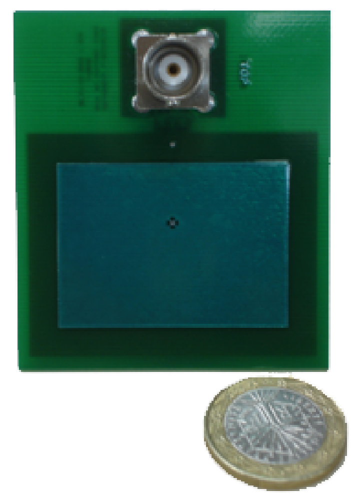


Image source: [22]

Rectenna

- Available power: low (microwatt). Expected power densities @ 50 meters from a typical base-station tower operating at 880 and 1990 MHz, are typically around 10^{-4} mW/cm^2. [4]
- The rectenna output power depends on the power flux density, frequency, incident angle of microwave, and rectifying circuit performance.
- Output voltage: low (mV)

Rectenna

- Rectenna efficiency depends both on antenna and diode efficiencies.
- First scenario: incident plane wave at frequency f_0, with power flux density S.
- The power P_{IN} collected by a lossless antenna perfectly aligned with the incoming plane wave is:

$$P_{IN} = S \cdot A_{eff}$$

- where A_{eff} is the antenna effective area
- The power P_{RF} at the antenna output is:

$$P_{RF} = \varepsilon_R \cdot S \cdot A_{eff}$$

- where ε_R is the antenna radiation efficiency (keeps into account conduction and dielectric losses)

Rectenna

- Part of the available power is reflected back due to antenna-diode mismatch loss M_L.
- The remaining RF power is converted to DC power P_{DC}, by the rectifying circuit with a diode efficiency ε_D:

$$P_{DC} = \varepsilon_D \cdot M_L \cdot P_{RF}$$

- The efficiency $\eta = P_{DC} / P_{IN}$ is given by:

$$\eta = \frac{P_{DC}}{P_{IN}} = \varepsilon_R(f_0) \cdot M_L(f_0, P_{IN}) \cdot \varepsilon_D(f_0, P_{IN}, Z_{DC})$$

- P_{DC} may be measured at DC for a given load R_L

$$P_{DC} = \frac{V_{DC}^2}{R_L}$$

Rectenna

- General case: various sources from various directions, in a frequency band $[f_L,f_H]$.

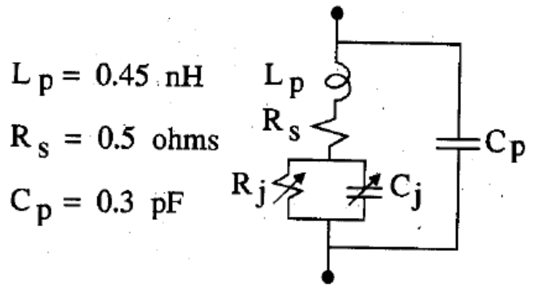
$$P_{RF}(t) = \frac{1}{f_H - f_L}\int_{f_L}^{f_H}\int_{0}^{4\pi} \varepsilon_R(f) S(\theta,\phi,f,t) A_{eff}(\theta,\phi,f)\, d\Omega\, df$$

- For a given frequency f_0:

$$P_{DC}(f_0) = P_{IN}(f_0)\cdot \eta\left(P_{IN}(f_0), \varepsilon_R(f_0), M_L(f_0, P_{IN}), Z_{DC}\right)$$

- NB: P_{DC} is a nonlinear function of P_{IN} and f!

Rectenna



Small signal equivalent circuit of GaAs diode and experimental values for parasitic elements.

Image source: [5]

Rectifying electronics issues

- Low barrier diode efficiency depends on:
  - Matching to the antenna
    - Lumped matching circuitry
    - Matched antenna design
    - Difficult to obtain for varying frequency!
  - Diode bandwidth (dominated by junction capacitance)
  - Diode nonlinearity (models needed, both low-signal and large signal analysis), affecting matching.
  - Diode nonlinearity, introducing harmonics.
- Outside [V_b,V_T] diode does not behave as a rectifier!

