Solar Photovoltaic Applications

Larry Caretto
Mechanical Engineering 483

Alternative Energy Engineering II

April 26, 2010

California State University Northridge

Outline

- Midterm exam results
- Meet on Wednesday at PPM Conference room for photovoltaic tour
- Photovoltaic basics
- Applications of photovoltaic systems
- Costs and cell efficiencies
- Conclusions

California State University Northridge 2

Midterm Results

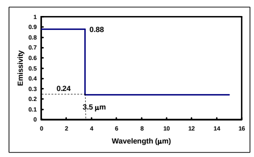
- Number of students: 30
- Maximum possible score: 90
- Mean: 43.8
- Median: 43
- Standard Deviation: 15.4

10	18	23	24	31	32	32	34	34	37
37	40	41	41	42	44	46	48	49	50
51	52	54	54	56	58	58	67	69	81

California State University Northridge 3

Midterm Problem One

- **Given:** Spectral emissivity
- **Find:** Solar radiation absorbed



$$\overline{\alpha}_{solar} = \overline{\varepsilon}_{solar} = 0.88[f(\lambda T = 20{,}3200\,\mu m \cdot K) - 0] + 0.24[1 - f(\lambda T = 20{,}300\,\mu m \cdot K)]$$
$$= 0.88(0.9859 - 0) + 0.24(1 - 0.9859) = 0.8710$$

For 800 W/m^2 incoming solar radiation the absorbed radiation is (0.8710)(800 W/m2) = ***696.8 W/m^2***.

b. If the surface is opaque, what happens to the radiation that is not absorbed? It is reflected.

California State University Northridge 4

Midterm Problem One II

c. What is the emissive power of the surface if its temperature is 340 K?

$$\overline{\alpha}_{340\,K} = \overline{\varepsilon}_{340\,K} = 0.88[f(\lambda T = 1{,}190\,\mu m \cdot K) - 0] + 0.24[1 - f(\lambda T = 1{,}190\,\mu m \cdot K)]$$
$$= 0.88(0.00201 - 0) + 0.24(1 - 0.00201) = 0.2413$$

$$E = \overline{\varepsilon}\sigma T^4 = (0.2413)\frac{5.6704x10^{-8}W}{m^2 \cdot K^4}(340K)^4$$ ***E = 182.8 W/m^2***

d. What is the total amount of radiant energy leaving the surface? It is sum of the emissive power, 182.8 W/m^2, plus reflected energy, 800 W/m^2 – 696.8 W/m^2 = 103.2 W/m^2. Total radiant energy leaving the surface is ***286.1 W/m^2***.

California State University Northridge 5

Midterm Problem Two

- **Given:** problem one surface is absorber plate in solar collector at 340 K. Glass plate has T = 320 K and ε = 0.85. h_{gap} = 3.5 W/m^2·K.
- **Find:** heat transfer, per unit areabetween the absorber plate and the lower glass plate?

$$Q_{top} = h_{p-g2}A_c(T_P - T_{g2}) + \frac{A_c\sigma(T_P^4 - T_{g2}^4)}{\frac{1}{\varepsilon_P} + \frac{1}{\varepsilon_{g2}} - 1} \Rightarrow \frac{Q_{top}}{A_c} = \frac{3.5W}{m^2 \cdot K}(340\,K - 320\,K)$$
$$+ \frac{\frac{5.6704x10^{-8}W}{m^2 \cdot K^4}\left[(340\,K)^4 - (320\,K)^4\right]}{\frac{1}{0.2413} + \frac{1}{0.85} - 1} = \boxed{\frac{107.8W}{m^2}}$$

California State University Northridge 6

Midterm Problem Two II

- **Is Q in part a less than, greater, than or equal to Q_{top}?** It is equal
- **Find:** heat transfer coefficient, U_{P-g2}, between the absorber plate and the lower glass plate?

$$U_{P-g2} = \frac{Q_{top}}{A_c(T_P - T_{g2})} = \frac{\frac{Q_{top}}{A_c}}{(T_P - T_{g2})} = \frac{\frac{107.8W}{m^2}}{(340\,K - 320\,K)} = \boxed{\frac{5.39W}{m^2\cdot K}}$$

