# Photovoltaics

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Heat Transfer & Alternative Energy Systems Group

National Institute of Standards and Technology

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# PV Team

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- David Allen – NIST Physics Lab
- Kang Chua – Physical Optics Corporation (SBIR)
- David King SNL/Daryl Meyers NREL

# Overview

- Photovoltaics 101
- Photovoltaic Industry
- Building Integrated Photovoltaics
- BFRL's PV Program
- Facility Tours

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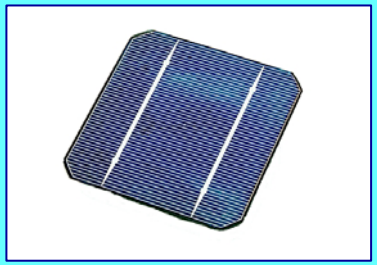
# Photovoltaic Terminology



- 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

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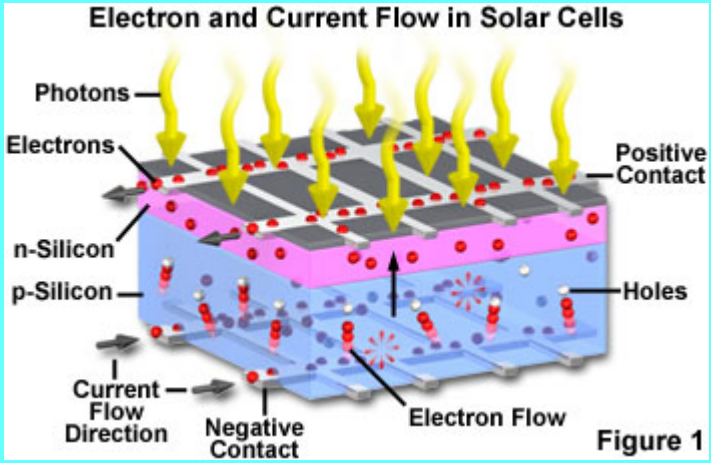
# PV Cells – How They Work

- Silicon absorbs photons from solar radiation
- If photon energy is great enough, an electron from the outer electron shell is freed
- Results in -
  - Hole – lack of an electron
  - Excess electron in crystal structure
  - Without a barrier, the excess electron would rapidly fill the hole
- A barrier is introduced inhibiting the free migration of electrons resulting in n layers and p layers
  - Buildup of electrons in n-layer
  - Deficiency of electrons in p-layer
- By connecting n and p layers through electrical circuit, current will flow

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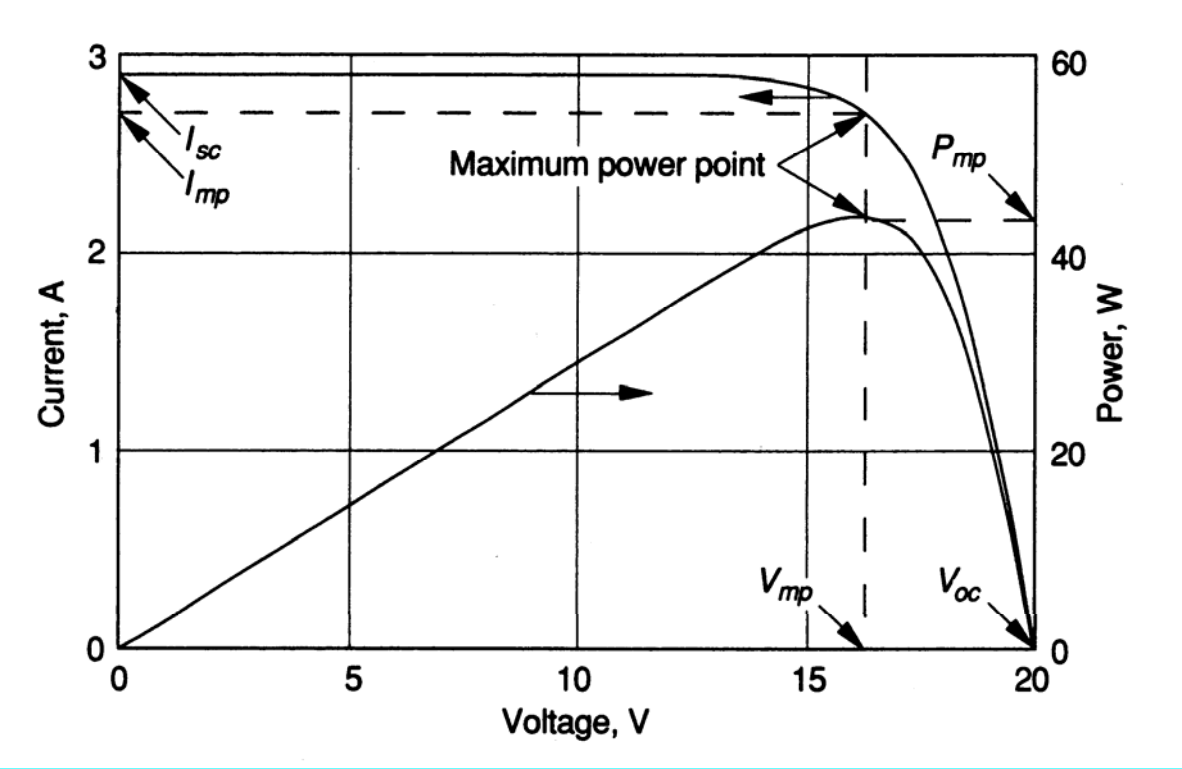
# Photovoltaic Terminology



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

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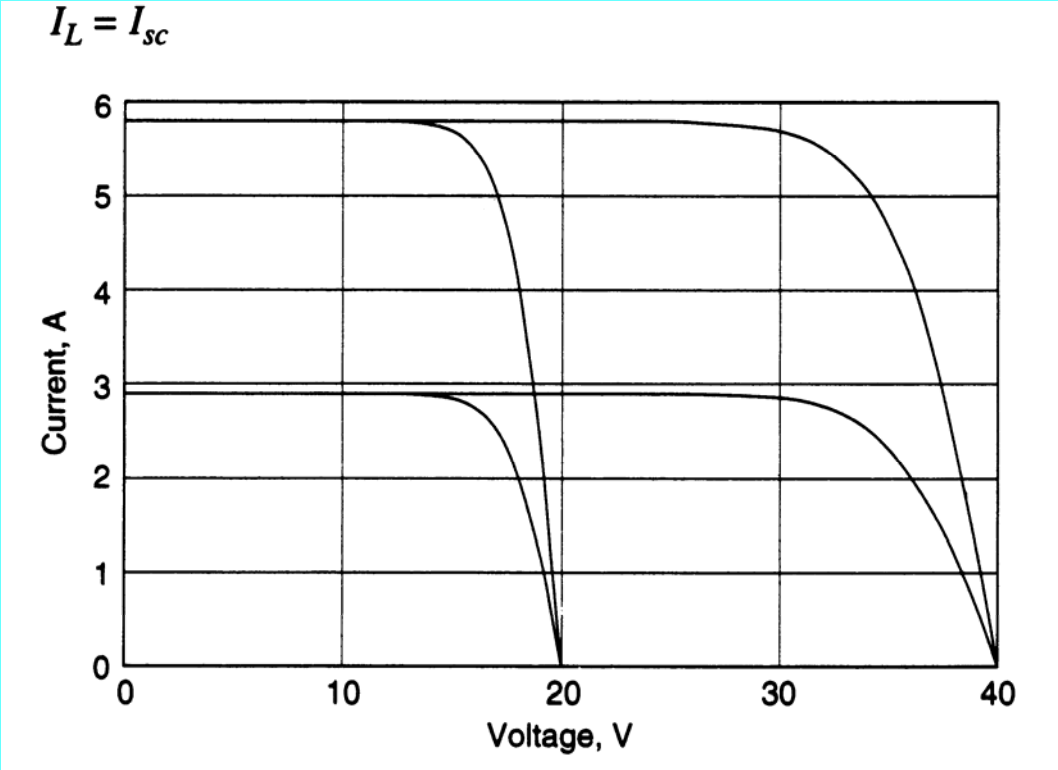
# Series and Parallel Connections




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

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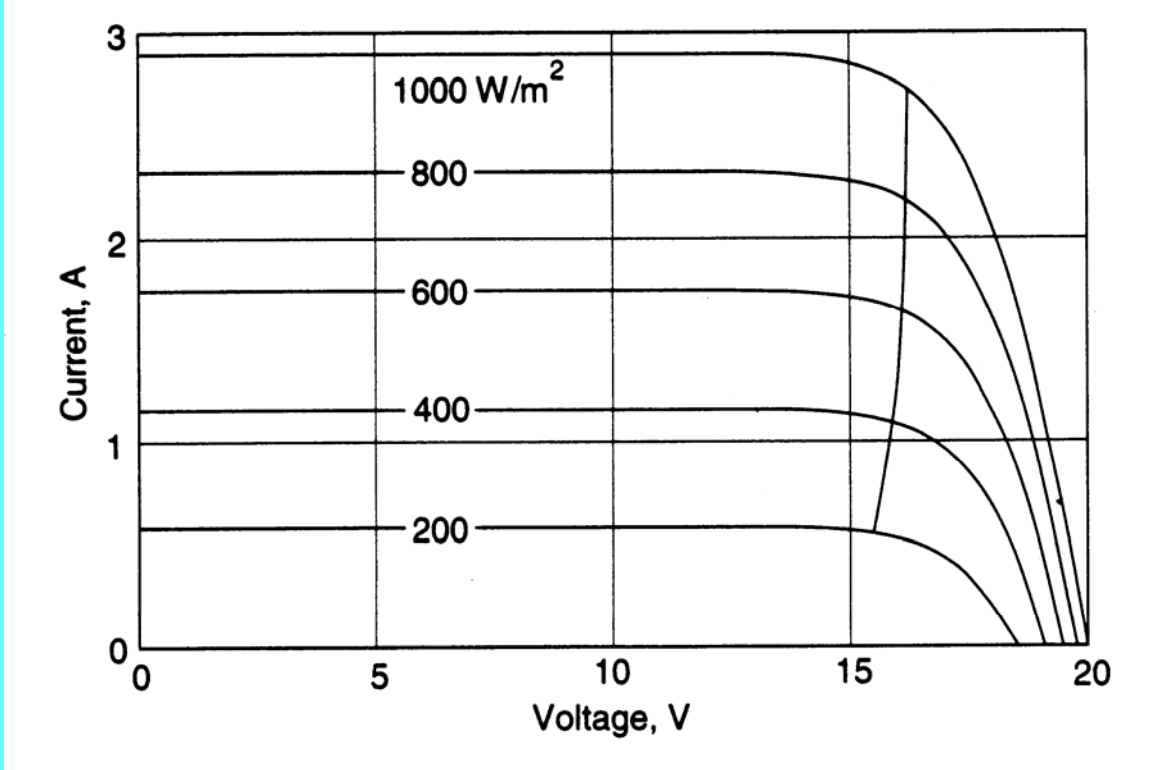
# Solar Irradiance Level Versus Output




