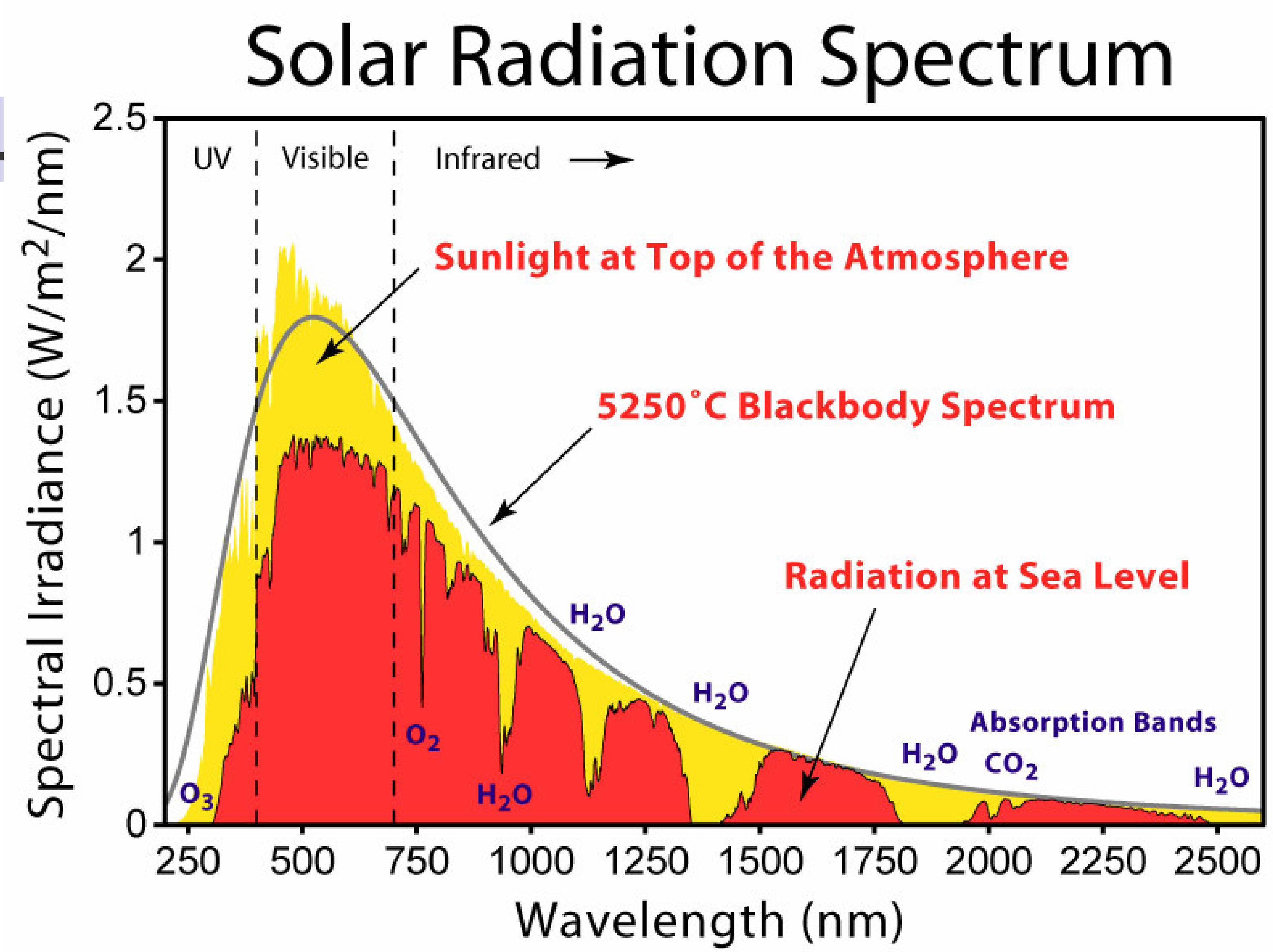
Solar PV Cells
Free Electricity from the Sun?

An Overview of Solar Photovoltaic Electricity

Carl Almgren and George Collins(editor)