Rectenna

- Overall diode efficiency:

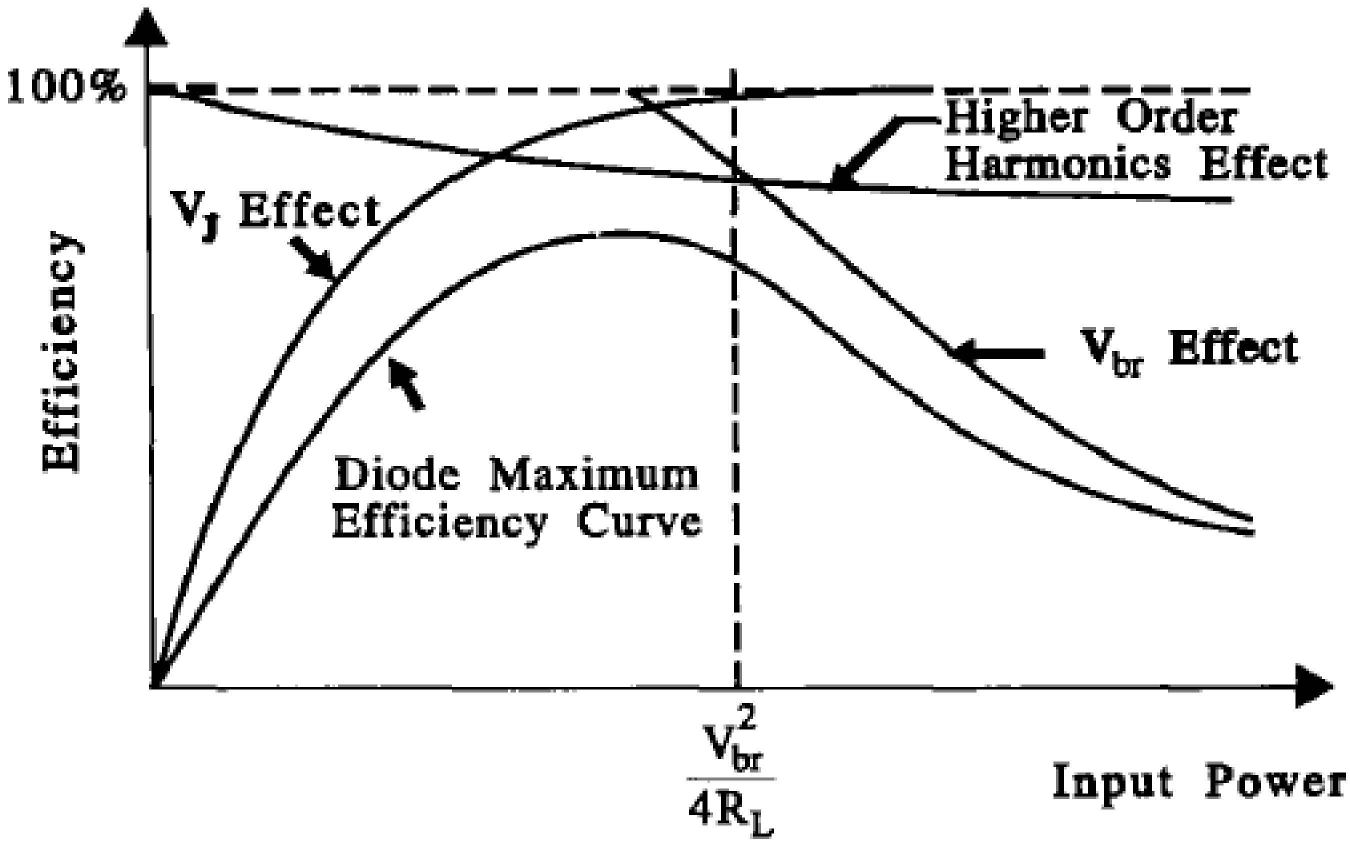


Fig. 2. General relationship between microwave to dc power conversion efficiency and input power.

Image source: [4,24]

Rectenna

- Multiple rectennas may be assembled into arrays
- Total power: lower than the sum of individual powers
- Series connection less efficient than parallel connection

