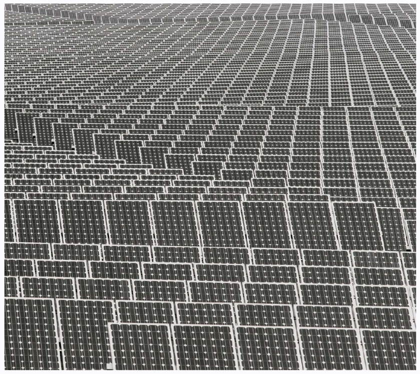
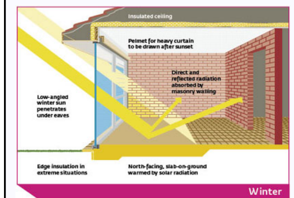


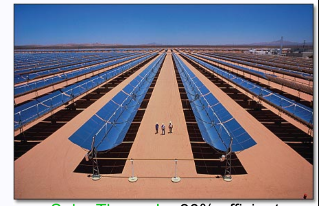
Solar Photovoltaics

Making Electricity from Sunlight

Methods of Harvesting Sunlight



Passive: cheap, efficient design; block summer rays; allow winter



Solar Thermal: ~30% efficient; cost-competitive; requires direct sun; heats fluid in pipes that then boils water to drive steam turbine

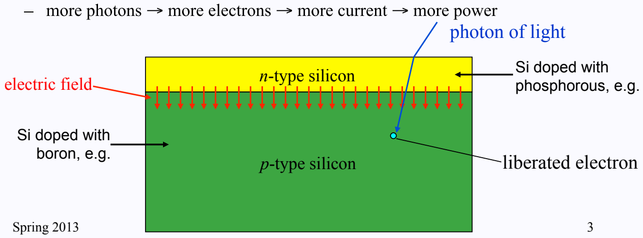
Solar hot water: up to 50% efficient; several $k to install; usually keep conventional backup; freeze protection vital (even in S.D.!!)

Photovoltaic (PV): direct electricity; 15% efficient; $5 per Watt to install without rebates/incentives; small fraction of roof covers demand of typ. home

Biofuels, algae, etc. also harvest solar energy, at few % eff.

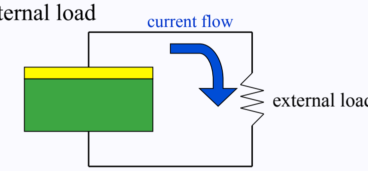
Photovoltaic (PV) Scheme

- Highly purified silicon (Si) from sand, quartz, etc. is "doped" with intentional impurities at controlled concentrations to produce a p-n junction
  - p-n junctions are common and useful: diodes, CCDs, photodiodes, transistors
- A photon incident on the p-n junction liberates an electron
  - photon disappears, any excess energy goes into kinetic energy of electron (heat)
  - electron wanders around drunkenly, and might stumble into "depletion region" where electric field exists (electrons, being negative, move *against* field arrows)
  - electric field sweeps electron across the junction, constituting a current
  - more photons → more electrons → more current → more power



Provide a circuit for the electron flow

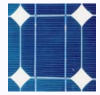
- Without a path for the electrons to flow out, charge would build up and end up canceling electric field
  - must provide a way out
  - direct through external load



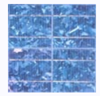
  - PV cell acts like a battery

PV types

- Single-crystal silicon
  - 15–18% efficient, typically
  - expensive to make (grown as big crystal)



- Poly-crystalline silicon
  - 12–16% efficient, slowly improving
  - cheaper to make (cast in ingots)

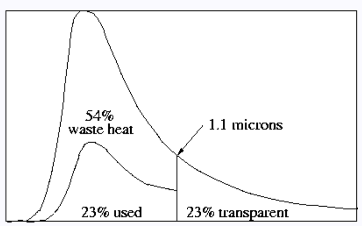


- Amorphous silicon (non-crystalline)
  - 4–8% efficient
  - cheapest per Watt
  - called "thin film", easily deposited on a wide range of surface types

How good can it get?