Terrestrial Energy from the Sun

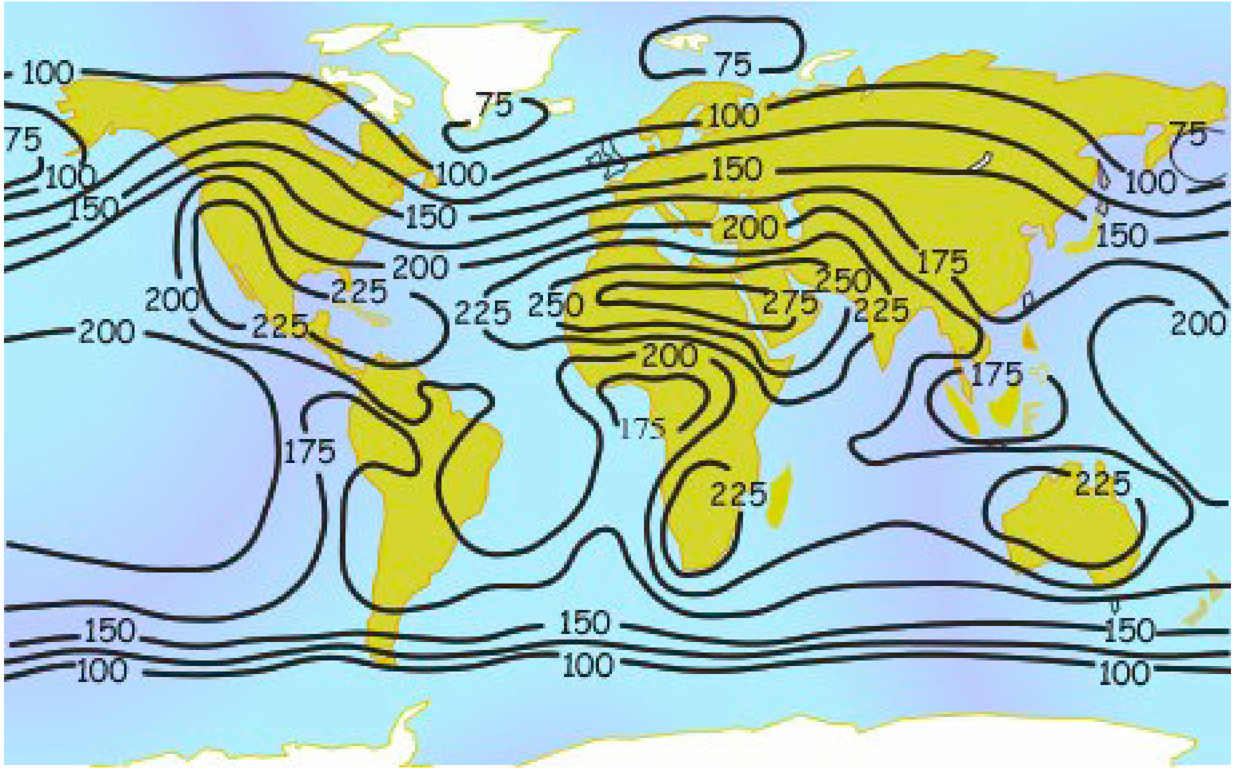


5 4 3 2 1 0.5

Electron-Volts per Photon

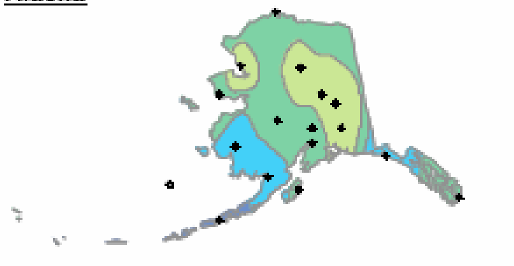
http://en.wikipedia.org/wiki/Image:Solar_Spectrum.png

Relative Solar radiation on Earth

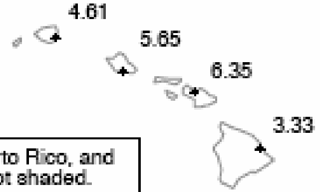


24 hour/365 day mean solar radiation received at the surface, in W/m2. It oscillates between a maximum of 275 M/m^2 in the deserts of the Middle East, to a low of 75 W/m^2 for misty isles in the Arctic.

Alaska



Hawaii



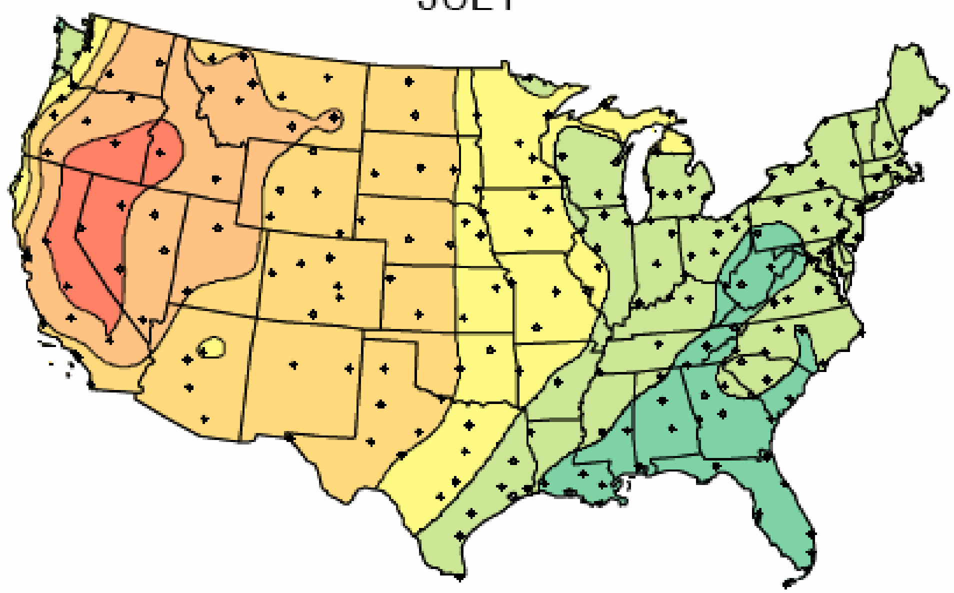
Hawaii, Puerto Rico, and Guam are not shaded.