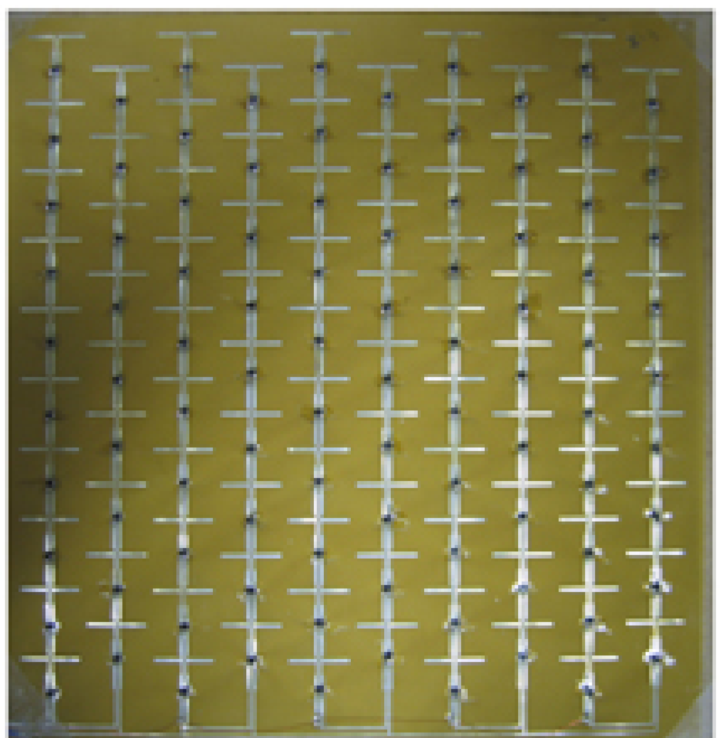


Image source: [6]

Cockroft-Walton Multiplier

- Antenna output voltage may be very low, about a very few hundreds of millivolts (when scavenging RF from commercial broadcasting).
- Usable voltage must exceed 1 V (low power)
- A single rectifying diode may be inefficient
- Transformers are bulky, with insufficient bandwidth (a few hundreds of MHz)

Cockroft-Walton Multiplier

- Cockroft-Walton multiplier: originally developed for high energy physics;

Image source: Wikipedia

Cockroft-Walton Multiplier

- Cockroft-Walton multiplies: originally developed for high energy physics;
- Uses a ladder network of capacitors and diodes.
- Easily to analyze with diode threshold model.

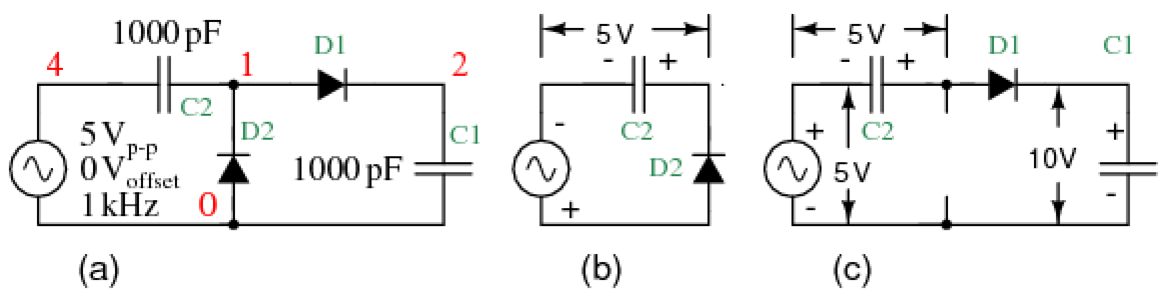


Image source: [7]

Cockroft-Walton Multiplier

- (a): full circuit
- (b): negative half wave equivalent circuit
- (c): positive halfwave equivalent circuit.
- Power scavenging requires low barrier voltage