- Silicon is transparent at wavelengths longer than 1.1 microns (1100 nm)
  - 23% of sunlight passes right through with no effect
- Excess photon energy is wasted as heat
  - near-infrared light (1100 nm) typically delivers only 51% of its photon energy into electrical current energy
    - roughly half the electrons stumble off in the wrong direction
  - red light (700 nm) only delivers 33%
  - blue light (400 nm) only delivers 19%
- All together, the maximum efficiency for a silicon PV in sunlight is about 23%
  - defeating "recombination loss" puts the limit in the low 30's %

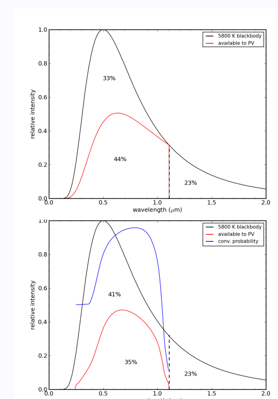
Silicon Photovoltaic Budget



- Only 77% of solar spectrum is absorbed by silicon
- Of this, ~30% is used as electrical energy
- Net effect is 23% maximum efficiency

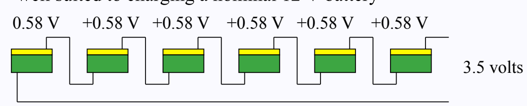
More Detail on Do the Math site

- Explains the physical factors involved in setting PV efficiency limits
  - http://physics.ucsd.edu/do-the-math/2011/09/dont-be-a-pv-efficiency-snob/

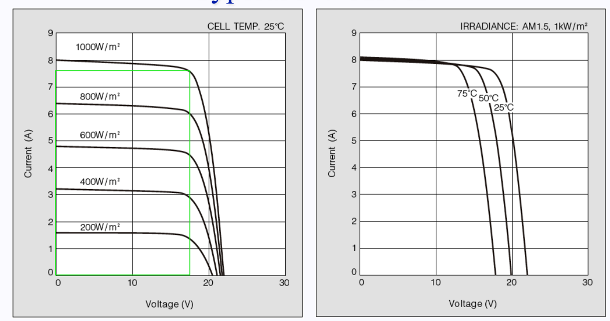


PV Cells as "Batteries"

- A single PV cell (junction) in the sun acts like a battery
  - characteristic voltage is 0.58 V
  - power delivered is current times voltage
  - current is determined by the rate of incoming solar photons
- Stack cells in series to get usefully high voltages
  - voltage ≠ power, but higher voltage means you can deliver power with less current, meaning smaller wiring, greater transmission efficiency
- A typical panel has 36 cells for about 21 V open-circuit (no current delivered)
  - but actually drops to ~16 V at max power
  - well suited to charging a nominal 12 V battery



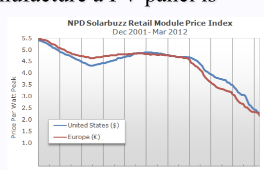
Typical I-V curves



- Typical single panel (this one: 130 W at peak power)
- Power is current times voltage, so area of rectangle
  - max power is 7.6 amps times 17.5 V = 133 W
- Less efficient at higher temperatures

How much does it cost?

- Solar PV is usually priced in dollars per peak Watt
  - or full-sun max capacity: how *fast* can it produce energy
  - panels cost $2.50 per Watt (and falling), installed cost $5/W
  - so a 3kW residential system is $15,000 to install
  - State rebates and federal tax incentives can reduce cost substantially
    - so 3kW system can be < $10,000 to install
- To get price per kWh, need to figure in exposure
  - rule of thumb: 4–6 hours per day full sun equiv: 3kW system produces ~15 kWh per day
- Mythbusting: the energy it takes to manufacture a PV panel is recouped in 3–4 years of sunlight
  - contrary to myth that…
  - they *never* achieve energy payback



Solar Economics

- Current electricity cost in CA is about $0.13 per kWh
- PV model: assume 5 hours peak-sun equivalent per day
  - in one year, get 1800 hours full-sun equivalent
  - installed cost is $5 per peak Watt capability, no rebates
  - one Watt installed delivers 1.8 kWh in a year
  - panel lasts at least 25 years, so 45 kWh for each Watt of capacity
  - paid $5.00 for 45 kWh, so $0.11/kWh
  - rebates can pull price to < $0.08/kWh
- Assuming energy rates increase at a few % per year, payback is < 10 years
  - thereafter: "free" electricity
  - but sinking $$ up front means loss of investment capability
  - net effect: cost *today* is what matters to most people
- Solar PV is on the verge of "breakout," but demand may keep prices stable throughout the breakout process

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Solar's Dirty Secret

- It may come as a surprise, but the sun is not always up
- A consumer base that expects energy availability at all times is not fully compatible with direct solar power
- Therefore, large-scale solar implementation *must* confront energy storage techniques to be useful
  - at small scale, can easily feed into grid, and other power plants take up slack by varying their output
- Methods of storage (all present challenges):
  - conventional batteries (lead-acid; cheapest option)
  - exotic batteries (need development)
  - hydrogen fuel (could power fleet of cars, but inefficient)
  - global electricity grid (always sunny somewhere)
  - pumped water storage (not much capacity)