San Juan, PR

Guam, PI

Average Daily Solar Radiation Per Month

JULY



North-South Axis Tracking Concentrator Tilted at Latitude

Collector Orientation

One-axis tracking parabolic trough with a horizontal north-south axis and tilted from the horizontal at an angle equal to the site's latitude

This map shows the general trends in the amount of solar radiation received in the United States and its territories. It is a spatial interpolation of solar radiation values derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The dots on the map represent the 239 sites of the NSRDB.

Maps of average values are produced by averaging all 30 years of data for each site. Maps of maximum and minimum values are composites of specific months and years for which each site achieved its maximum or minimum amounts of solar radiation.

Though useful for identifying general trends, this map should be used with caution for site-specific resource evaluations because variations in solar radiation not reflected in the maps can exist, introducing uncertainty into resource estimates.

Maps are not drawn to scale.

$kWh/m^2/day$

- 10 to 14
- 8 to 10
- 7 to 8
- 6 to 7
- 5 to 6
- 4 to 5
- 3 to 4
- 2 to 3
- 0 to 2
- none

* NREL

National Renewable Energy Laboratory
Resource Assessment Program

C1XLA07-46

Origin of Photovoltaic cells

- The term "photovoltaic" comes from the Greek :*phos* meaning "light", and "voltaic", from the name of the Italian physicist Volta, after whom the unit Volts is named..
- The modern age of solar power technology began in 1954 when Bell Laboratories, discovered that silicon doped with certain impurities was able to generate electricity for satellites.

What happens in the cell?

- Photons in sunlight hit the solar panel and are absorbed by semiconducting materials, such as silicon—creating a dc V-I source to extract energy from.

An array of solar panels converts solar energy into a usable amount of DC electricity.

Power Electronics Inverters convert the DC to mains AC to feed the grid

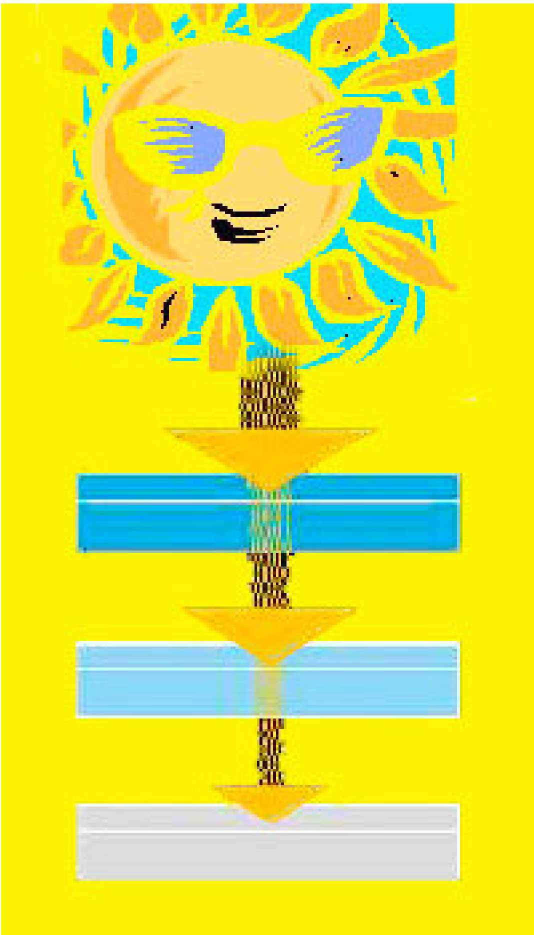
Quantum characteristics of solar cells

- A photon need only have greater energy than that of the semiconductor band gap in order to create electron-hole pairs but to penetrate deeply into the semiconductor the energy must be not far away from the band gap which for silicon is 1.1 eV and a wavelength of about 1 micron
  - However, the solar frequency spectrum is composed of photons with energies greater than the band gap of silicon. These higher energy photons will be absorbed by the solar cell, but the difference in energy between these photons and the silicon band gap is converted into undesired heat (via lattice vibrations called phonons) rather than into usable electrical energy.

Photon absorption

- When a photon is absorbed, its energy is given to an electron-hole pair in the crystal lattice. The electrons and holes have to move to the collection electrodes of the solar cell to create a V-I source.
- To keep from shadowing sunlight to the active solar area the top collections electrodes are made from a transparent conducting oxide like ITO