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

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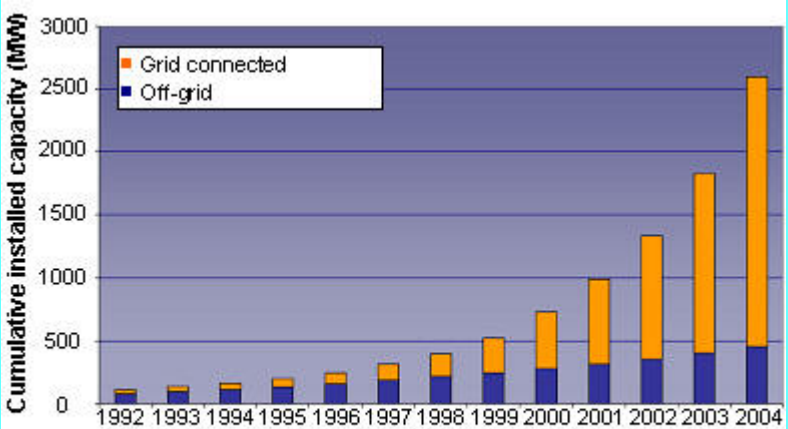
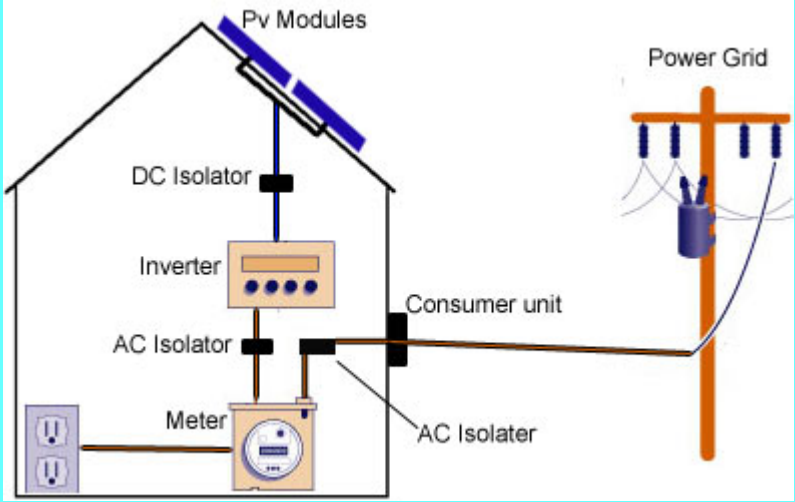
# Grid Interconnected Systems




Cumulative installed PV power by application area in the IEA-PVPS reporting countries (Source: http://www.iea-pvps.org), IEA Photovoltaic Power Systems Programme



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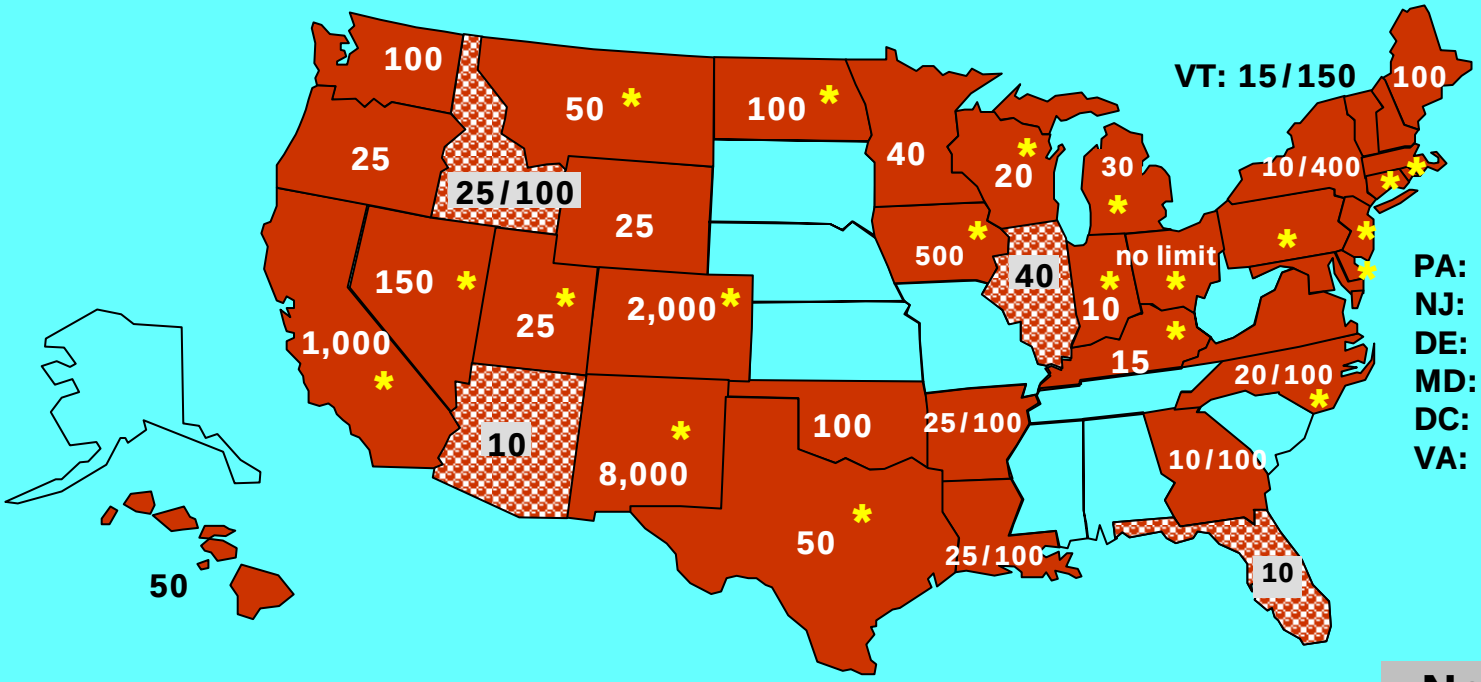
# Net Metering State by State

www.dsireusa.org

January 2007




NH: 25
MA: 60
RI: 25 *
CT: 100

PA: 50/1,000/2,000
NJ: 2,000
DE: 25
MD: 500
DC: 100
VA: 10/500

**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

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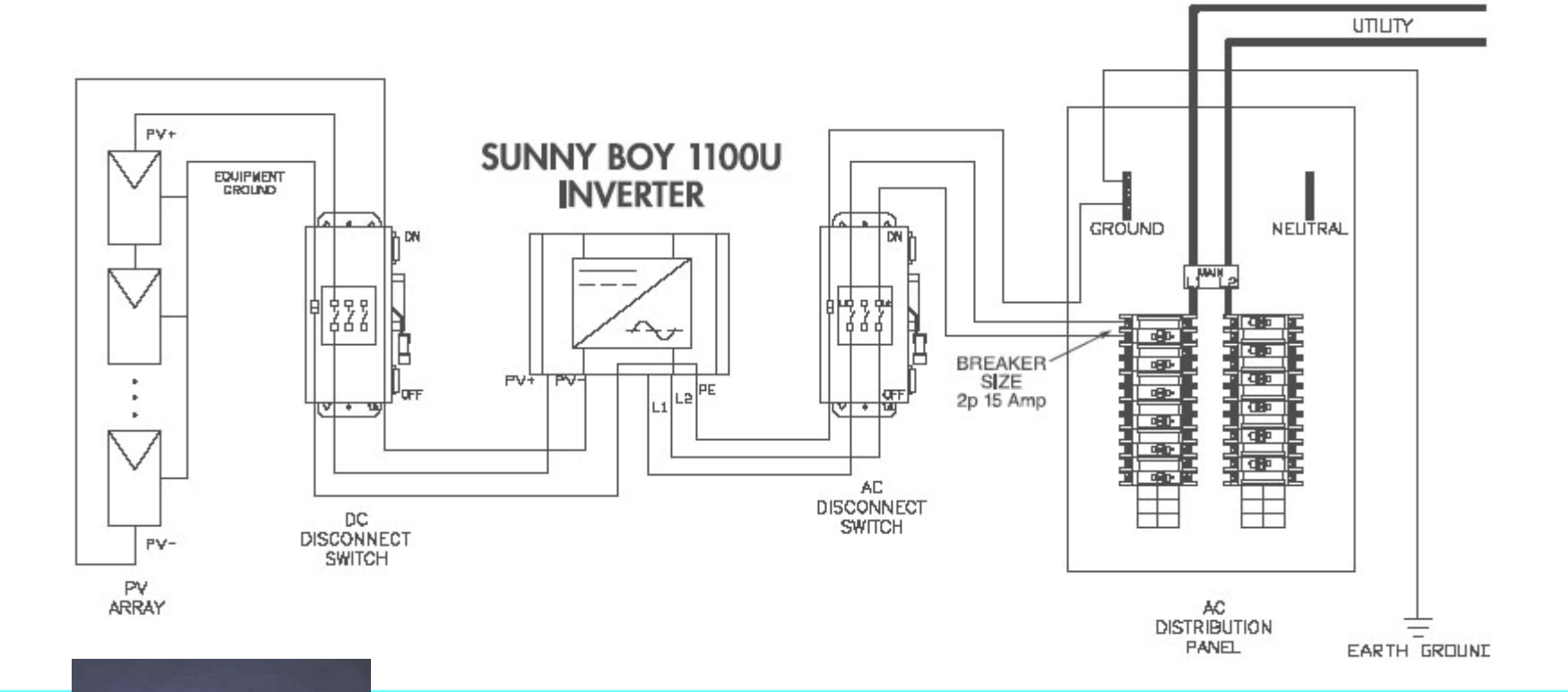
# Grid-Connected PV Wiring Schematic



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# 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 $\tau$ is the time interval selected for monitoring, h.