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A Modest, Stand-Alone System

- In 2007, I set up a small PV system to power my living room
- Used two different panel types, explored a number of charge controllers and configurations
- Built mounts to allow seasonal tilt adjustments
- Larger panel is 130 W poly-crystalline silicon at 16% efficiency
- Smaller is 64 W thin-film triple-junction at 8% efficiency
- Large panel handled TV, DVD/VCR (system A), smaller one powered lights (system B)

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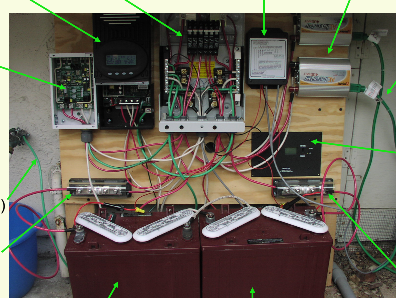
Dual System Components (covers removed)



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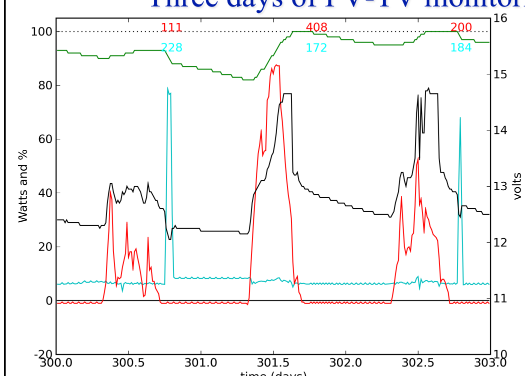
Three days of PV-TV monitoring



Home PV monitor for three late-October days in 2007: first very cloudy, second sunny; third cloudy

Spring 2013 see http://www.physics.ucsd.edu/~tmurphy/pv_for_pt.html for more examples 16

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System Upgrades

extensions on mounts allow tilts to 50°
portion shown here only gets 10° and 20°

- Over time, system has grown
  - but into single system
- Four 130 W panels shown at left
- Beefy inverter (3.5 kW max)
- “Smart” control to switch to grid power when batteries low
- Started running refrigerator most of the time off these four panels
- Expanded to 6 panels
- Now 8 panels after we moved
  - handles 60% of electricity

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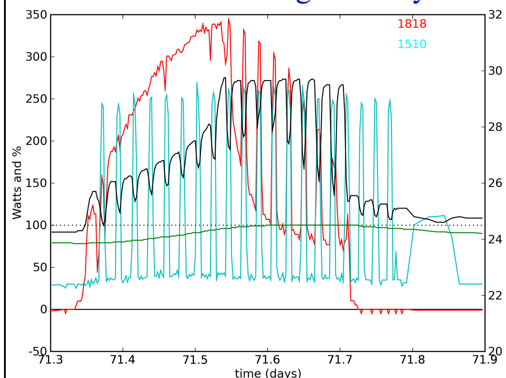
Refrigerator Cycles



With three panels, I could tackle something more worthy, like the refrigerator…

Can see cyclic behavior as fridge turns on and off

Once battery reaches absorb stage voltage (~29.5 V), can relax current to battery (falling red envelope)

When fridge pops on, need full juice again

Some TV later in day

In this period, got 1818 W-h from sun, used 1510 W-h

Getting 1818 W-h from 340-W capacity → 5.3 hours equiv. full sun

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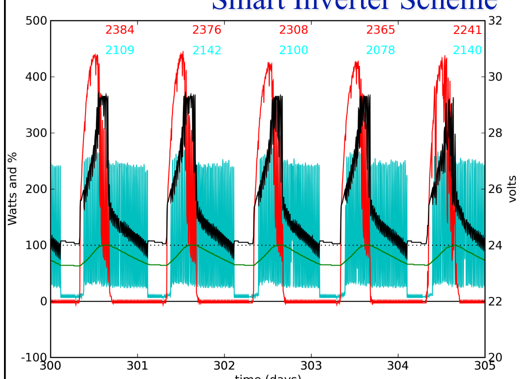
Smart Inverter Scheme



Using solar for fridge 75% of time; otherwise grid (4 panel setup)

A smart inverter can shut off when battery gets low, using grid power to supply to loads

Inverter comes back on when battery voltage hits a certain level

Note consistency of energy supplied (red numbers) and energy used (cyan numbers)