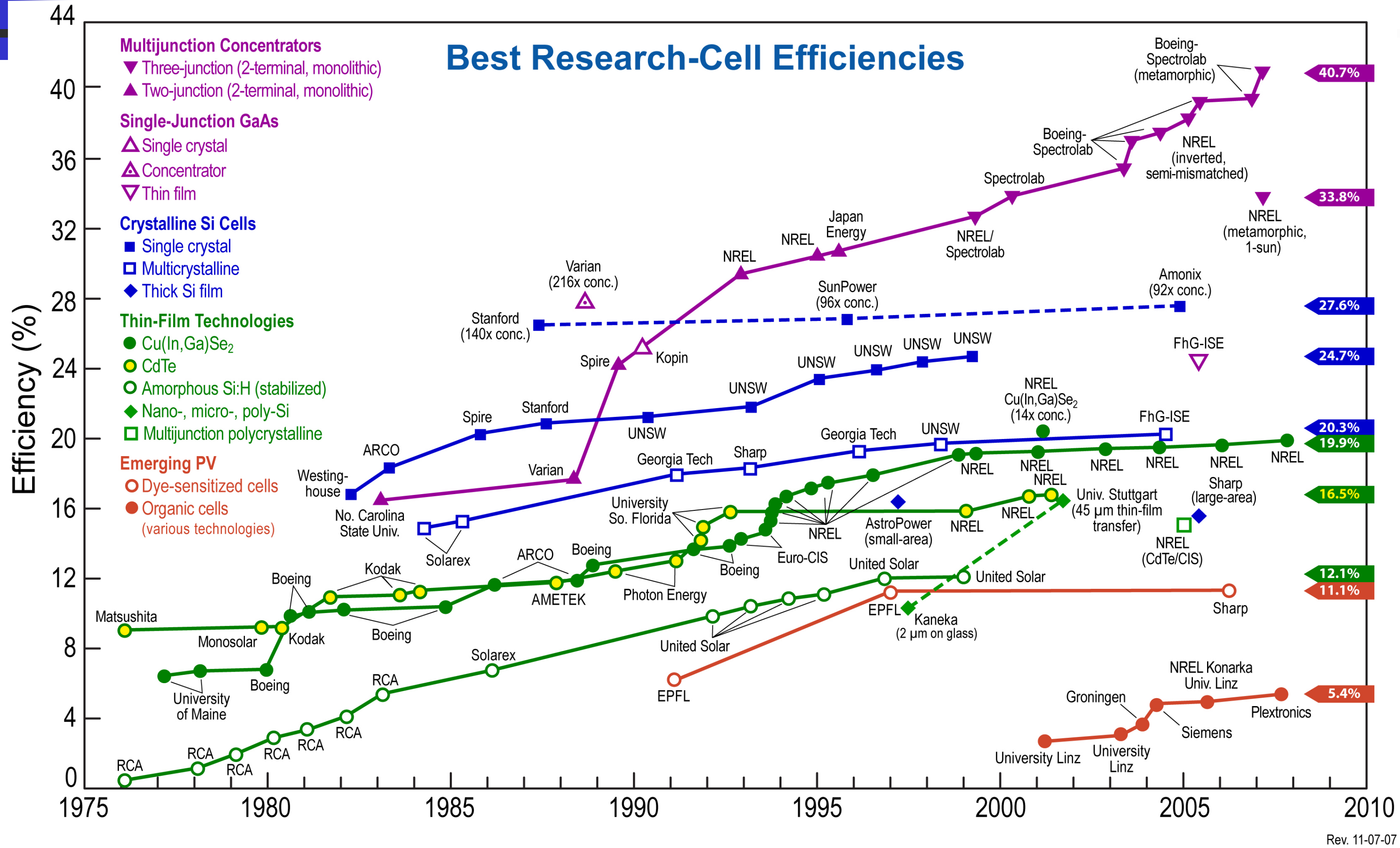
Maximizing efficiency



- **A one-layer solar cell is limited to 20 percent efficiency in converting light to power, but materials with different bandgaps can be stacked in multijunction cells. Each layer responds to a different photon energy of sunlight to achieve 40 % efficiency.**

http://www.lbl.gov/Science-Articles/Archive/MSD-perfect-solar-cell.html

Solar cell efficiencies



Courtesy of L.L. Kazmerski, NREL

Maximum Power Point

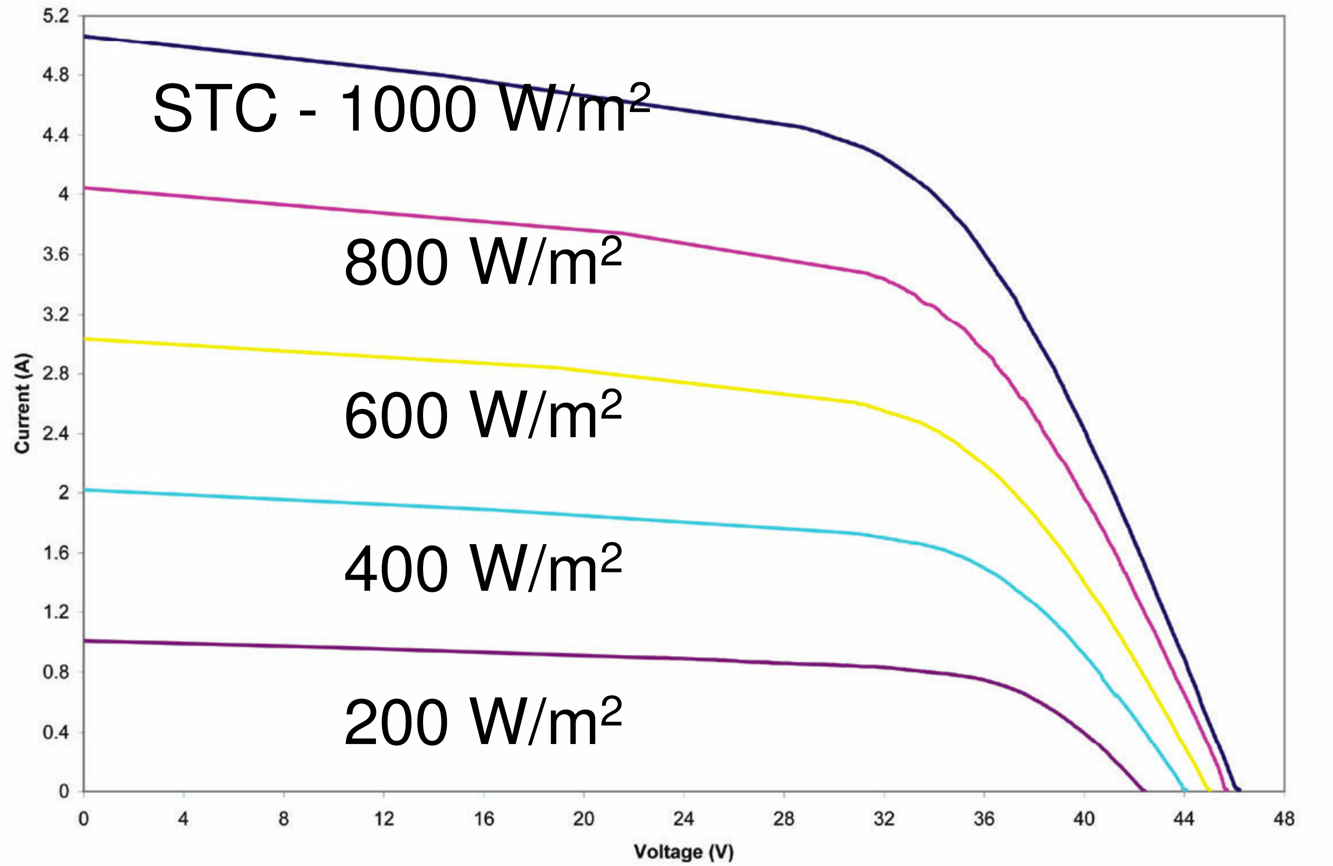
- A solar cell has a maximum-power point where the product of VI is maximum.
- The maximum power point of a PV cell varies dynamically with incident solar illumination.
- A maximum power point tracker tracks instantaneous power and uses this information to dynamically adjust the load so the maximum power is *always* transferred, regardless of the variation in lighting.