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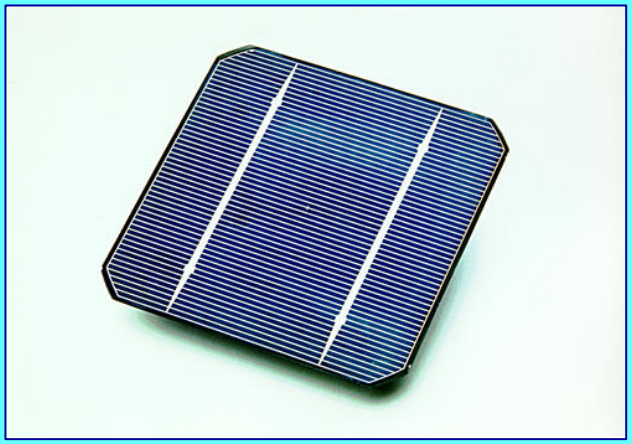
# Photovoltaic Technologies



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% |

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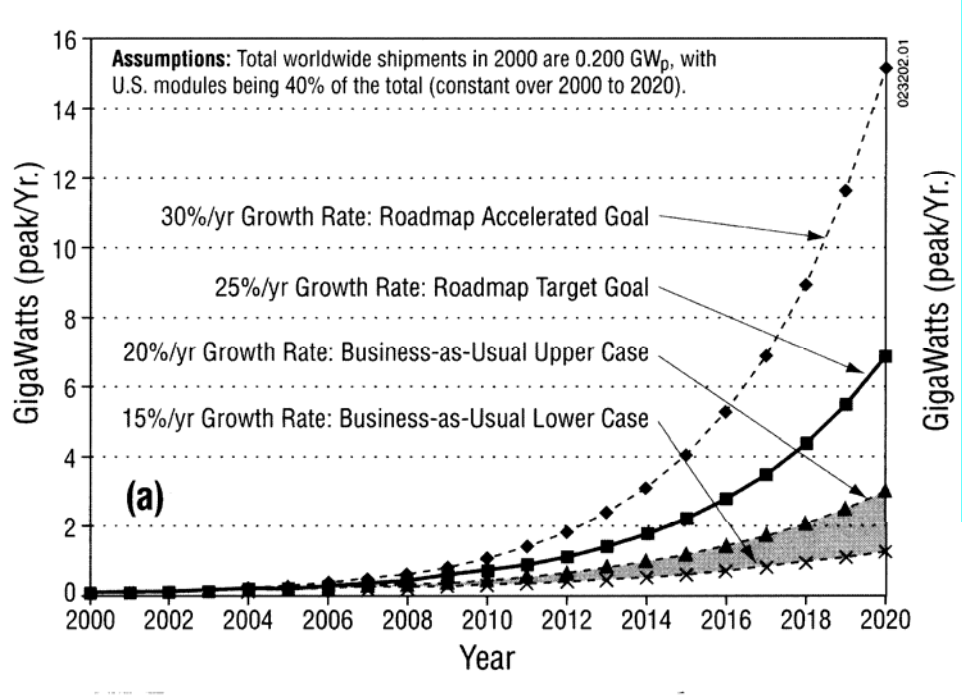
# The Photovoltaic Industry

- 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

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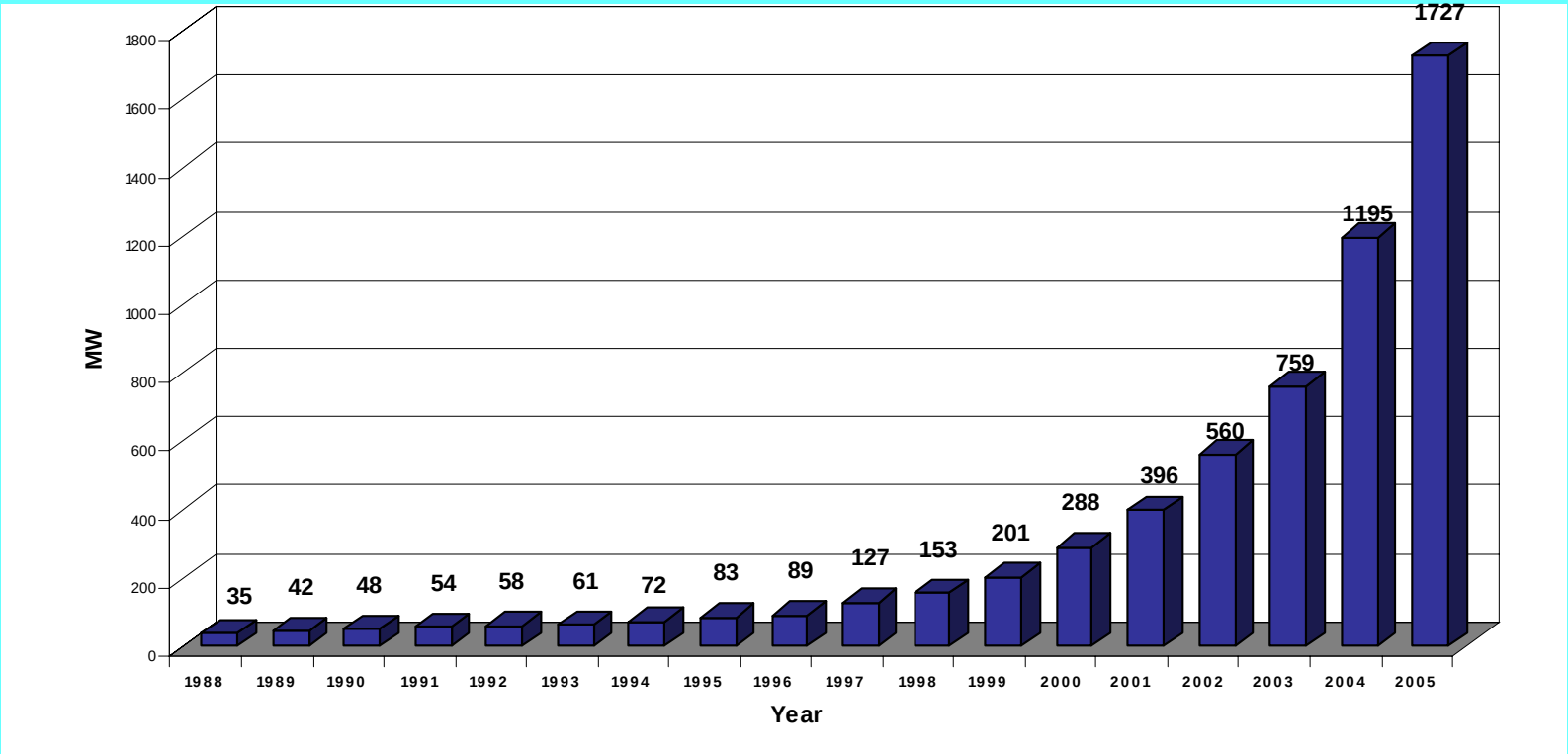
# Photovoltaic Industry

- 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

# Worldwide PV Module Manufacturing Activity




Sources - Photovoltaic News, March 2006

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# 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

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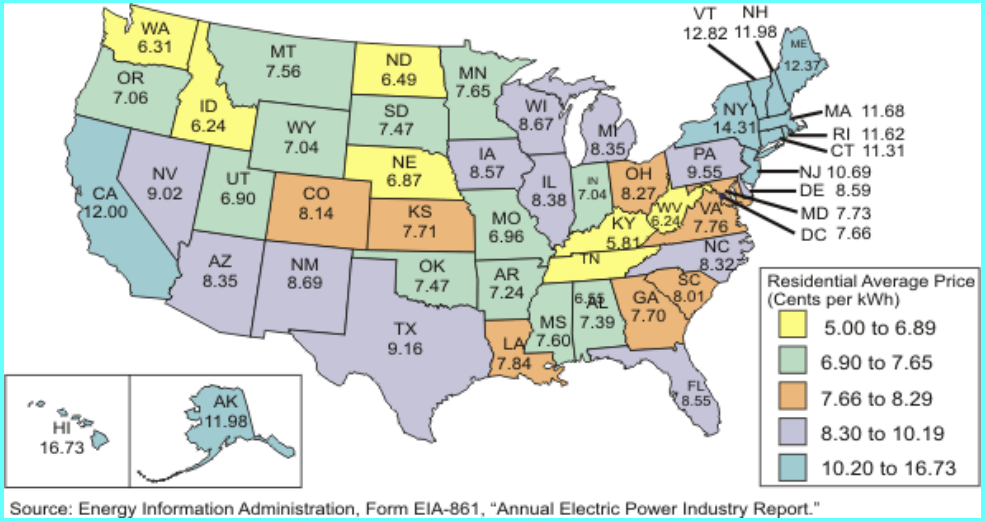
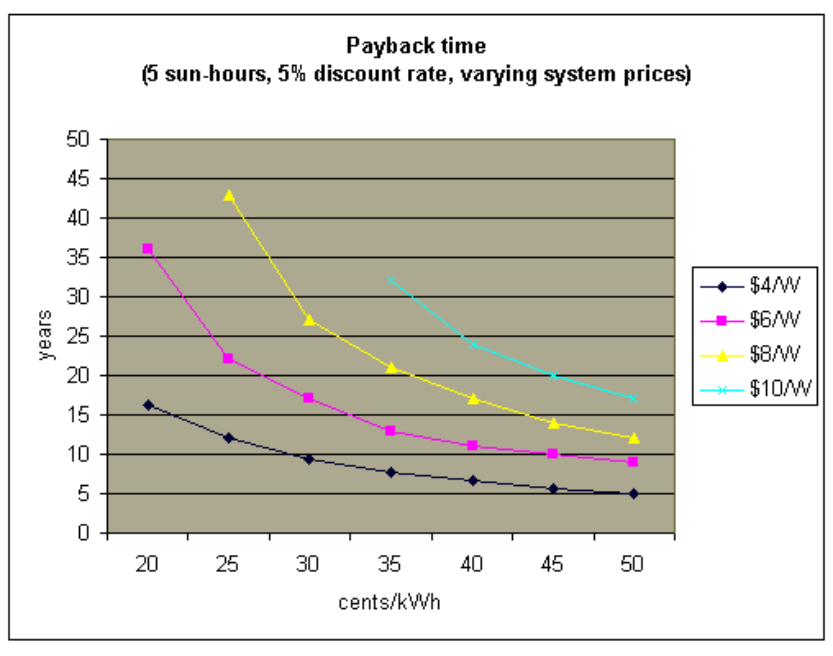
# Photovoltaic Economics