Infer 2107/2358 = 89% efficiency across first four days (efficiency of sending solar juice to inverter, including battery)

getting most out of system, without wasting solar potential

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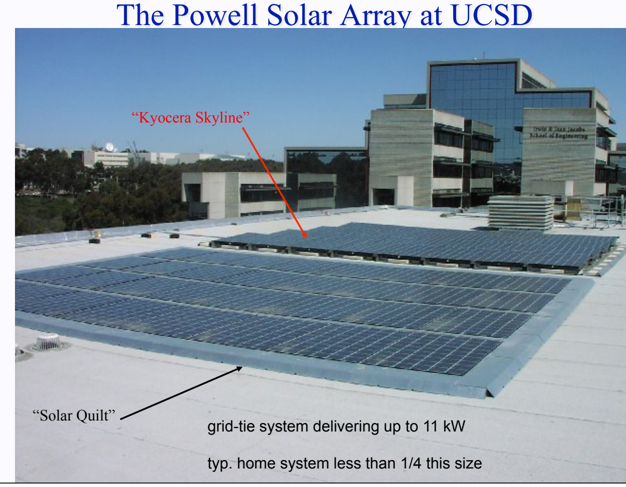
The Powell Solar Array at UCSD



grid-tie system delivering up to 11 kW

typ. home system less than 1/4 this size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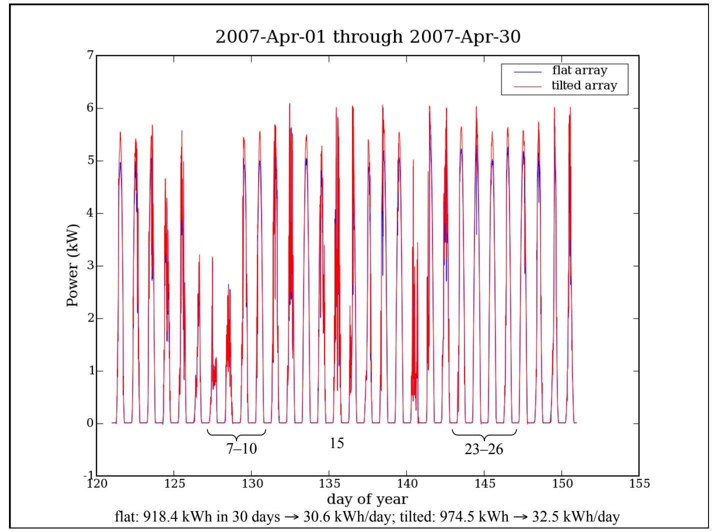
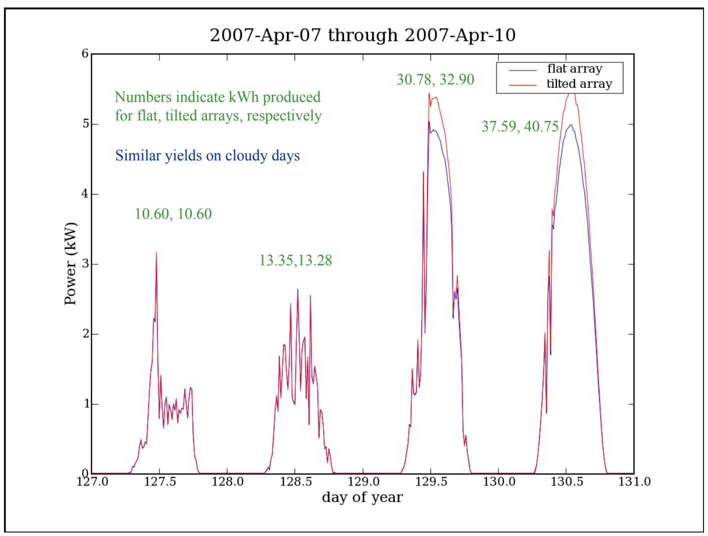
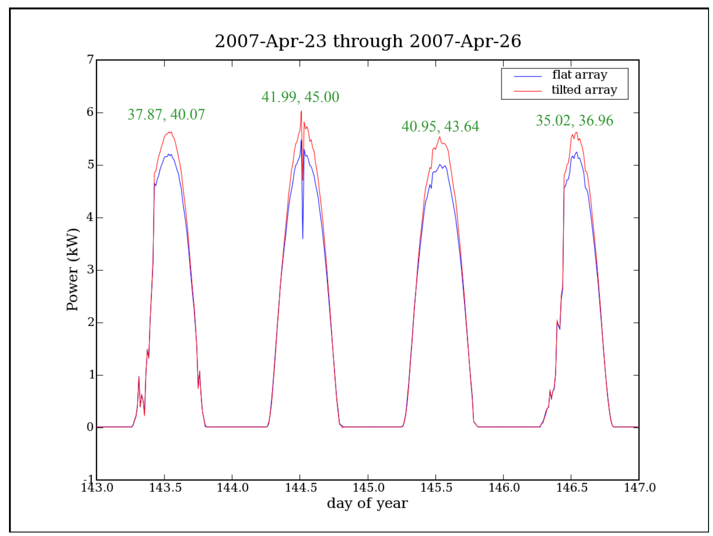
Powell PV Project Display
Power Output
4.0 kW
KYOCERA - UCSD
PV DEMONSTRATION PROJECT