- **Is U_{P-g2} less than, greater, than or equal to U_{top}?** It is greater; it has the same heat flow, Q_{top}, with a smaller temperature difference

California State University Northridge 7

Midterm Problem Three

- **Given:** solar collector rating sheet.
- **Find:** efficiency for T_{in} = 40°C, I = 800 W/m² and ambient temperature = 20°C

$$\eta = 0.709 - 3.26090\frac{P}{I} - 0.01203\frac{P^2}{I} = 0.709 - 3.26090\frac{20}{800} - 0.01203\frac{20^2}{800} = \boxed{62.1\%}$$

- **Find:** T_{out} for water using test flow rate from sheet and previous data

$$T_{out} = T_{in} + \frac{Q_u}{\dot{m}c_p} = T_{in} + \frac{\eta I A_c}{\dot{m}c_p} = 40^oC + \frac{(62.1\%)\frac{800W}{m^2}(2.411m^2)\frac{1J}{W\cdot s}}{\frac{48mL}{s}\frac{1000kg}{m^3}\frac{m^3}{10^6mL}\frac{4184J}{kg\cdot{}^oC}} = \boxed{46.1^oC}$$

California State University Northridge 8

Midterm Problem Three II

- **Find:** fraction of 90 therms/month from collector for solar radiation = 4 kWh/m²/day for 30-day month with $\tau\alpha/(\tau\alpha)n$ = 0.94, $\overline{T}_a$= 17.8°C, and F'_R/F_R = 0.97.
- F_RU_c = negative slope = 3.975 W/m²·°C and $F_R(\tau\alpha)n$ = intercept = 0.715; 90 therms/mo = (90x10⁵Btu/therm)(1.055 kJ/Btu)(GJ/10⁶ kJ) = 9.495 GJ/mo. H_{total}= (30 days) (4 kWh/m²/day) (0.0036 GJ/kWh) = 0.432 GJ/m²/month. F_RU_c = (3.975 W/m²·°C)(10⁻⁹ GJ/W·s)(3600 s/hr)(24 hr/day)(30 days/mo) = 0.01030 GJ/m²/mo,

California State University Northridge 9

Midterm Problem Three III

$$X = A_c\left[F_RU_c\frac{F'_R}{F_R}\frac{\Delta t}{D}\left(T_{ref} - \overline{T}_a\right)\right] = \left(2.411m^2\right)\left[\frac{0.01030GJ}{m^2\cdot mo}(0.97)\frac{mo}{9.495GJ}\left(100^oC - 17.8^oC\right)\right] = 0.2086$$

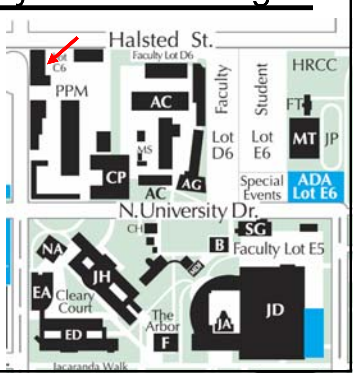
$$Y = A_c\left[F_R(\tau\alpha)_n\frac{F'_R}{F_R}\frac{\overline{\tau\alpha}}{(\tau\alpha)_n}\frac{H_{i,total}}{D}\right] = \left(2.411m^2\right)\left[(0.715)(0.97)(0.94)\frac{\frac{0.432GJ}{m^2\cdot mo}}{\frac{9.495GJ}{mo}}\right] = 0.0715$$

- f = 1.029Y – 0.065X – 0.245Y² + 0.0018X² + 0.0215Y³ = 1.029(0.0715) – 0.065(0.2086) – 0.245(0. 0715)² + 0.0018(0.2086)² + 0.0215(0.0715)³ = ***5.89% of the monthly heating load is supplied by solar***

California State University Northridge 10

Wednesday Class Meeting

- Meet in PPM Conference room
- Entrance from Lot C6
- Near corner of Halsted and Etiwanda



California State University Northridge

Photovoltaics

A. Hunter Fanney

Heat Transfer & Alternative Energy Systems Group

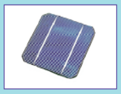
National Institute of Standards and Technology