***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

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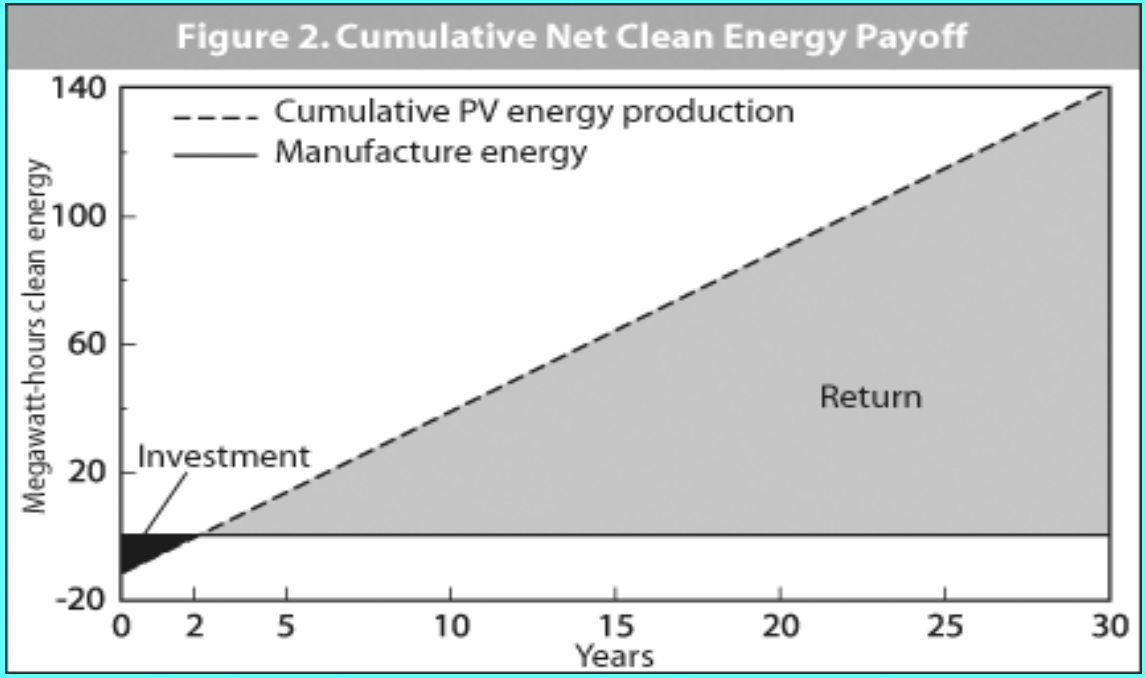
# Photovoltaic Energy Payback and Avoided Emissions




- 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

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# Building Integrated Photovoltaics

- Architectural Integration
  - Roofing Materials
  - Wall Components
  - Glazing
- System Integration
  - PV System and Building's Electrical Systems
  - PV System and Utility Grid

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# Benefits of Photovoltaics at Building Site

- May Be Integrated into Building
  - Architecturally Clean
  - Offsets Cost of Façade/Roofing/Glazing Materials
- Eliminates Central Power Plant to Building Electrical Distribution Losses
- Reduces Energy Consumption/Peak Load Requirements
- Provides Premium Power
  - Sensitive Manufacturing Processes
  - Building Emergency Services

# Building Integrated Photovoltaics

4 Times Square

First Major Office Building to be constructed in NYC since 1990's.

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# Building Integrated Photovoltaics

Standing-Seam Roofing

NAHB Solar Townhouse, Bowie, MD

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# Building Integrated Photovoltaics

PV Shingles

Integrated PV Into Grid Connected Building

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# Barriers to Widespread Adoption of PV

- Life Cycle Cost
- Lack of Standardized Grid Interconnection Protocols
- Uniform Net Metering Rules/Regulations
- Lack of Performance Data
- Lack of Predictive Performance Tools
- Uncertainty in Module Performance Ratings
- Balance of System Components' Reliability
- Lack of Qualified System Designers/Installers

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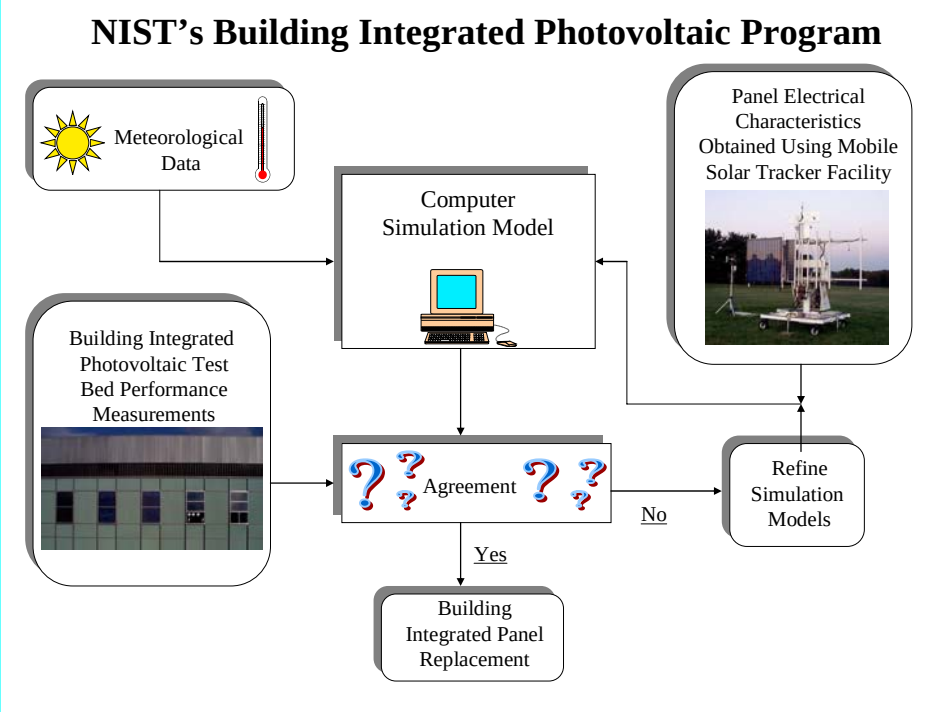
# BFRL's PV Program

- How Do Different PV Technologies Compare Under "Real World Conditions"?
  Lack of Performance Data
  - Solution - Provide "In-Situ" Performance Data
    - Commercial Building Wall and Roof Applications
    - Residential Roofing Applications
    - NIST's 35 kW Grid-Connected PV System
- How Much Energy Can I Produce ?
  Lack of Validated Tools to Predict PV System Energy Production
  - Solution - Improve/Validate Performance Prediction Models
    - Partners: David King - Sandia National Laboratories, Mike Pelosi –Maui Software
- Am I Receiving What I Paid for?
  Uncertainty in Module Performance Ratings
  - Solution - Stimulate Development of Innovative LED Simulator
    - Partners: David Allen – Physics Laboratory, Kang-Bin Chua – Physical Optics Corporation
  - Solution - Reduce PV Module Power Rating Uncertainty Associated with Conventional Flash Simulator
    - Partners: Howard Yoon – Physics Laboratory

# Performance Data/Predictive Performance Tools

- Characterize Photovoltaic Panels
  - Temperature Coefficients
  - Incident Angle Response
  - Air Mass (Solar Spectrum) Response
  - Performance at Rating Conditions
- Measure Photovoltaic Panel Performance
  - Vertical Façade
  - Residential Roofing
  - Commercial Roofing
  - 5 Minute Data Collection Internal
- Measure Meteorological Conditions
  - Vertical Irradiance
  - Horizontal Irradiance
- Run Simulation Model
- Compare Predicted to Measured Results

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# PV Panel Characterization -NIST Solar Tracker

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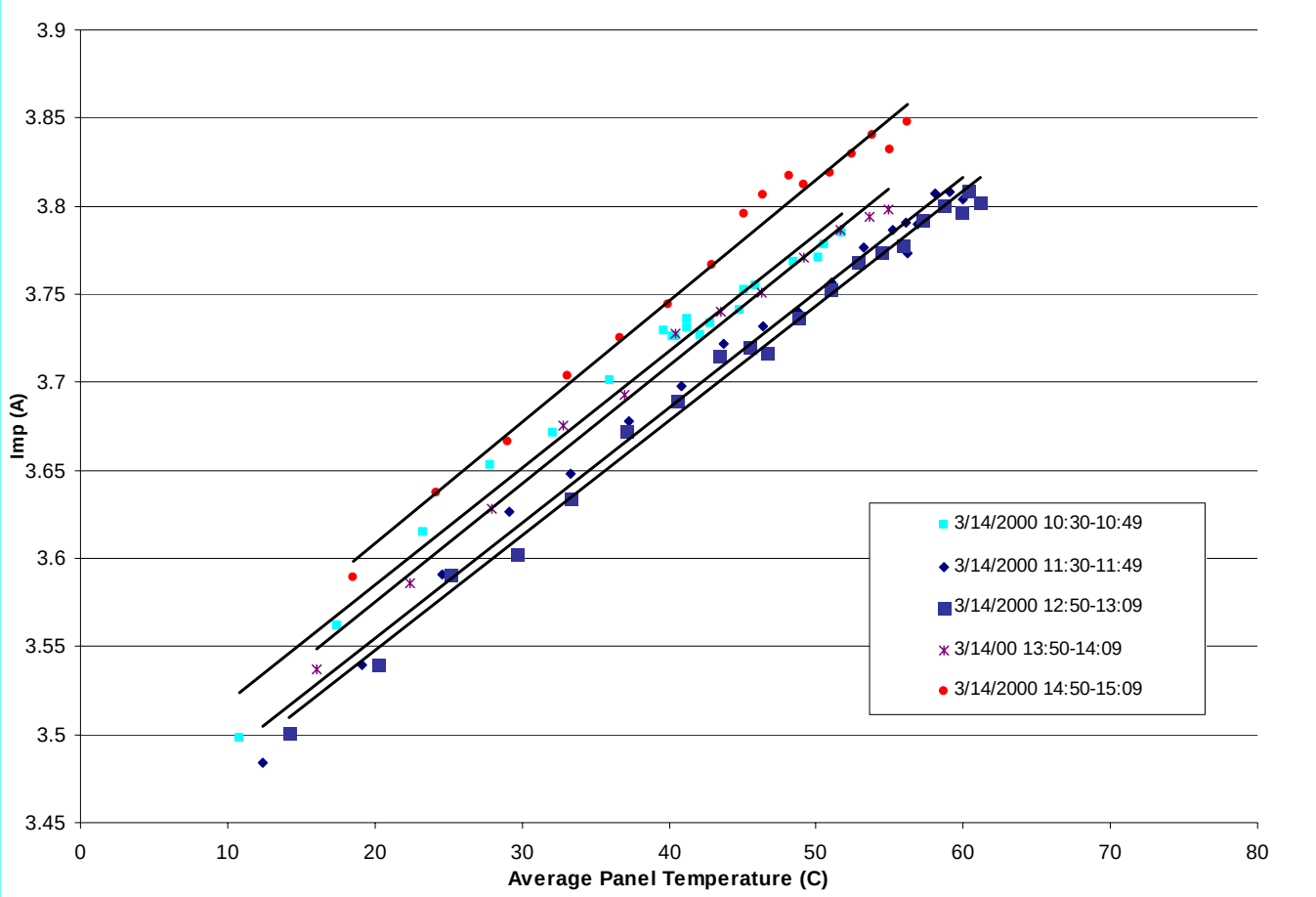
# Maximum Power Current vs Temperature

