Overview to Solar PV

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Solar PV Training Session I
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Outline – Week 1

• Review of Solar Energy Potential
• How PVs Work
• Materials New and Old
• Theoretical Limits/Next Generation
  ____Break____
• PV Configurations and Wiring
• PV Toys!
• Conclusions
In 2002 the world burned energy at a rate of \(13.5 \text{ TW/yr}\).

How fast will we burn energy in 2050?

If we use energy like in U.S. we will need \(102 \text{TW}\).

Conservative estimate: \(28-35 \text{TW}\).

How much is 13TW per Year?

- 100 Billion 100W Bulbs Running all Year
- 82,000 Billion Hamburgers = 32 burgers per day per person!
- Drive in car (40mi/gal.) = Driving 1 time around earth per person per year
Where do we use energy:

U.S. Energy Consumption by Sector, 2009

**INDUSTRIAL 30%**
- Top Industrial Sources:
  - Petroleum
  - Natural Gas
  - Electricity*

**COMMERCIAL 19%**
- Top Commercial Sources:
  - Electricity*
  - Natural Gas
  - Petroleum

**TRANSPORTATION 29%**
- Top Transportation Sources:
  - Petroleum
  - Biomass
  - Natural Gas

**RESIDENTIAL 22%**
- Top Residential Sources:
  - Natural Gas
  - Electricity*
  - Petroleum

*Electricity is an energy carrier, not a primary energy source
Note: Figures are rounded.
Data: Energy Information Administration
How does the US use energy?

**Net Primary Resource Consumption ~97 Quads**

- Electrical system energy losses: 26.9
- Electrical power sector: 38.3
- Residential/commercial: 19.8
- Industrial: 19.0
- Transportation: 26.2
- Lost energy: 36.2

**Sources:**
- Production and end-use data from Energy Information Administration, Annual Energy Review 2002.
- Net fossil fuel electric imports.
- *Renewable includes wind, wave, solar, geothermal, biofuels, and fuel.

Motivation for Clean Renewable Energy

**Climate Change Predictions**

- A2: High growth
- A1B: Moderate growth
- B1: Low growth

IPCC 4th Assessment Report, plot from NASA
Potential of Alternative Energy Sources

Practical potential (10% eff., 1.5% of Land)

Photovoltaics

- 13TW – Worldwide Consumption, 3TW - US consumption
- 120,000 TW provided by the sun
- 300 x 300 km² at 10% = 3TW <2% of land mass

N. Lewis "Powering the Planet" (MRS Bulletin 32, 2007)
There are several Major Reasons

• It costs too much. And it requires a lot of area (even though it is a small fraction)

• Our Electrical grid can only handle ~20% input from intermittent sources

• There is no Sun at night → so we need BIG batteries

There are several Major Reasons

• It costs too much. And it requires a lot of area (even though it is a small fraction)

• Our Electrical grid can only handle ~20% input from intermittent sources

• They can be unsightly
Flavors Of Solar Energy Generation

Solar Electrical – PV

Solar Thermal - Heating

Solar Thermal - Geometric Collector
Steam Turbine Electricity

\[ \eta_P < \eta_{\text{abs}} \eta_{\text{Carnot}} \quad \eta_{\text{Carnot}} < 1 - \frac{T_C}{T_H} \]

Luminescent Solar Concentrator

Cost

Electricity Production Costs in U.S.

- LEC Low
- LEC High

US Average 2010: 5¢/kW-hr
20% Most Expensive 2010: 12¢/kW-hr

Present AVERAGE Cost of Deploying Solar Energy is 20¢ to 40¢/kWh

TODAY SOLAR CAN COMPETE IN SOME OF THESE ELECTRICITY MARKETS (without additional government incentives)

Aim to capture 10% of electrical generation with Solar PVs

US Average 2010: 5¢/kW-hr
20% Most Expensive 2010: 12¢/kW-hr
Cost

Figure 1. Cost Breakdown of Conventional U.S. PV Systems ca. 2010

DOE, $1/Watt White Paper

Costs (Cont.)

DOE Targets

DOE, $1/Watt White Paper
Costs (Cont.)

Solar PV Experience Curves:
Leading Technologies: Crystalline Silicon (c-Si), Cadmium Telluride (CdTe)
Source: (CdTe) First Solar Earnings Presentation, SEC filings; (c-Si) Navigant, Bloomberg NEF, NREL internal cost models

DOE Targets

Practical lower cost limits: materials, efficiencies

DOE, $1/Watt White Paper

Costs (Cont.)

c-Si Module Manufacturing Costs:
Technical (Cost) Improvement Opportunities

DOE, $1/Watt White Paper
What happens if we get to $1/W Equivalent?

Locations (by State) where Solar PV become price competitive

DOE White Paper: “$1/W Photovoltaic Systems”

Efficiency Comparison

Long list of Manufacturers:
Approaching Shockley-Quiesser

GaAs $\rightarrow$ 85% of SQ, Si $\rightarrow$ 75% of SQ

Which is more widespread? Depends on Application

Figures of Merit:
- kW/m$^2$
- $$/kW-hr
- kW/kg
- kW-hr$/kg$

Cost of Si

- High Temperature Processing: 1687K-2000K
- $1/g \rightarrow$ $20/m^2$ (Raw Material Cost), $200-400/m^2$ (full device)
- Ultra High Purity Needed

$$\alpha = 10^2 \text{ cm}^{-1}$$
Cost of Organic Materials

- Abundant: ~100,000 tons of CuPc/year
- Low materials costs: ~$1/gm → 17¢/m², $20-100/m² (full device)
- Low Temperature Processing RT-500K

\[ \alpha = 10^5 \text{ cm}^{-1} \]

This is where Chemical Engineers Come in!