Photogeneration of charge carriers

- When a photon hits a piece of silicon, one of three things can happen:
  - The photon can pass straight through the silicon
    - This generally happens for lower energy photons.
  - The photon can reflect off the surface
  - The photon can be absorbed by the silicon which either:
    - Generates heat
    - Generates electron-hole pairs, if the photon energy is higher than the silicon band gap value.
      - If a photon has an integer multiple of band gap energy, it can create more than one electron-hole pair. However, this effect is usually not significant in solar cells.

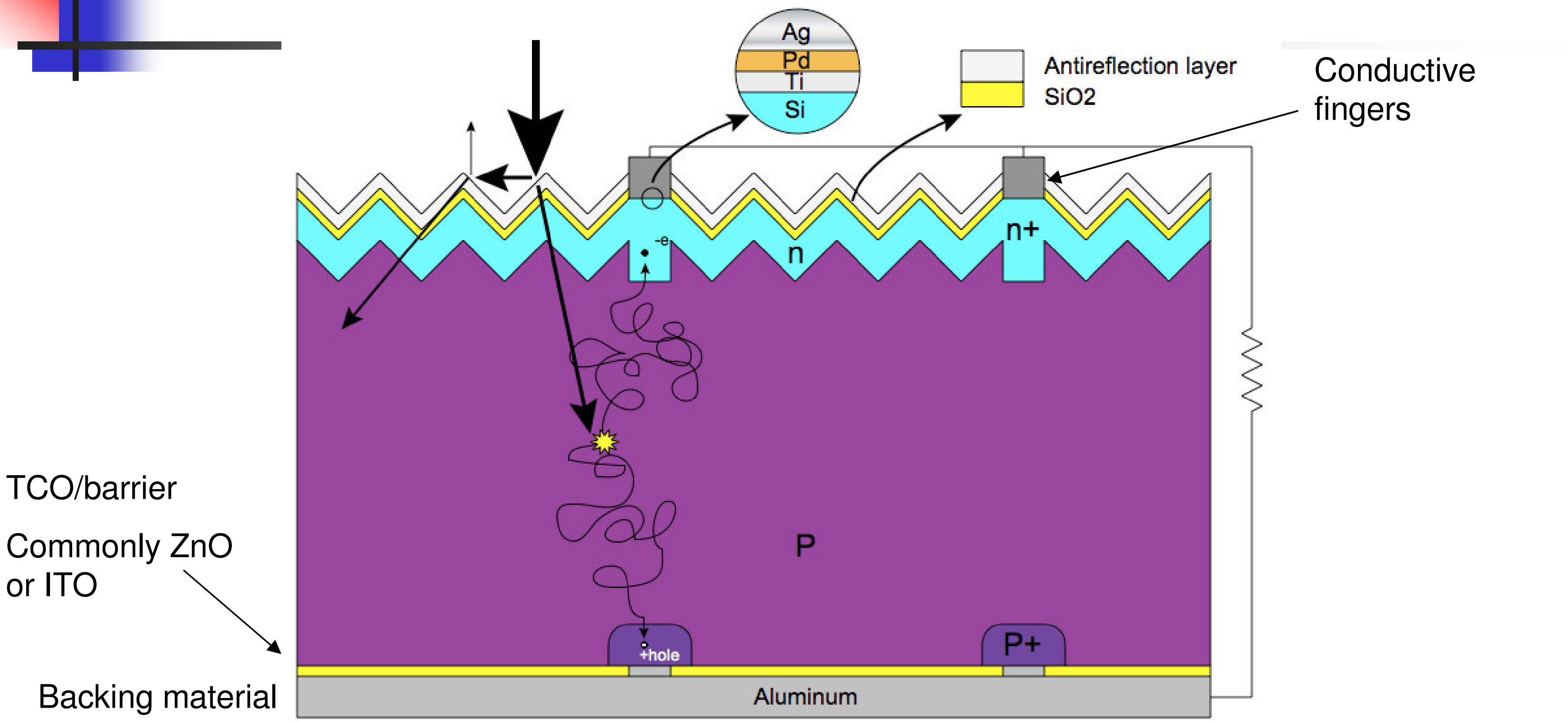
Sample of I-V curves at various levels of irradiance