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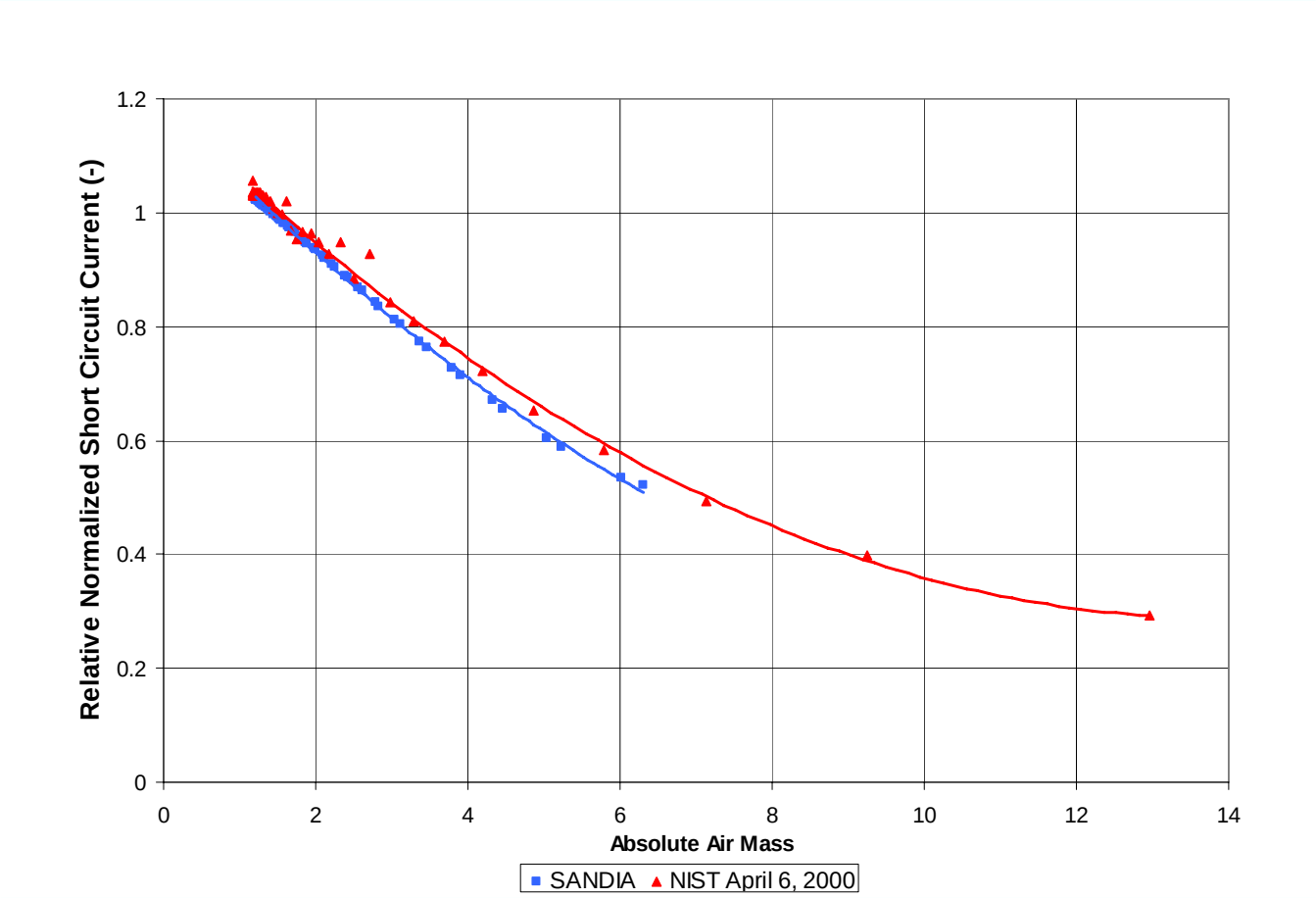
# Short Circuit Current vs Air Mass
# Clear Sky Only

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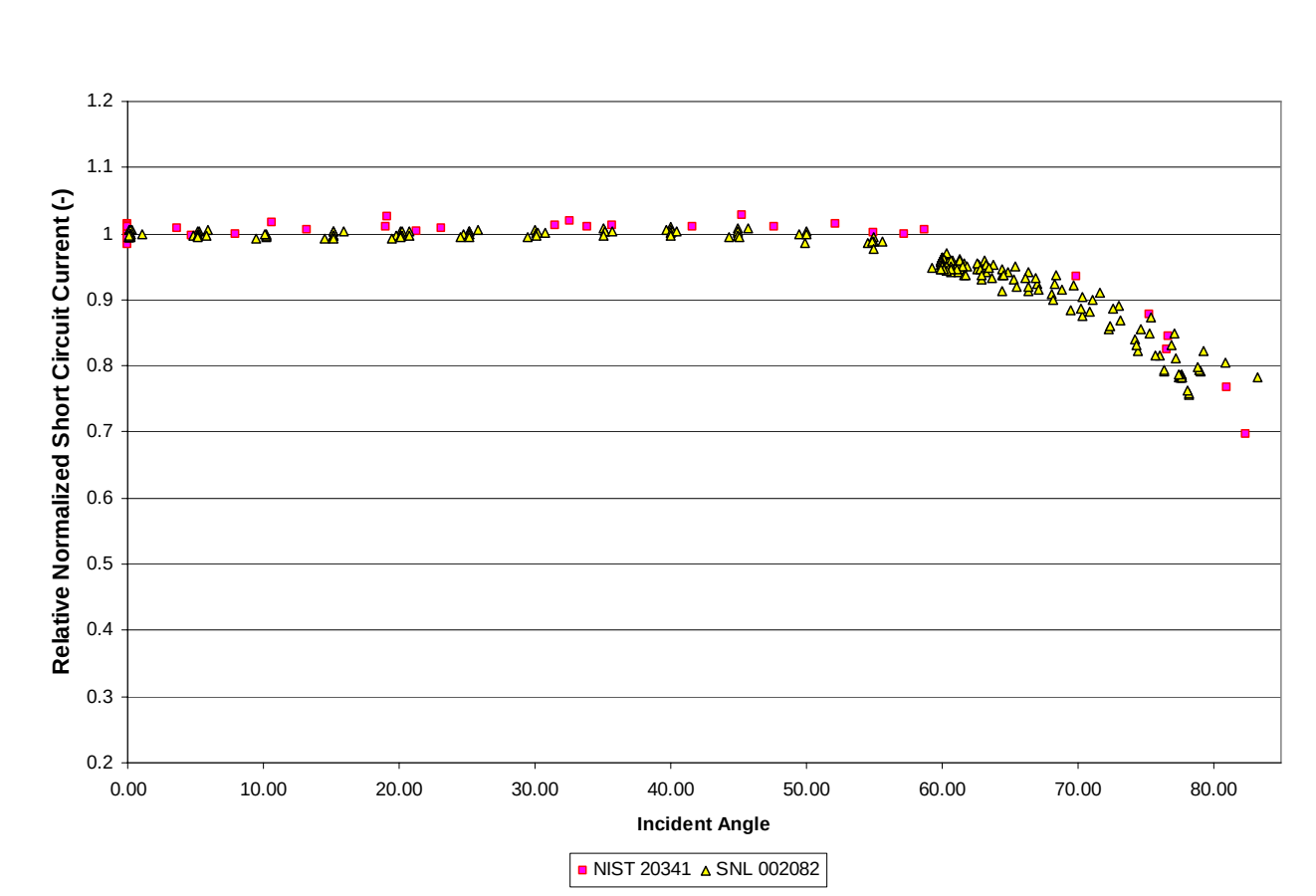
# Incident Angle Function

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# Vertical Wall Test Facility Test Configuration – 2004

- Vertical South-Facing Façade BIPV Installation
  - Gaithersburg, MD (Latitude 39.1, Longitude 77.2)

- 12 Month Comparison
  - January 1 - December 31, 2004
  - 5 Minute  Data Collection Interval

- Various Cell Technologies and Glazings
  - Monocrystalline with Glass
  - Polycrystalline with
    - Glass
    - Tefzel
    - Kynar
  - Tandem Junction with Glass
    - With Extruded Polystyrene Rear Insulation (3.5 $m^2 \cdot K/W$)
    - Without Insulation
  - Copper Indium Diselenide
    - With Extruded Polystyrene Rear Insulation (3.5 $m^2 \cdot K/W$)
    - Without Insulation