Operating Principles
Solar Flux

Absorption Spectra of PV Materials
Processes in PV

\[ \eta = \eta_A \eta_{DS} \eta_{CC} \]

Processes in Bilayer PV

\[ \eta = \eta_A \eta_{ED} \eta_{CT} \eta_{DS} \eta_{CC} \]
Processes in Organic Bilayer PV

Current-Voltage Simplified Equation

\[ J = \frac{I_{ph}}{A_{area}} = \left( \frac{R_s}{R_s + R_p} \right) J_0 \left[ \exp \left( \frac{qV}{nkT} \right) - 1 \right] - J_{sc} \]

Ideal Diode

Power = VI
Max Power = \( V_{oc} \cdot I_{sc} \cdot FF \)
Third Generation Concepts

• Primary Losses of Efficiency for Single-Junction
  1) Incomplete Absorption,
  2) Thermal Relaxation (Heating),
  3) Carrier Recombination,
  4) $V_{OC}$ must be $< E_G$,
  5) Shape of Photocurrent curve

Henry, C. JAP 51, 4494, 1980

Third Generation Concepts

• Concepts to go beyond Single Junction Limits
  – Primarily to reduce thermal, voltage, or abs. losses:
    (Hot-carrier, Concentrator, Singlet Fiss., MEG, Tandem)
    Up-Converter

Henry, C. JAP 51, 4494, 1980
A Taste of The Research That We Do Here at MSU

- Windows – 55-80% Transmission
- Sig. surface area with glass surfaces
- Glass $\rightarrow$ 1/3 Module Cost
- Infrastructure – 1/2-2/3 BOS Cost

Is there a way to do this with inorg. SC?

Can Do it with Molecules $\rightarrow$ Excitons!
Absorb NIR, Transmit VIS

Need OPV with abs. peak outside VIS
### Transparent Solar Cells

- 2/3 Solar Flux in NIR/IR → Single Junction Limit (20%), 10-cell Tandem (33%)
- Use Excitonic Materials to optimize Transparency and Efficiency

### Practical Demonstration

**Single Devices:**

**Large-Area Integration:**

**Monolithic Series Integration:**

Lets Talk PV Practicals!

PV Configuration

Off-Grid DC system (with/without inverter):

Grid-tied with battery backup system.

PVinsights.com
Panel Assemblies

- How much voltage do we get in each cell, panel?
- Why are they wired up this way?
Which way does the Current Flow?

Solar Charger
Solar Charger

Why Do we Use Two Batteries in Series?!

Can we do this?!
Solar Charger

It depends on the Sun Intensity!

Can we do this?! Yes, Sometimes.

Solar Charger

Charging Battery
Solar Charger

Charging iPod

Battery Acts as Buffer!
We use it for Temporary Storage
If there is not a lot of light, we will not charge battery!

We will DISCHARGE BATTERY!

Diode acts a one-way valve for the Current Flow
How Long will it Take to Charge?

What will it depend on?
1) Area of Solar Cell
2) Amount of Sunlight
3) Solar Cell Efficiency
4) Solar Cell Orientation

Let's do a calculation

Determine Local Solar Insolation

NREL, PVWatts v1
Units for Solar Calculation!

\[ W = \frac{J}{s} \quad \text{Watts} = \text{Energy Flux} \]

\[ kW \cdot hr = 3.6 \times 10^6 J \quad \text{Used in electricity billing!} \]

\[ \frac{kW \cdot hr}{m^2 \text{day}} = 41 \frac{W}{m^2} \quad \text{Solar Insolation Units} \]

Sun Intensity at High Noon average for US (titled at 37° tilt):

\[ 1Sun = 1000 \frac{W}{m^2} \]

Average over year in Lansing (including night) for flat panel:

\[ 3.83 \frac{kW \cdot hr}{m^2 \text{day}} = 160 \frac{W}{m^2} \]

Max flux higher! (~760W/m²)

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Ideal Diode

To get here: we need a load:

\[ R_{LOAD-MP} = \frac{V_{MP}}{I_{MP}} = \frac{V_{OC}}{I_{SC}} \]

\[ \text{Power} = VI \]

\[ \text{Max Power} = V_{OC}I_{SC}FF \]
PV Configurations

Series Connection:
\[ V = V_A + V_B \]
\[ I = I_A = I_B \]

Parallel Connection:
\[ V = V_A = V_B \]
\[ I = I_A + I_B \]

Combination:

Maximum Power Point Tracking

Current-Voltage Characteristics are Dependent on Light Intensity

Current-Voltage changes, changes Maximum Power Point

Added electronics to get most power out of Solar Cells – Add Cost
Finger Spacing – Collecting Charges

Degradation and Failure

Solar Cell Degradation (Corrosion, H2O, O2)
Short-Circuited Cells
Open-Circuited Cells
Module Glass Breakage
Module Delamination
Hot-Spot Failures
By-Pass Diode Failure
Encapsulant Failure
There is enough solar energy to power USA, and entire World!

To do this we need:
- Better Grid
- Better Energy Storage
- Cheaper Solar Cells
  - Inexpensive materials and processing
  - Lightweight

We Learned about practical aspects
- Types of Solar Energy
- Factors impacting efficiency, cost
- Configuration/Wiring
- Calculate charging time