January 26, 2007

Slides with NIST logo shown here taken from this presentation

NIST

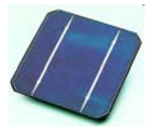
Photovoltaic Terminology



- CELL - basic building block in factory
- MODULE - smallest unit that can do real-world work; building block in the field
- ARRAY - electrically interconnected modules
  - Series Wired to Increase Voltage
  - Parallel Wired to Increase Current

Cells in Modules in Arrays

- Solar cell



- Solar module

- Solar array

California State University Northridge 14

Basic Concepts

- Direct conversion of light energy into electrical current
- Based on adsorption of light photon with energy $E = h\nu = hc/\lambda$
  - Planck's constant: $h = 6.62607 \times 10^{-23}$ J·s
  - Light speed: $c = 299{,}792{,}458$ m/s
  - frequency(s^{-1}) = ν wavelength (m) = λ
- $E = h\nu$ also basis for spectrum of blackbody radiation

California State University Northridge 15

Semiconductors

- Conductors have lots of free electrons to conduct heat and electricity
- Insulators have almost no free electrons
- Pure semiconductors can produce some free electrons leaving electron-deficient atoms known as holes
- Doped semiconductors add materials with different number of valence electrons

California State University Northridge 16

Semiconductors II

- Silicon has 4 electrons in valence band
- Adding phosphorus with 5 electrons in its valance band makes it easier for the doped material to release free electrons
  - This is called an n-type material
- Adding aluminum with 3 electrons in its valance band makes it easier for the doped material to produce holes
  - This is called a p-type material

California State University Northridge 17

Semiconductors III

- Joining n-type and p-type materials results in a pn junction
- Electrons and holes flow across junction to rejoin
- External circuit is more efficient mechanism for electrons to rejoin holes
- Solar cell is pn junction where photons provide energy for electrons to become free electrons

California State University Northridge 18

Semiconductors to Solar Cells

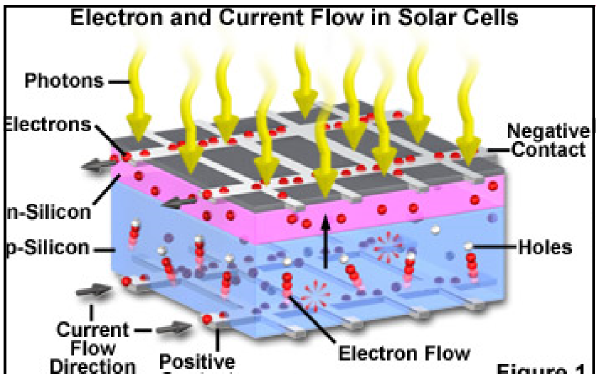
- Physics of solids visualizes valance band where electrons are linked to atom and conduction band for free electrons
- Free electrons have higher energy
- Band gap is energy difference between valance band and conduction band
- Photon from sunlight must have enough energy to move electron from valance to conduction band

California State University Northridge 19

Silicon Band Gap = 1.11 eV

- E = 1.11 eV = hc/λ gives λ = 1.12 μm
- Less energetic photons (λ > 1.12 μm) will not release an electron
- Higher energy photons (λ < 1.12 μm) will release electron and produce heat
- Radiant energy not releasing electron will be reflected or absorbed
- For $\lambda T \leq$ (1.12 μm)(5800 K) = 6578.45 μm·K solar fraction is 77.5% (not all used)

California State University Northridge 20



Link to Demo

California State University Northridge

http://micro.magnet.fsu.edu/primer/java/solarcell/javasolarcellfigure1.jpg 21

Solar Cell Current Density

$$J_L = J_s + J_o - J_o e^{\frac{e_0 V}{kT}}$$

- See Hodge pp 231-232 for derivation
  - Current density $J_L = I_L/A$ delivered to load
  - Internal current densities across p-n junction: p-to-n, J_0, and n-to-p, J_r, net $J_j = J_r - J_o$
  - Cell output current density J_s; $J_L = J_s - J_j$
  - e_0 = electron charge = 1.60218x10^{-19} J/V
  - k = Boltzmann's constant = 1.381x10^{-23} J/K
  - V = cell voltage