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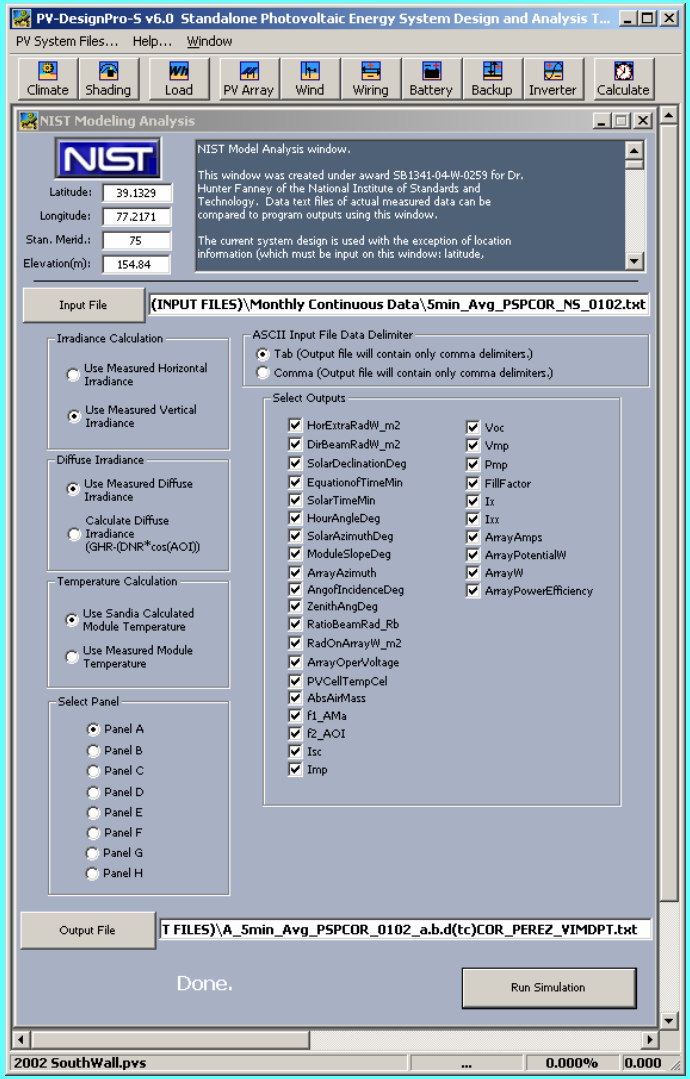
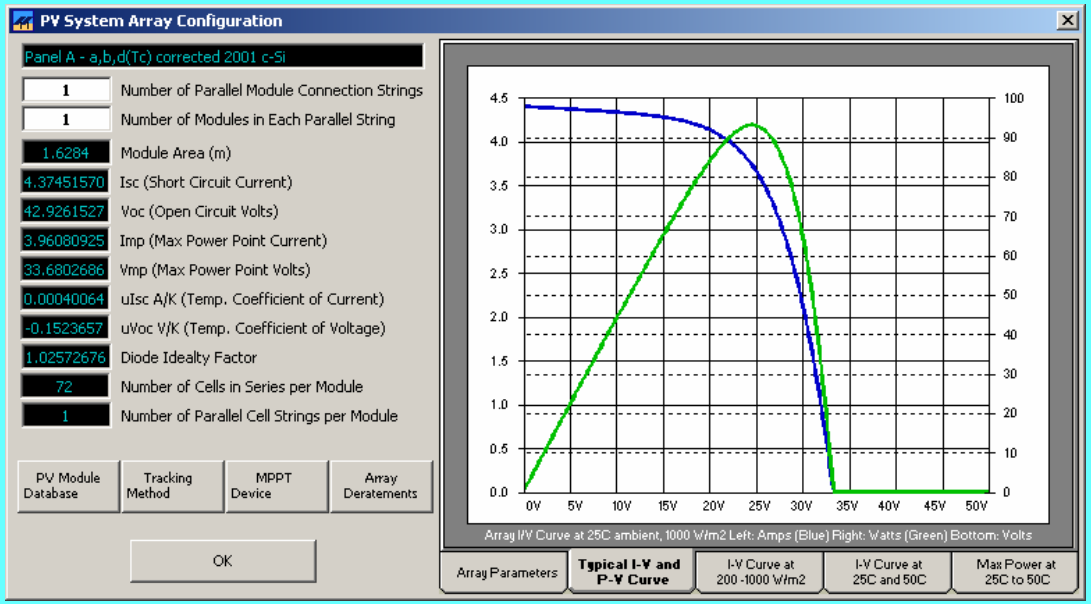
# PV Design Pro Simulation Tool
# Sandia National Laboratories/Maui Software/NIST

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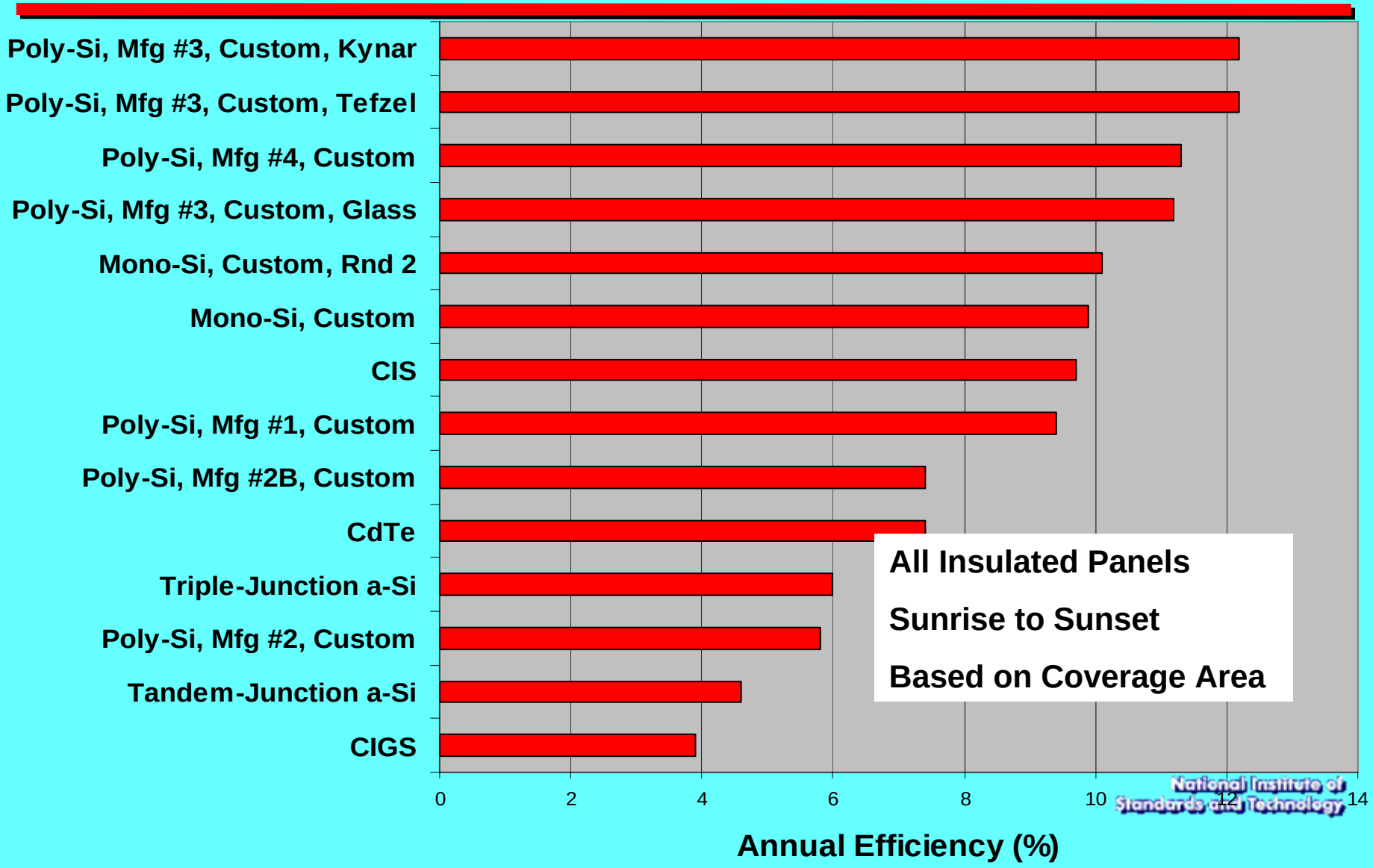
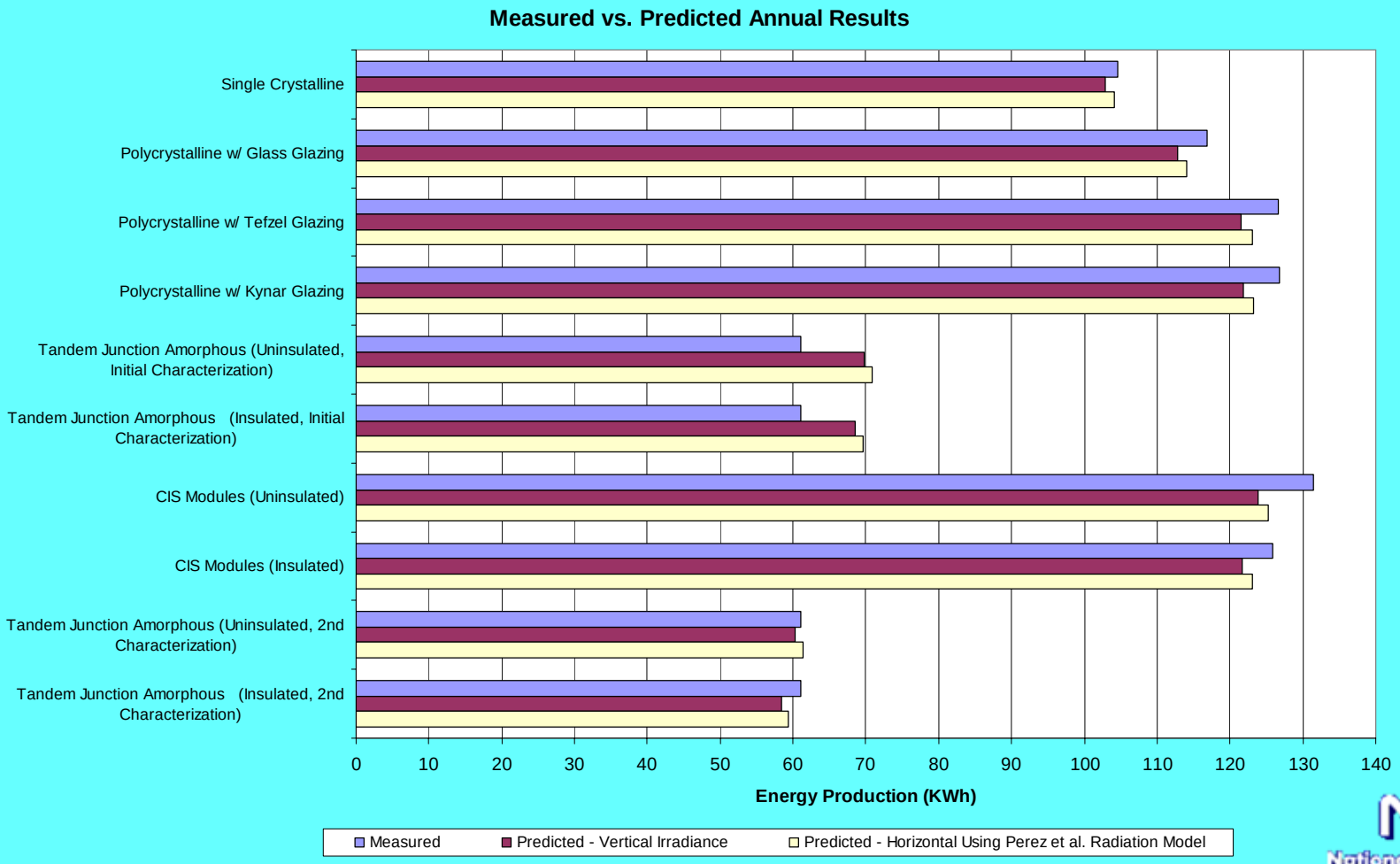
# Annual Efficiencies – NIST Vertical Wall Test Facility