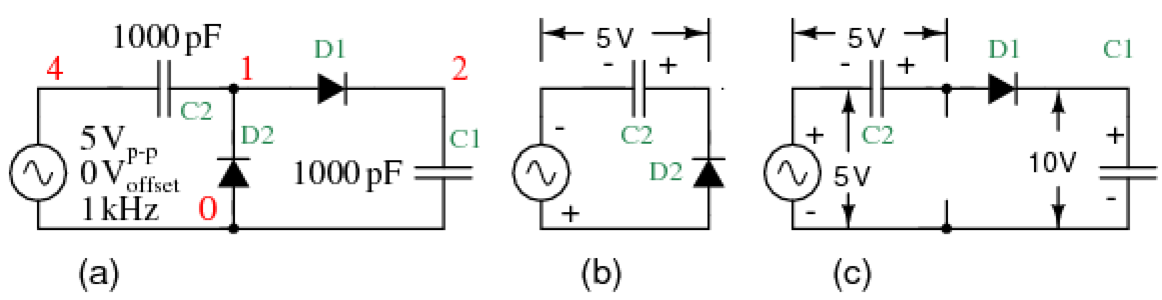
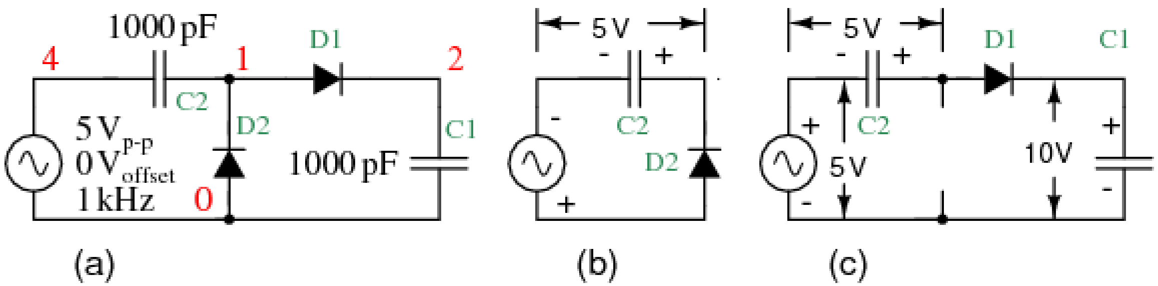


Image source: [7]

Cockroft-Walton Multiplier



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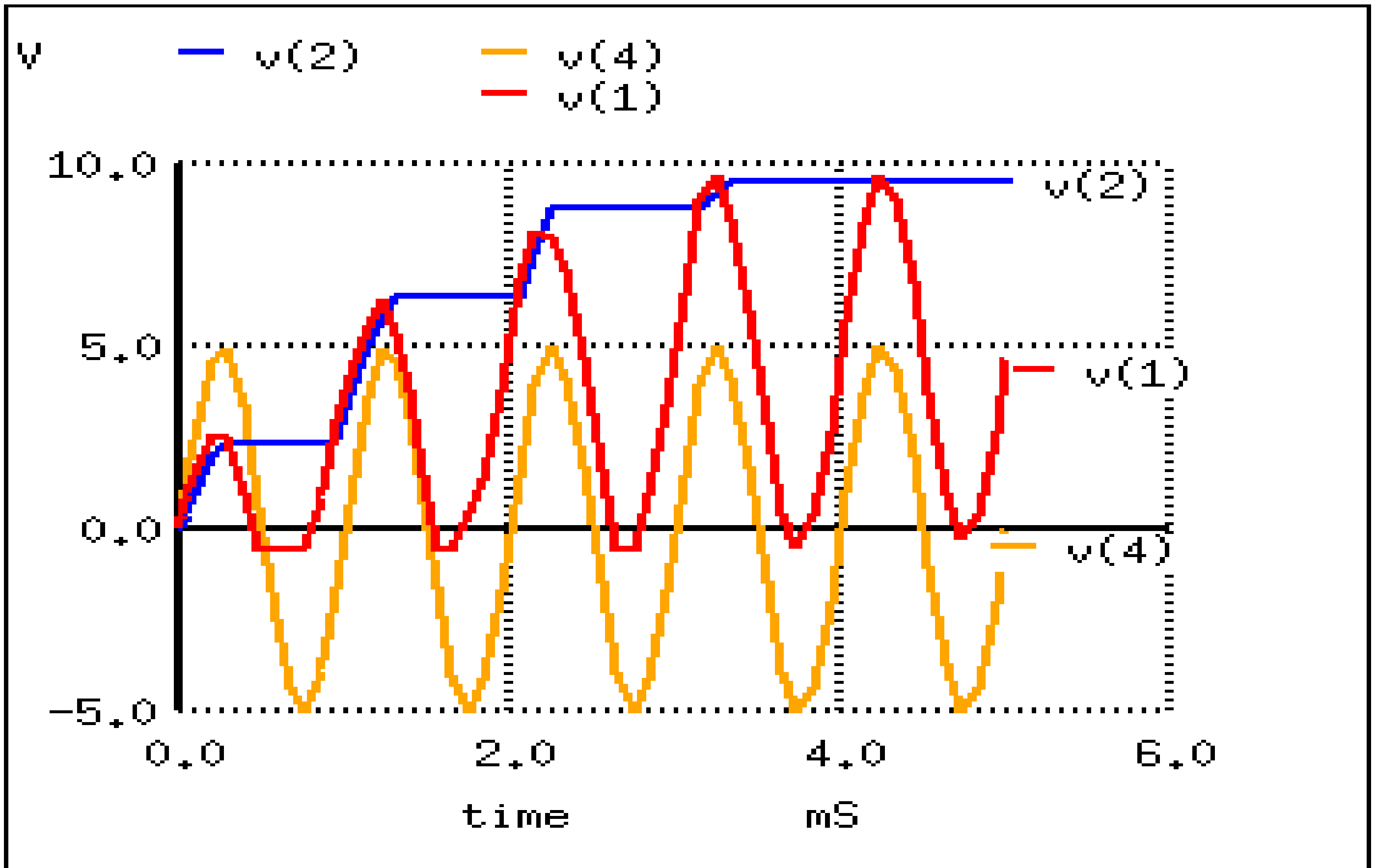