California State University Northridge 22

Solar Cell Output

- J_L = 0 gives open circuit voltage

$$J_L = J_s + J_o - J_o e^{\frac{e_0 V}{kT}} = 0 \quad \Rightarrow \quad V_{oc} = \frac{kT}{e_0}\left(\frac{J_s}{J_o} - 1\right)$$

- V = 0 gives short circuit current

$$J_L = J_s + J_o - J_o e^{\frac{e_0 0}{kT}} = J_s + J_o - J_o = J_s$$

$$J_L = J_s + J_o - J_o e^{\frac{e_0 V}{kT}} \quad \Rightarrow \quad \frac{J_L}{J_s} = 1 + \frac{J_o}{J_s} - \frac{J_o}{J_s} e^{\frac{e_0 V}{kT}}$$

California State University Northridge 23

Solar Cell Output II

- For given open circuit voltage, e_0 and temperature, T, find J_0/J_s

$$= \frac{kT}{e_0}\left(\frac{J_s}{J_o} - 1\right) \quad \Rightarrow \quad \frac{J_0}{J_s} = \frac{1}{\frac{e_0 V_{oc}}{kT} + 1}$$

- Use this J_0/J_s to plot J_L/J_s *versus* V

$$\frac{J_L}{J_s} = 1 - \frac{J_o}{J_s}\left[e^{\frac{e_0 V}{kT}} - 1\right] = 1 - \frac{e^{\frac{e_0 V}{kT}} - 1}{\frac{e_0 V_{oc}}{kT} + 1}$$

California State University Northridge 24

Solar Cell Power

- $P = I_L V = J_L AV$

$$P = J_L AV = J_s AV \frac{J_L}{J_s} = J_s AV\left(1 - \frac{e^{\frac{e_0V}{kT}} - 1}{\frac{e_0V_{oc}}{kT} + 1}\right)$$

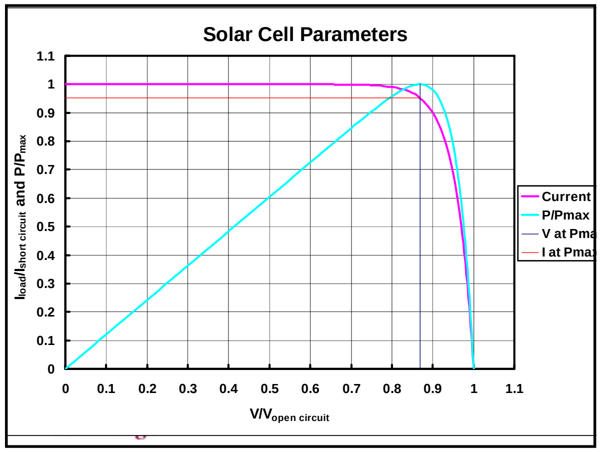
- dP/dV = 0 gives P_{max}

$$\frac{dP}{dV} = J_s A\left(1 - \frac{e^{\frac{e_0V}{kT}} - 1}{e^{\frac{e_0V_{oc}}{kT}} + 1}\right) + J_s AV\left(\frac{\frac{e_0}{kT} e^{\frac{e_0V}{kT}}}{e^{\frac{e_0V_{oc}}{kT}} + 1}\right) = J_s A\left(\frac{e^{\frac{e_0V_{oc}}{kT}} + 1 - e^{\frac{e_0V}{kT}} + 1 + \frac{e_0V}{kT} e^{\frac{e_0V}{kT}}}{e^{\frac{e_0V_{oc}}{kT}} + 1}\right)$$

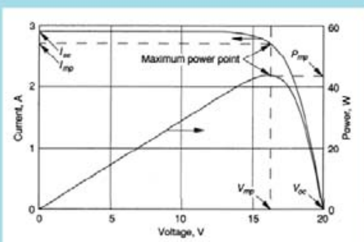
$$\frac{dP}{dV} = 0 \Rightarrow 2 + e^{\frac{e_0V_{oc}}{kT}} + e^{\frac{e_0V_{P\max}}{kT}}\left(\frac{e_0V_{P\max}}{kT} - 1\right) = 0$$