# Annual Energy Production – Measured and Predicted

# NIST's Vertical Wall Test Facility

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# Photovoltaic Roofing Test Facility

*Residential Roof Test Facility*

*Commercial Roof Test Facility*

Residential Roofing PV Products (Tiles, Slates, Shingles)

- Poly crystalline
- Mono crystalline
- Mono crystalline with Back Contacts
- Triple-Junction Amorphous Silicon - Tefzel

Commercial Roof PV Products

- Mono crystalline with Back Contacts –Tefzel
- Mono crystalline with Thin Amorphous Layers
- Triple-Junction Amorphous Silicon - Tefzel

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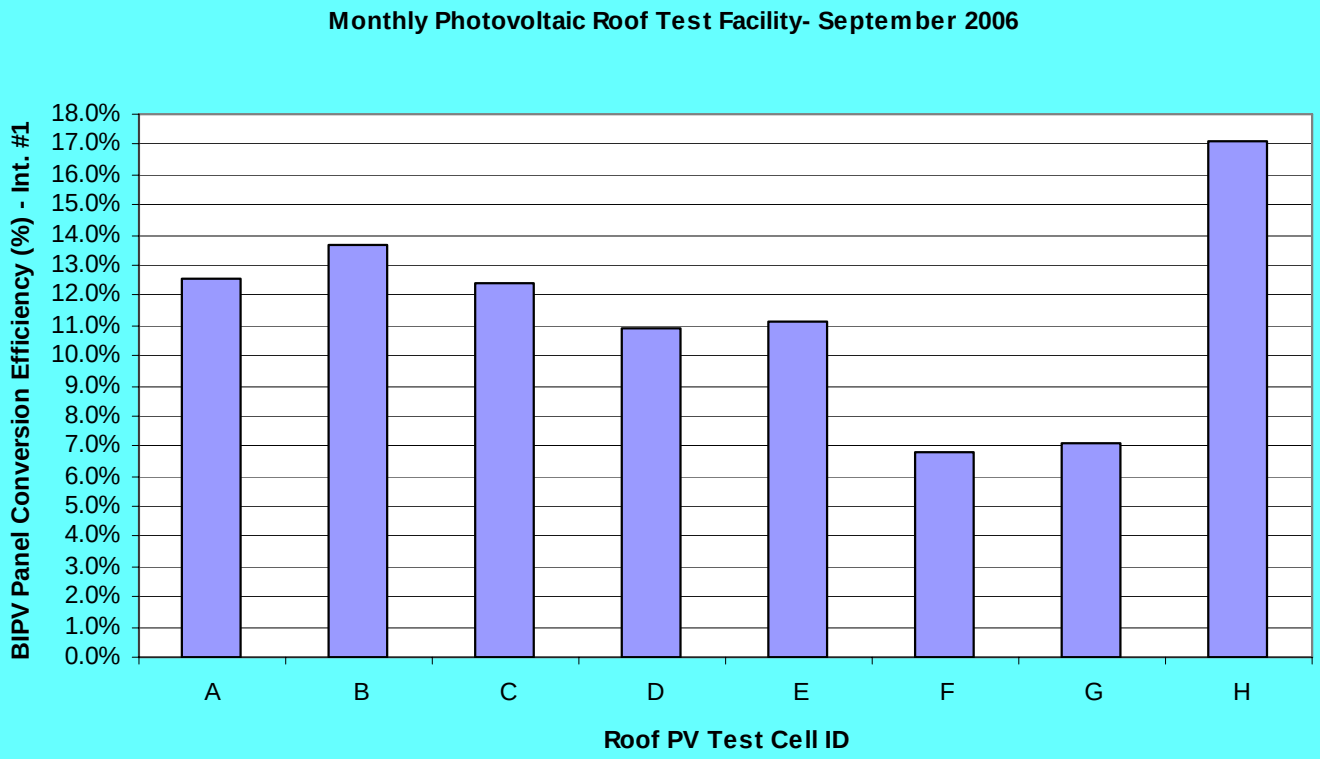
# Efficiencies Associated with PV Roofing Products

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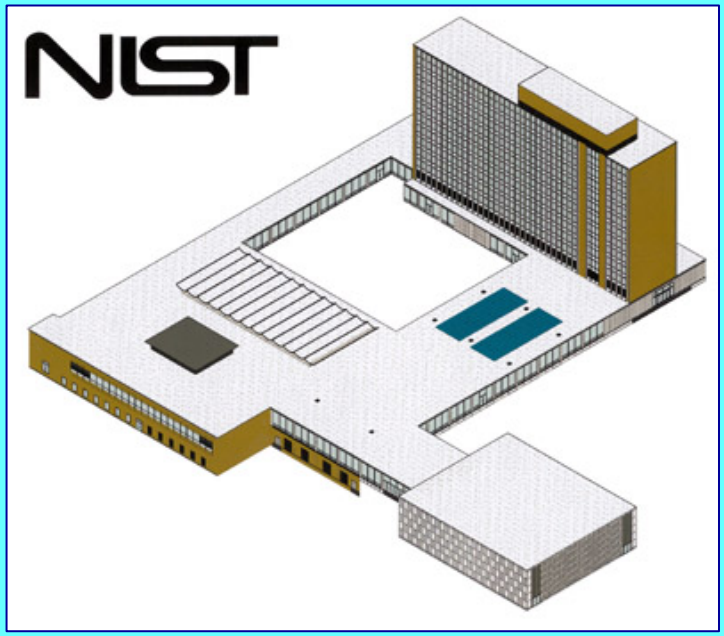
# NIST Administration Building's PV System

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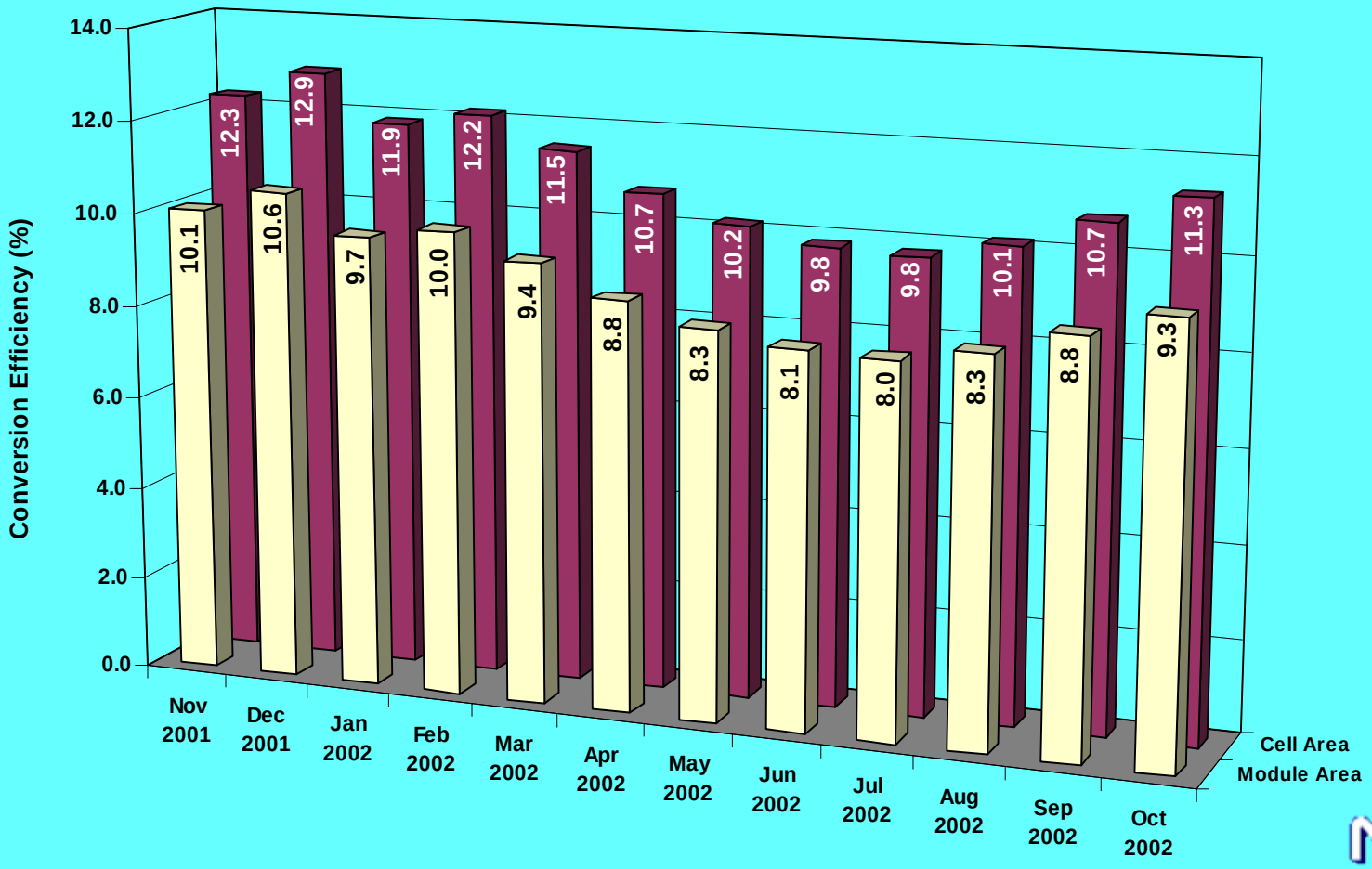