UniSolar PVL 136 Thin Film laminate cells



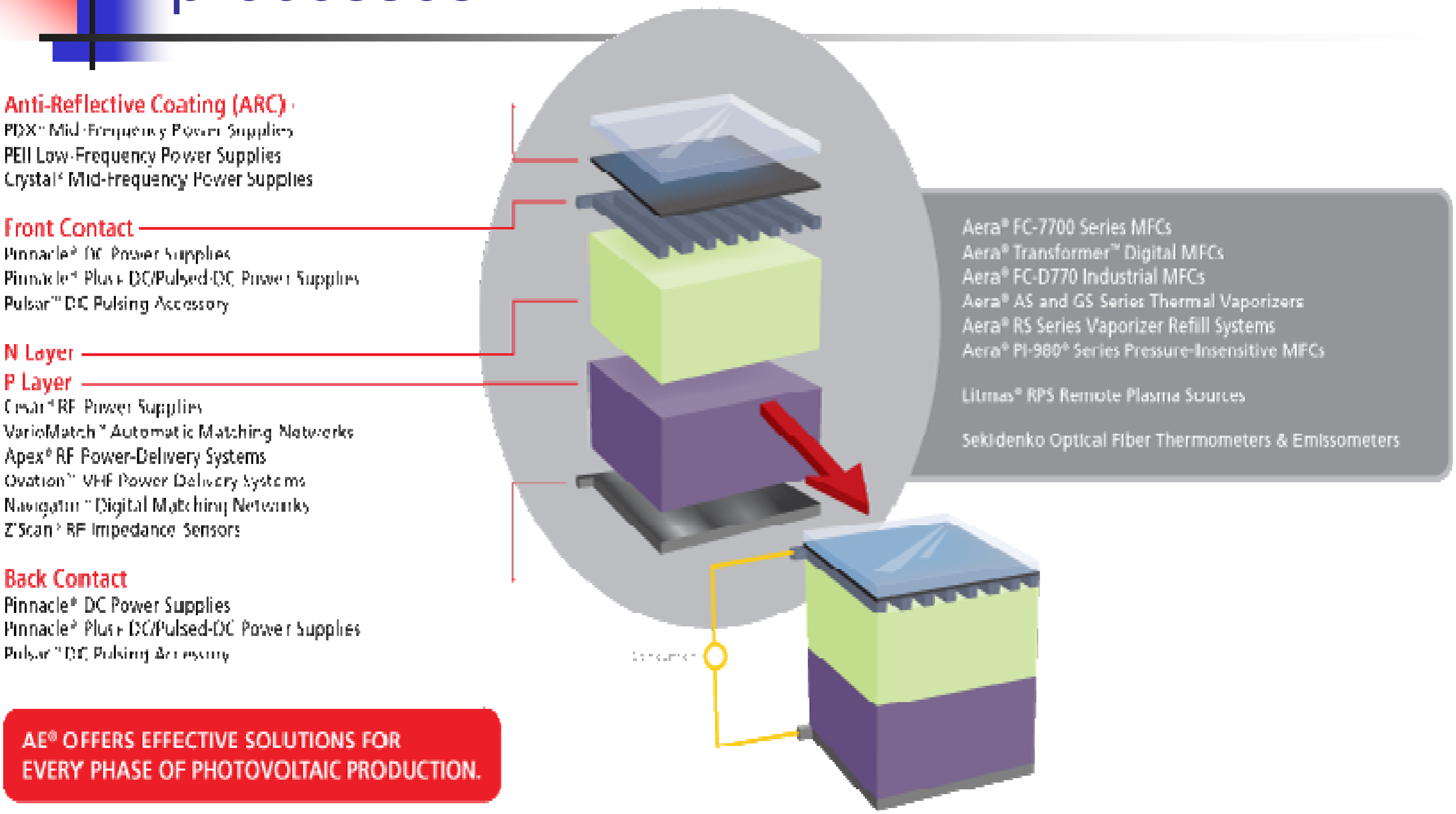
Air Mass 1.5 and 25C cell temperature

Anatomy of a PV Solar Cell

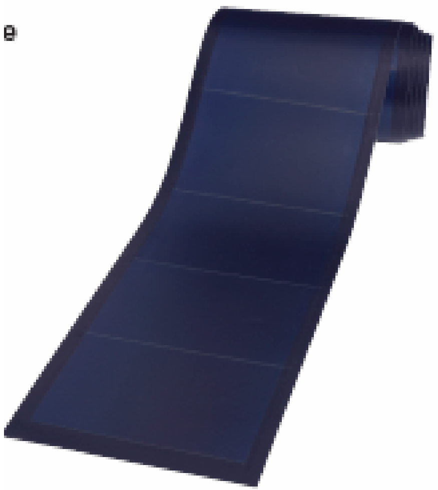


Other parts of a cell are needed to enable production of electricity

Solar cell layers and how they are fabricated with plasma deposition processes



Types of PV Cells



Monocrystalline vs. thin film

The Energy Problem

- Worldwide, an additional 10 TW electric energy will be needed by the year 2050. This is about 4 GW of capacity per week.
- How to supply this additional needed power
  - Fossil fuel production is stretched - and releases CO_2
  - Would need one new 1 GigaWatt nuke every other day
  - Biofuels would consume massive amounts of agricultural resources like water,energy and fertilizer(NO gas from fertilizer is 300 times worse greenhouse gas)
  - Nuclear Plants with no fossil fuel pollution at all

http://www.greenandgoldenergy.com.au/

The role of Solar energy

- A part of the solution as follows
  - On an average day, the earth at sea level is absorbing solar energy at rate of 120,000 TW but 170,000TW are entering the outer atmosphere.
  - In space massive solar arrays could both cool the earth by shadowing and transmit power by microwaves
  - 10% efficient terrestrial cells are common

    And 40% cells are achieved in research
  - Both heat and electricity can be harvested on solar farms. In Japan and in America's SW solar water heaters are common

How Solar Photovoltaic Cells are used

- Use is divided by size and purpose
  - Provide low, independent power with no grid connection: i.e. calculators and garden lights.
  - Power in remote areas difficult or costly to connect to the power grid
  - Home-sized arrays to reduce grid-based electricity consumption
  - Large industrial arrays on large scale buildings for reducing both peak and total grid power consumption(Walmart is a great example)

PV Cell Power generation

Efficiencies and Costs

- Thin films cheap, but low conversion efficiency (10%) while crystaline cells give 40% they are expensive
- As of 2005, photovoltaic electricity generation costs ranged from ~60 cents/kWh down to ~30 cents/kWh in regions of high solar irradiation.

- Solar electric systems cost between 5 and 9 US$ per peak Watt, installed
  - Peak watts x 20% x 24 hrs = AVERAGE Watt-hrs/day
  - example: 1 kW peak = 4.8 kW-hrs/day
- Payback is not there without government assistance

What do we do with this electricity?

- Mostly converted to AC using power electronics inverters

The inverter turns the DC electricity into AC electricity of the correct voltage and frequency needed for the grid.

- The electricity is then distributed to be used, either on-site or back into the distribution grid.