Solve numerically for V_{Pmax} = V at P_{max}

California State University Northridge 25



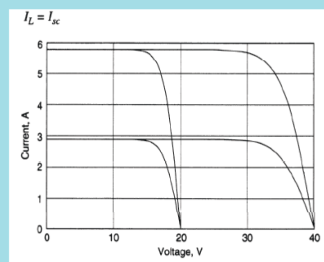
Photovoltaic Terminology



Typical I-V and P-V curves for a PV module

NIST

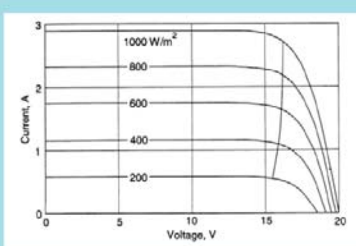
Series and Parallel Connections



IV curves for PV modules connected in various series and parallel arrangements.

NIST

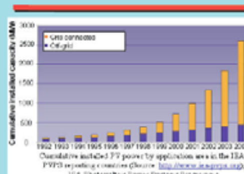
Solar Irradiance Level Versus Output

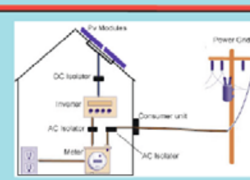


IV curves for a PV MODULE at several radiation levels. The locus of maximum power points is shown.

NIST

Grid Interconnected Systems





NIST

Net Metering State by State

www.dsireusa.org

January 2007

Net metering is available in 40 states + D.C.

- State-wide net metering for all utility types
- State-wide net metering for certain utility types (e.g., IOUs only)
- Net metering offered by one or more individual utilities

#s indicate system size limit (kW); in some cases limits are different for residential and commercial as shown

Conversion Efficiency

$$\eta_c = \frac{\int_o^\tau P_o d\tau}{A\int_o^\tau H_T d\tau}$$

where

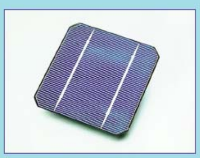
A is a representative area, m^2,

H_T is the incident solar radiation, W/m^2,

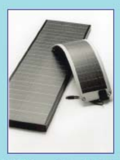
P_o is the panels electrical power output, W

and τ is the time interval selected for monitoring, h.

Photovoltaic Technologies



Conventional - 94% of Market

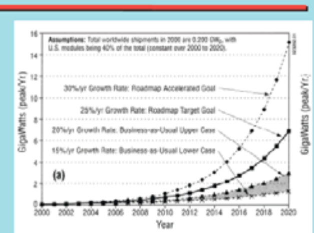


Thin Film – 6% of Market

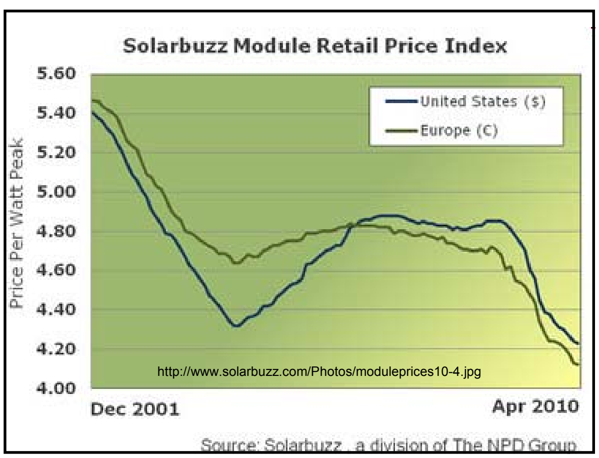
Material	Laboratory Cell Efficiency	Laboratory Module Efficiency
Crystalline Silicon	24.7%	23%
Multi Crystalline Silicon	20.3%	15.3%
CIGS	18.8%	13.4%
CdTe	16.5%	10.7%

The Photovoltaic Industry

- Worldwide PV Shipments
  - 1998 - $1.5 billion
  - 2020 - $27 billion
- Price History
  - 1959 - $1000 per Watt
  - 1973 - $100 per Watt
  - 1980 - $10 per Watt
  - 12/06 - $5.47 per Watt