Cockroft-Walton Multiplier

- Several multipliers may be cascaded for higher multiplying factor
- Load insertion usually reduces output voltage with respect to open circuit conditions
- Diode power consumption and losses limit the number of stages

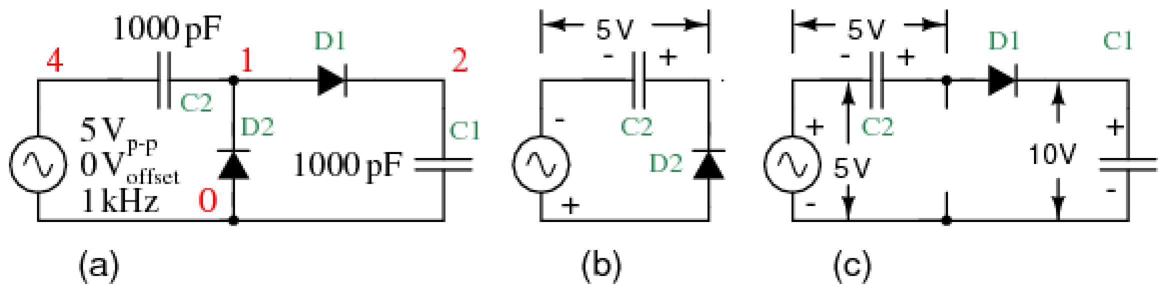
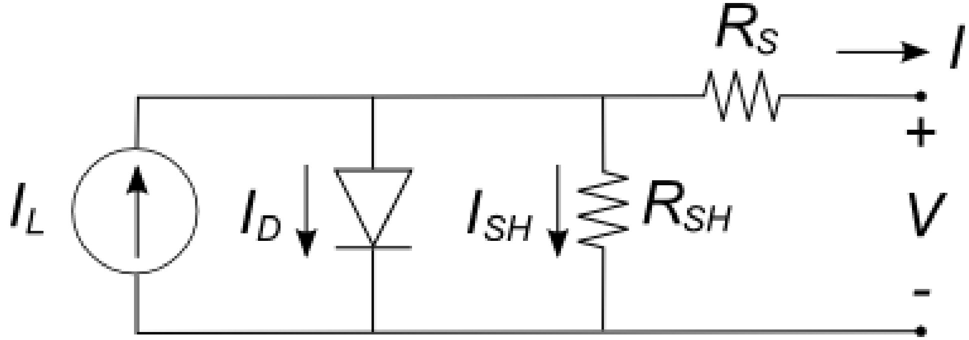


Image source: [7]

Solar Radiation, Photovoltaic

- Principle: quantum device, based on photoelectric effetc applied to semiconductors (bandgap about 1 eV). Photons with compatible energy induce formation of electron-hole couples.
- Cell model: one diode or two diode based



Basics and PV Cell Modeling

- Theoretical Efficiency given by Shockley-Queisser Limit: <30% single p-n junction, <55% 2-junctions, 86% asymptotic.
- Limiting factors: blackbody radiation, recombination, spectrum losses.
- Efficiency may be increased in several ways (Concentration, tandem cells, infrared capture, fluorescent down-conversion, impurities/intermediate band…) [23].
- May be connected into arrays (series: less efficient in presence of partial shading).
- Actual efficiency: about 20% single junction, 40% multi-junction.