Commercial 333 kW Inverter - Advanced Energy Solaron^{TM}

Alternative solar materials

- Silicon is an "indirect band gap " semiconductor, in which with the creation of an electron-hole pair requires participation of the crystal lattice vibrations, wasting a lot of an incoming photon's energy in the form of heat. In direct band gap semiconductors, however, light of the right energy does not vibrate the lattice; thus it creates electron-hole pairs more efficiently as regards electrical conversion.

- All direct-bandgap semiconductors combine elements from group III of the periodic table, like aluminum, gallium, or indium, with elements from group V, like nitrogen, phosphorus, or arsenic. The most efficient multijunction solar cell yet made -- 30 percent, out of a theoretically possible 50 percent efficiency -- combines just two materials, gallium arsenide and gallium indium phosphide

Future options

- Solar cell light absorbing materials can be stacked to take advantage of different light absorption and charge separation mechanisms.
- Currently available solar cells are primarily made of silicon which is well understood in both bulk and thin-film configurations.
- Other future materials such as CdTe and organic polymers) as well as nanocrystals and quantum dots embedded in a supporting matrix.

Storing energy for high usage or low shine

- Simplest is battery system
  - Backup batteries - 212 AH@ 12V - 25 kWH in 62 kg battery
    http://www.solarexpert.com/Batteries/Concorde.html

- Flywheel systems can be very efficient with less degradation over time
  - Flywheel efficiency up to 99% - Eaton Powerware
    http://www.powerware.com/ups/PF2_Flywheel_features.asp
  - Motor and generator efficiency - about 90% readily available
    http://www.reliance.com/pdf/motors/data_sheets/raps1190.pdf

- So is it worth it?
  - Solar power savings calculator
  - http://sunpowercorp.cleanpowerestimator.com/default.aspx

Almgren's conservation efforts-- effective?

City of Fort Collins Utilities

Utility Services Billing

330 South College Avenue P.O. Box 580 Fort Collins, CO 80522-0580 (970) 221-6785

Account Number: 91499801-02-8

TOTAL AMOUNT DUE: $152.98
Due Date: October 22, 2000
Billing Date: September 27, 2000

CARL W ALMGREN
2925 GARRETT DR
FT COLLINS CO 80526-6222

Service Address:
2925 GARRETT DR
FT COLLINS CO 80526-6222

Billing and Payment Summary

Payment due last billing period......................	$364.50
Utility payments received since last billing..........	$364.50
Previous balance due:	$0.00
Charges for utility services this billing period......	$152.98
TOTAL AMOUNT DUE:....................................	$152.98

This bill may not reflect recent payments.