PV Growth Strategy 2000-2020
PV Technology Roadmap Workshop, 6/99

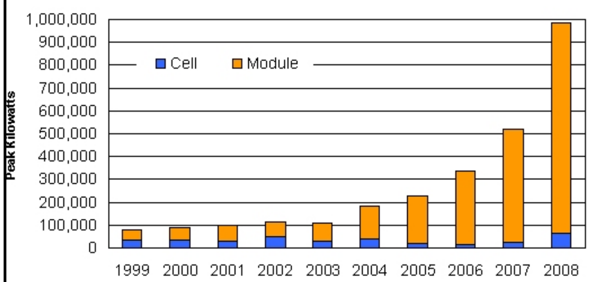


http://www.solarbuzz.com/Photos/moduleprices10-4.jpg

Photovoltaic Industry

- PV Manufacturers and Technologies
  - Single-Crystalline – SolarWorld, Sun Power (Back Contact)
  - Polycrystalline – BP Solar, Sharp, Kyocera Solar, Mitsubishi, GE
  - Polycrystalline String Ribbon – ASE Americas, Evergreen Solar
  - Silicon Film – General Electric
  - Amorphous Silicon – United Solar Ovonic Corporation
  - Cadmium Telluride – First Solar
  - Copper Indium Diselenide/Copper Indium Gallium Diselenide – Wurth Solar, Global Solar, Shell Solar

Photovoltaic Shipments



http://www.eia.doe.gov/cneaf/solar.renewables/page/solarreport/solarpv,html

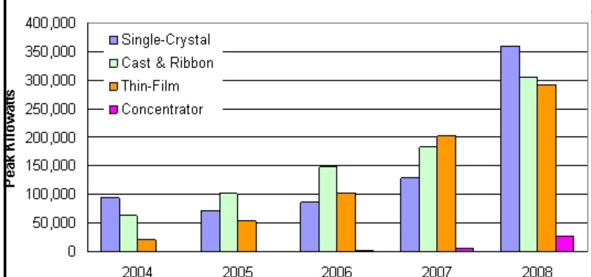
California State University Northridge 37

Module Types

- Crystalline silicon from a wedge of single-crystal or polycrystalline silicon
  - Cast, thin-film, or ribbon
- Thin-film from layers of semiconductor material, such as amorphous silicon (a-Si), cadmium telluride (CdTe), or copper indium gallium selenide (CIGS)
- Concentrator uses lenses that gather and concentrate sunlight onto the cell

California State University Northridge 38

Type of Modules Shipped

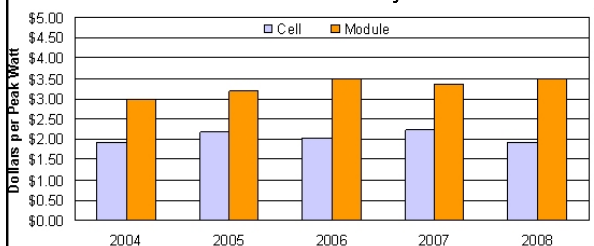


http://www.eia.doe.gov/cneaf/solar.renewables/page/solarreport/solarpv,html

California State University Northridge 39

Cell and Module Costs

- From manufacturers' survey



http://www.eia.doe.gov/cneaf/solar.renewables/page/solarreport/solarpv,html

California State University Northridge 40

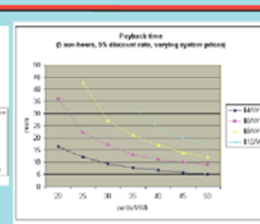
DOE's Solar America Initiative Program Goals

Market Sector	Current Market Price	PV Generated 2005	PV Generated 2010	PV Generated 2015
Residential	5.8 -16.7	23-32	13-18	8-10
Commercial	5.4 – 15.0	16-22	9-12	6-8

Prices are cents per kWh
Current prices based on electric generation with conventional sources
Market goals based on grid-tied sources

NIST National Institute of Standards and Technology

Photovoltaic Economics



PV Incentives
30%Federal Tax Credit
▪Maryland – Lesser of 20% or $3K Grant
▪Germany –Rebate of $0.54 per kWh declining at 5% per year

Example
2000 Watt System in Maryland
2000 watt @ $9/watt = $18,000
Less $5,000 Tax Credit, Less $3,000
Net Cost 10K or $5/watt