Rectenna and nantenna

- Nantenna: nanoscale rectantenna (nanoscopic rectifying antenna)
- Designed to collect energy of solar radiation
- Photovoltaic: based on corpuscolar nature of light
- Nantenna: based on wave nature of light

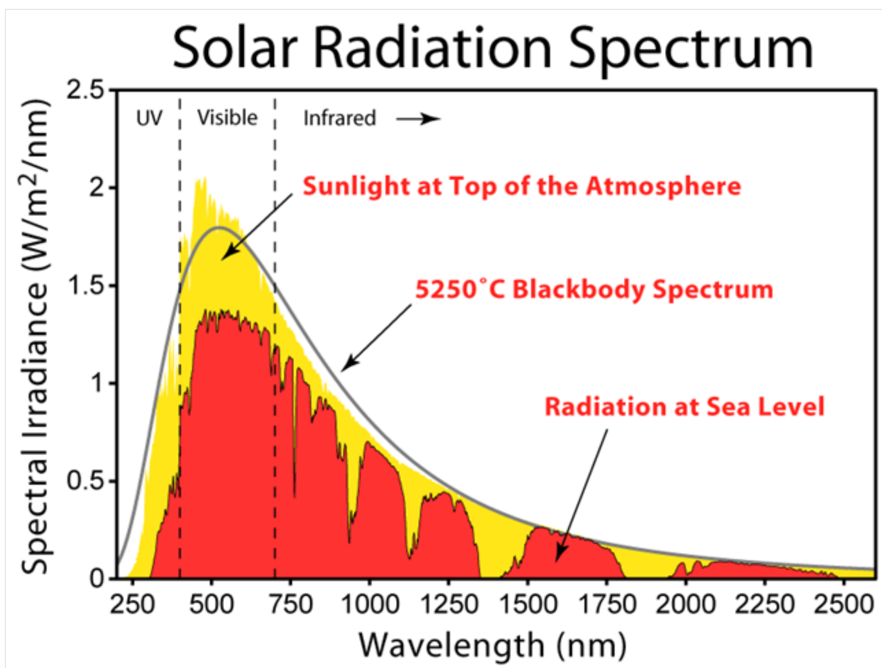
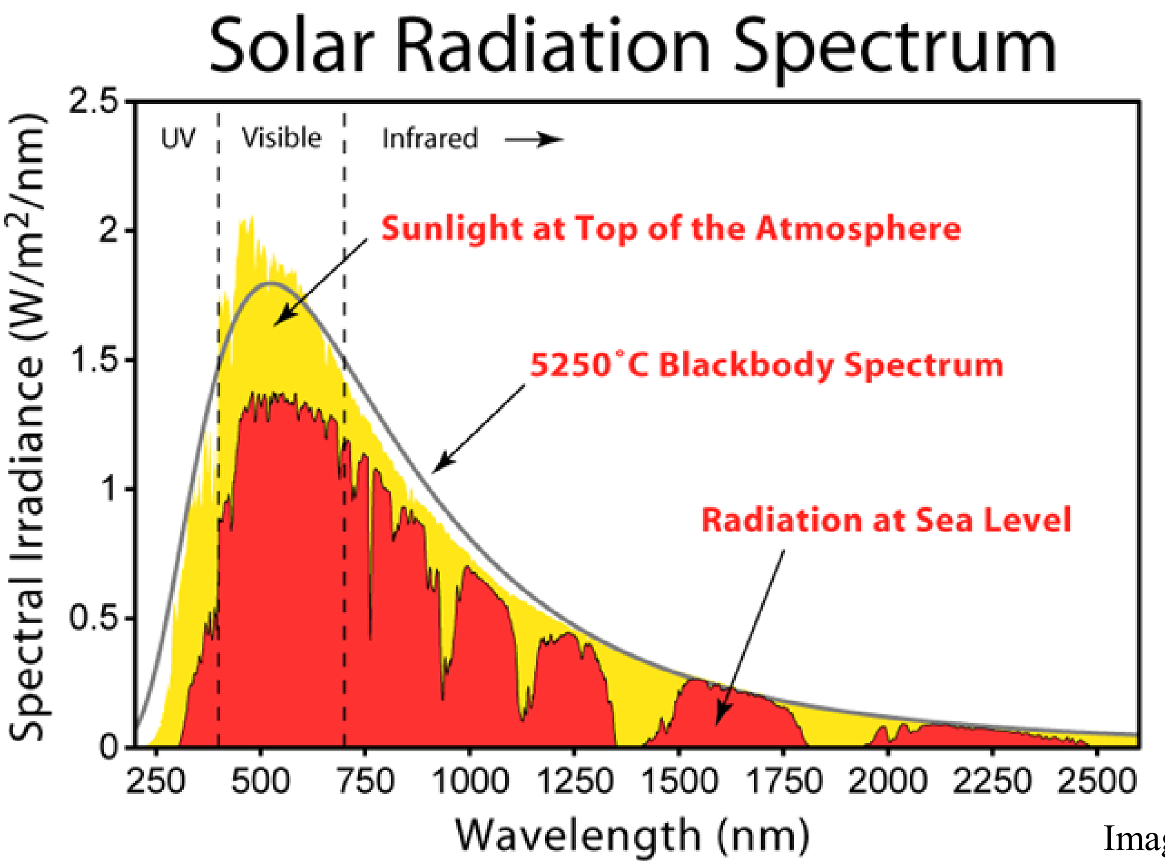