Summary of Charges for Utility Services

Service	Rate Code	Service Date From	Service Date To	Days	Meter Readings Previous	Meter Readings Present	Mult	Units	Charge for Service
Electric	E100	08/22/00	09/20/00	29	5625	6667		1042 kWh	$61.19
Stormwater IMP	H116	08/29/00	09/27/00	29					$7.32
Stormwater O&M	H110	08/29/00	09/27/00	29					$3.90
Water	W220	08/22/00	09/20/00	29	15881	16169	100	28800 Gal	$49.46
Wastewater	Q221	08/22/00	09/20/00	29					$29.38

Your utility bill is under construction. Check this month's insert for details about what will be changing soon.

Sub-total	$151.25
City sales tax on electricity	$1.73
Total charges for services	$152.98

Your average daily cost for water: $1.71
Your average daily electric cost: $2.11

See reverse side for customer information and explanation of abbreviations.

Water Billing History

Read Date	Days	Use in 1000 Gal	Average Gal/Day	Total Billed
09/20/00	29	29	993	$49.46
08/22/00	33	35	1055	$56.88
07/20/00	29	32	1110	$53.67
06/21/00	33	35	1070	$57.49
05/19/00	31	22	713	$41.18
04/18/00	28	16	571	$33.64
03/21/00	32	15	463	$32.16
02/18/00	28	13	468	$30.05
01/21/00	35	18	506	$35.74
12/17/99	29	14	479	$29.43
11/18/99	30	15	510	$31.06
10/19/99	28	12	432	$27.33
09/21/99	32	21	650	$37.47

Electric Billing History

Read Date	Days	Use kWh	Average kWh/Day	kW Meter	kW Billed	Total Billed
09/20/00	29	1042	36			$61.19
08/22/00	33	1460	44			$84.41
07/20/00	29	1445	50			$83.58
06/21/00	33	1122	34			$65.64
05/19/00	31	938	30			$55.42
04/18/00	28	919	33			$54.37
03/21/00	32	977	31			$57.58
02/18/00	28	1006	36			$59.19
01/21/00	35	1420	41			$82.19
12/17/99	29	1341	46			$77.80
11/18/99	30	1017	34			$59.81
10/19/99	28	851	30			$50.58
09/21/99	32	962	30			$56.75

Printed on recycled paper

City of Fort Collins Utilities

Fort Collins Utilities
Customer Service
330 S. College Ave.
Hours: 8 a.m. to 5 p.m., weekdays

Phone: (970) 212-2900
E-mail: utilities@fcgov.com
Web: www.fcgov.com/utilities

c19

Account Number	Customer Name	Service Address	Bill Date	Date Due	Amount Due
405774-74035	CARL W. ALMGREN	2925 GARRETT DR	10-29-07	11-23-07	$134.82

See reverse side for customer information and explanation of abbreviations.

Billing and Payment Summary

Payment due last billing period . . . . $	133.38
Payments received since last billing . . . . $	133.38
Charges for this billing period due 11-23-07 . . . . $	134.82
Total amount due . . . . $	134.82

Service	Rate Code	Service Date From	Service Date To	Days	Meter Readings Previous	Meter Readings Present	Multiplier	Usage	Charge
Electric Energy	E100	09-19-07	10-22-07	33	88297	89035	1	738 KWH	$50.85
Stormwater	H116	09-19-07	10-22-07	33					$15.00
Wastewater	Q221	09-19-07	10-22-07	33				7500 WQA	$24.14
Water		09-19-07	10-22-07	33	36020	37120	10	11000	
Base Charge	WB20								$12.72
Tier 1	W220							7700 GAL	$15.16
Tier 2	W220							3300 GAL	$7.47
Green Energy	E730	09-19-07	10-22-07	33				738 KWH	$7.82
					Sub-total				$133.16
					City Sales Tax				$1.66
					Total charges this billing period				$134.82

Water Billing History

Read Date	Days	Use in Gals	Gal/Day
10-22-07	33	11000	333
09-19-07	30	9600	320
08-20-07	32	16300	509
07-19-07	29	20500	706
06-20-07	34	16800	494
05-17-07	28	7600	271
04-19-07	29	6350	218
03-21-07	28	6750	241
02-21-07	30	6850	228
01-22-07	33	8850	268
12-20-06	33	8300	251
11-17-06	30	7750	258
10-18-06	28	8550	305

Electric Billing History

Read Date	Days	Use in kWh	kWh/Day
10-22-07	33	738	22
09-19-07	30	758	25
08-20-07	32	1342	41
07-19-07	29	1076	37
06-20-07	34	773	22
05-17-07	28	566	20
04-19-07	29	545	18
03-21-07	28	581	20
02-21-07	30	625	20
01-22-07	33	849	25
12-20-06	33	791	23
11-17-06	30	641	21
10-18-06	28	613	21

Make checks payable to Fort Collins Utilities. Return this portion with payment to ensure proper credit. c19

City of Fort Collins Utilities

Account Number	Service Address	Bill Date	Date Due	Amount Due
405774-74035	2925 GARRETT DR	10-29-07	11-23-07	$134.82

FORT COLLINS UTILITIES
PO BOX 1580
FORT COLLINS CO 80522-1580

CARL W. ALMGREN
2925 GARRETT DR
FORT COLLINS, CO 80526-6222

5004 9988 405774740356 0000013482

- Total kW-hrs down from 13458 to 8863/yr = 35% savings.