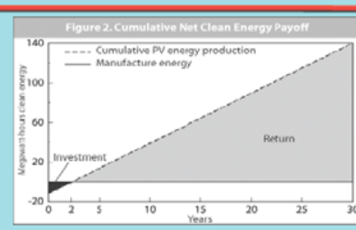
NIST National Institute of Standards and Technology

SF Valley Photovoltaic Costs

- From www.findsolar.com
- Supply 25% of average 860 kWh/mo
- 1.49 kW (peak) – 148 ft^2 area
- Cost $10,416 ($2,531 after incentives)
  - $7000/kW(peak) for entire system
- Savings $22/month, $10,995 for 25 years with 4%/year cost increase
- Return on investment = 9.3% with incentives, –3.24% without incentives

California State University Northridge 43

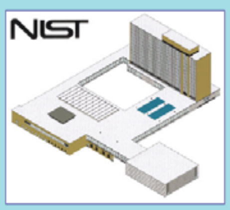
Photovoltaic Energy Payback and Avoided Emissions



- A PV system that meets 50% of average household use would
  - Eliminate 0.5 tons of SO_2 and 0.3 tons of NO_x
  - CO_2 emissions avoided would offset the operation of two cars for 28 years

Source- What is the Energy Payback for PV? DOE's National Center for Photovoltaics

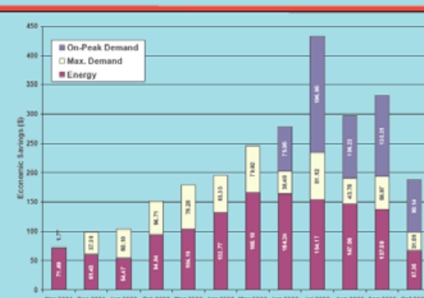
NIST Administration Building's PV System

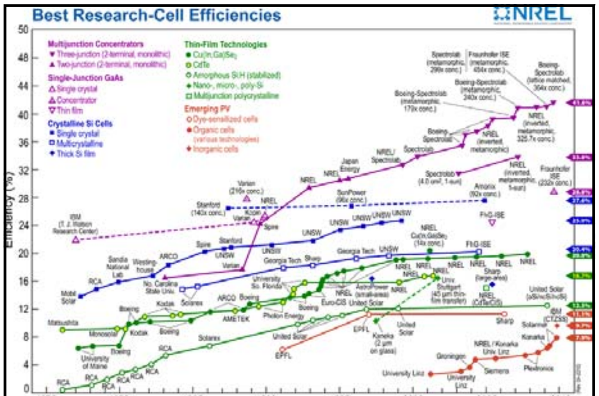


NIST Administration Building's PV System

NIST Administration Building's PV System

NIST Administration Building's PV System





California State University Northridge 49

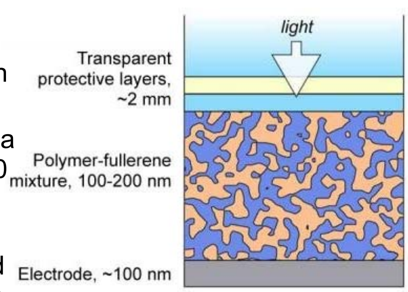
Is Efficiency Important?

- Yes and no
- Solar energy is free
- What is cost per square meter of solar photovoltaic cell?
  - Solar cell costs most expensive
    - Low efficiency, low cost could be better
  - Auxiliary costs for structure
    - High efficiency will always be better here

California State University Northridge 50

Organic Photovoltaic

- η < 6%
- Lower cost than Silicon
- Lifetime a few 1000 hours
- Goals: 10% and 10,000 h



http://www.robaid.com/wp-content/gallery/cache/198__400x300_nist-organic-photovoltaics.jpg

California State University Northridge 51

Solar Conclusions

- Promise of large amounts of pollution-free energy with significant limitations
  - Low energy flux requires large area
  - Costs for current solar materials are not justified by cost savings
  - Solar peak matches electricity demand and thermal storage extends generation time
  - Science of solar energy well understood, but problems with pervious commercial
  - Still need significant cost reductions to make solar PV cost effective

California State University Northridge 52