Image source: Wikipedia

Rectenna and nantenna

- Nantenna should collect efficiently radiations of wavelength comparable to its own size (claimed expected efficiency: 85%)



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Rectenna and nantenna

- Implementing an array of variously sized nantennas is potentially much easier than implementing an array of semiconductor alloys with various bandgaps.

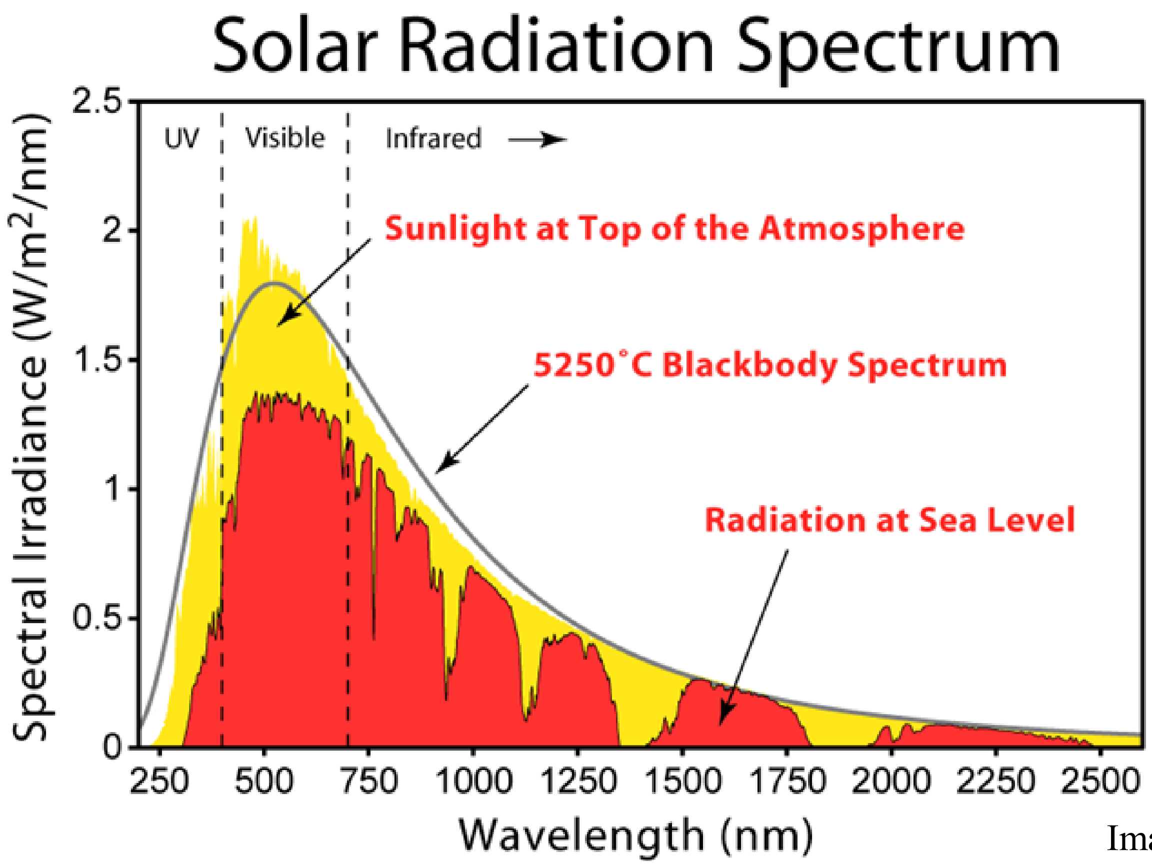

Image source: Wikipedia

Rectenna and nantenna

- nantennas radiation diagram may be exploited to reduce tracking requirements.