2007-Apr-01 through 2007-Apr-30
flat array
tilted array
Power (kW)
7–10
15
23–26
day of year
flat: 918.4 kWh in 30 days → 30.6 kWh/day; tilted: 974.5 kWh → 32.5 kWh/day


2007-Apr-07 through 2007-Apr-10
flat array
tilted array
Numbers indicate kWh produced
for flat, tilted arrays, respectively
Similar yields on cloudy days
10.60, 10.60
13.35,13.28
30.78, 32.90
37.59, 40.75
Power (kW)
day of year


2007-Apr-23 through 2007-Apr-26
flat array
tilted array
37.87, 40.07
41.99, 45.00
40.95, 43.64
35.02, 36.96
Power (kW)
day of year

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Powell Array Particulars

- Each array is composed of 32 panels, each containing a 6×9 pattern of PV cells 0.15 m (6 inches) on a side
  - 95% fill-factor, given leads across front
  - estimated 1.15 m² per panel; 37 m² total per array
- Peak rate is 5,500 W
  - delivers 149 W/m²
  - At 15% efficiency, this is 991 W/m² incident power
- Flat array sees 162, 210, 230 W/m² on average for February, March, April
  - includes night and cloudy weather
- Cloudy days deliver 25% the energy of a sunny day
  - 1 kW rate translates to 180 W/m² incident during cloudy day

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UCSD 1 MW initiative: Gilman = 200 kW

At present, UCSD has installed 1 MW of solar PV, online since Dec. 2008.
UCSD uses 30 MW, 25 MW generated on campus (gas turbines, mainly)

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The Biggest of the Big

- Biggest PV installations
  - http://en.wikipedia.org/wiki/List_of_photovoltaic_power_stations
  - 250 MW in AZ; 214 MW in India; 200 MW China; 166 MW Germany; 150 MW in AZ
- Global totals:
  - Solar hot water: 196 GW (120 GW China; 15 GW U.S.)
  - PV: 98 GW (32 GW in Germany; 7.2 GW U.S.; 7 GW China)
    - 74% growth in the industry in 2011; average 65% since 2007
  - Solar thermal: 1.5 GW
    - 1 GW in U.S. (354 MW in CA); 0.5 GW in Spain
- Added together: 296 GW
  - but this is peak capacity
  - day/night/weather reduce by typically factor of 5
  - so call it 60 GW continuous → ~0.5% of global energy demand

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Solar Economics, revisited

- In remote locations, routing grid power is prohibitively expensive, so stand-alone PV is a clear choice
- For my experimental system at home, the cost is not competitive with retail electricity
  - small does not scale favorably: a system monitor can cost as much for a small system as for a large system
- But dollars and cents should not be the only considerations
  - consider: CO_2 contributed by burning fossil fuels, and climate change
  - consider: environmental damage in mining coal
  - consider: environmental damage in drilling/transporting oil
  - consider: depletion of finite resources: robbing future generations
  - consider: concentrated control of energy in a few wealthy hands
- Going (partially) solar has been worth every penny for me, personally
  - learning, independence, environmental benefit, etc. all contribute

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Announcements and Assignments

- Read Chapter 4
- Optional from Do the Math
  - 13. Don't be a PV Efficiency Snob
  - 54. My Modest Solar Setup
- HW 4 due Friday
- Midterm Monday, May 6, York 2622 at 3PM
  - need red half-page scan-tron with ID NUMBER section
  - and # 2 pencil
  - calculator okay (just for numbers, no stored info!)
  - study guide posted on web site
    - problems com *from this study guide*!
  - review session: Thursday 6:00 – 7:50 PM, Solis 110
- Quiz still on for Fridays (this week and next)

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