Rectenna and nantenna

- Some nantenna open issues (deviation from rectantenna assumptions):
- Efficiency prediction is not fully theoretically established;
- Mostly surface current conduction due to skin effect (non ohmic material, increased resistance);

$$J = J_S e^{-\frac{d}{\delta}}, \quad \delta = \sqrt{\frac{2\sigma}{\omega \ \ \mu}} = \sqrt{\frac{2\sigma}{2\pi f \mu_0 \mu_r}} \cong \sqrt{\frac{\sigma}{4\pi^2 10^{-7} f \mu_r}} \cong 503.3\sqrt{\frac{\sigma}{f \mu_r}}$$

- Copper ($\sigma \cong 1.68\times10^{-8}$ Ω·m, $\mu_r \cong 1$) @200 THz: δ≅4.6 nm
- Standard photolithography is not (yet…) mature for nanometer form factor (requires electron beam litography, more expensive).

Rectenna and nantenna

- Some nantenna open issues (continued):
- Schottky diodes work satisfactorily up to 5 THz, 0.4-1.6 μm wavelengths (maximum solar irradiance) correspond to 187-750 THz. Diode junction capacitance will reduce power conversion efficiency (THz require attoFarad capacitance);
- Metal Insulator Metal (MIM) tunneling diodes are currently being studied to increase bandwidth;
- Currently developed nantennas mostly work in the infrared (8-10 μm wavelengths), and perform much below the expected conversion efficiency.

Rectenna and nantenna

- Defense Advanced Research Project Agency (DARPA):
- Hybrid Photovoltaic/nantenna panel

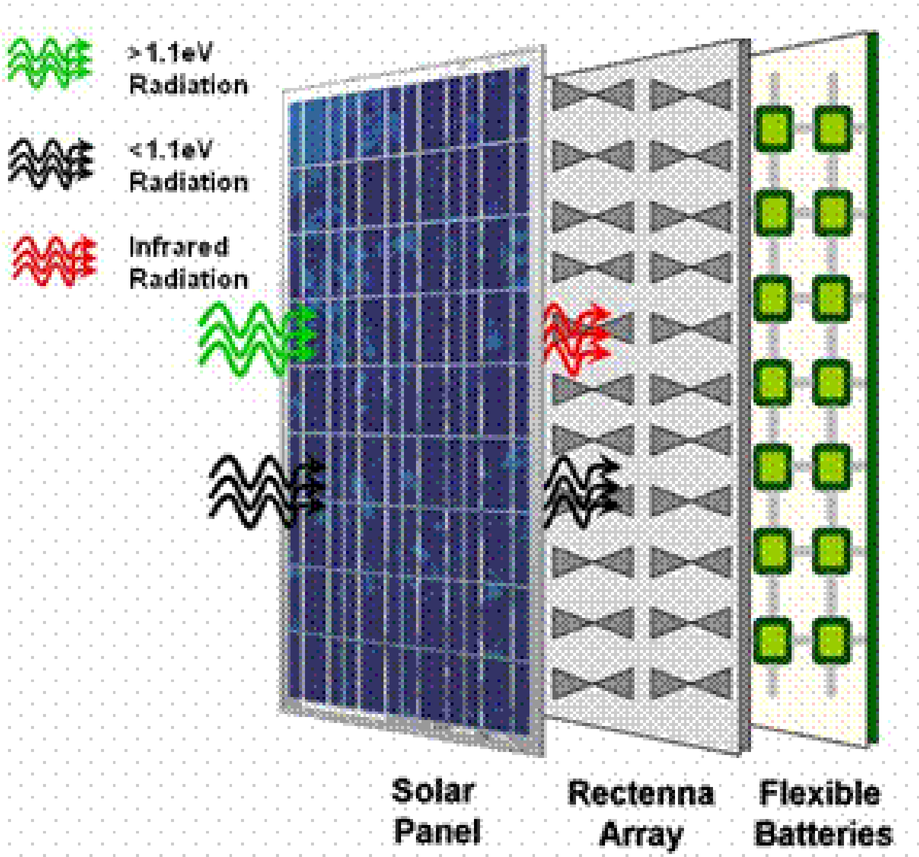

Image source: [8]

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Image sources

Various

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