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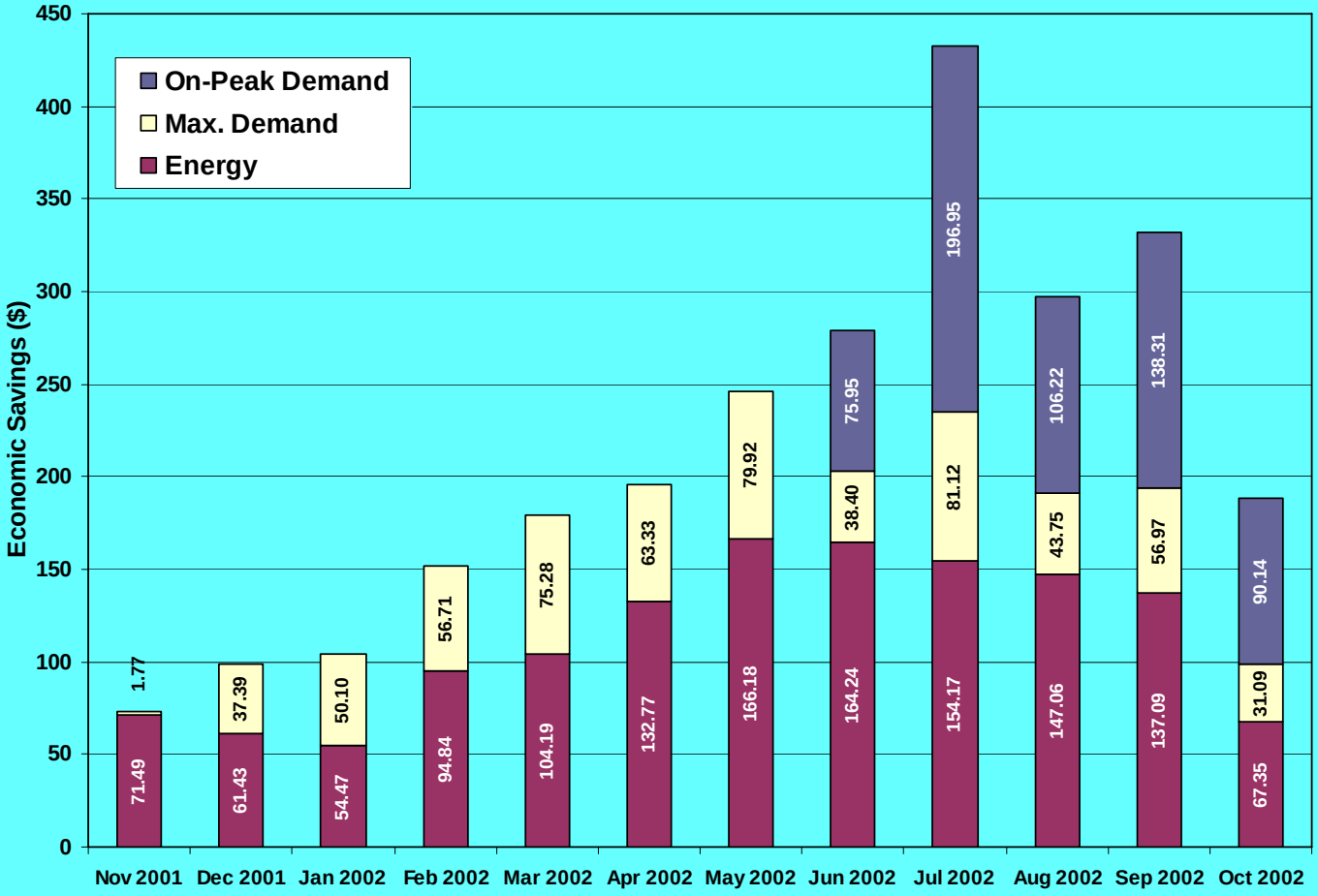


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# NIST Administration Building's PV System

- Costs
  - $239,945
  - $6.86 per DC Watt
- Benefits
  - Total Annual Electric Utility Savings = $2578.65
    - $607.57 Peak Demand
    - $615.81 Maximum Demand
    - $1355.27 Energy
  - Annual Avoided Emissions
    - 321 kg $SO_2$
    - 134 kg $NO_x$
    - 52.6 metric tons $CO_2$
  - Corporate Image

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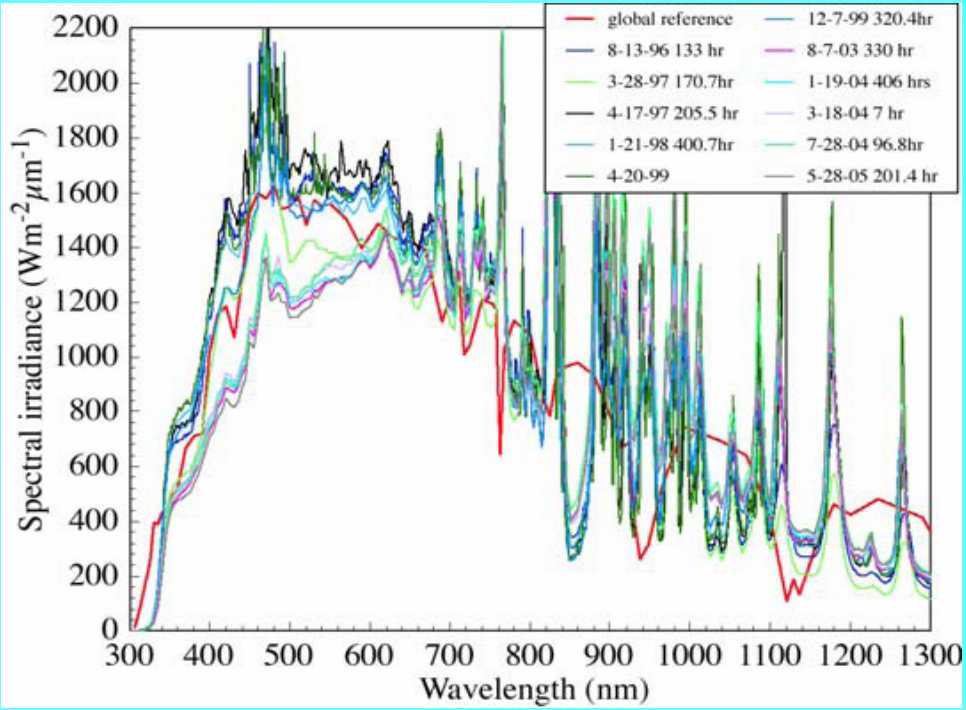
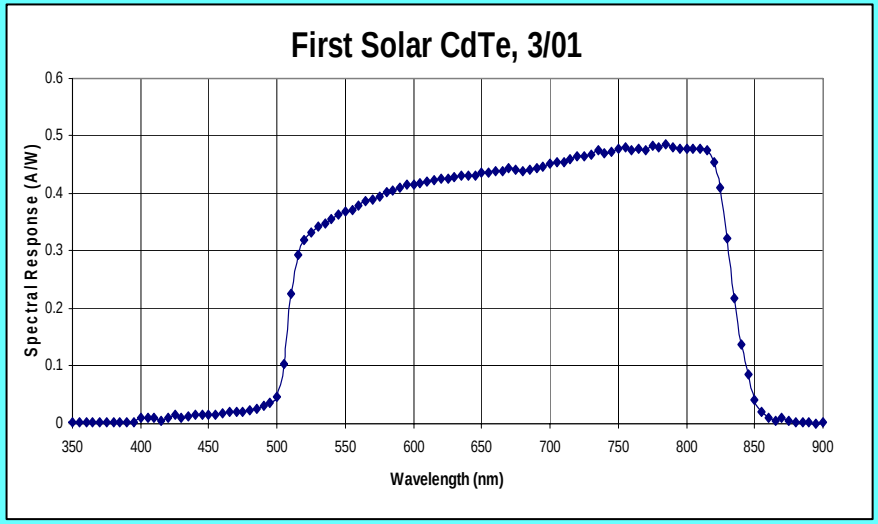
# Indoor Testing Challenge

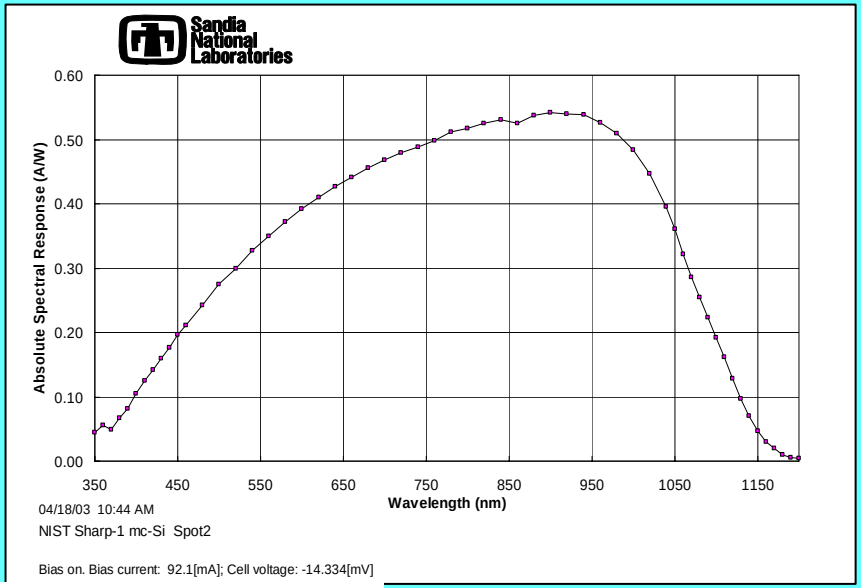
- Difficult to Replicate Outdoor Spectrum
- PV Cell Performance Function of Spectrum




***"If NIST could improve the methods used to rate PV modules it could have a dramatic impact on the PV industry"***

**-Juris Kalejs, RWE Schott Solar, Vice President of Research**



# NIST Long-Pulsed Solar Simulator Specifications

- IEC Standard 60904-9 Class AAA Simulator
  - ✓ Spectral match: 0.75-1.25 for 6 -intervals
  - ✓ Irradiance non-uniformity: $\leq \pm 2$ %
  - ✓ Irradiance temporal instability: $\leq \pm 2$ %
- Flash Plateau: 30 ms
  - ✓ IV scan interval: $\leq 1$ ms
  - ✓ Variable scan delay : 1 – 12 ms
- Irradiance Range: ~ 500 – 1100 W/m$^2$
- Maximum irradiated area: 2.4 m diagonal
- Spectral composition filters
- Constructed 12/2006 – On Tour

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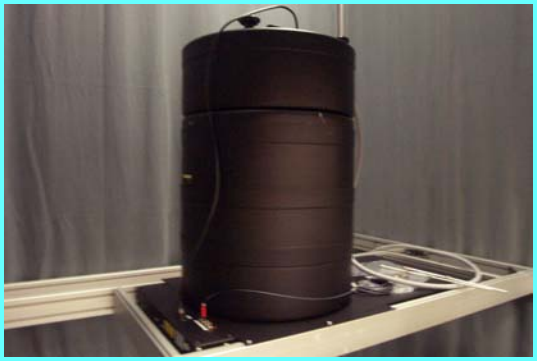
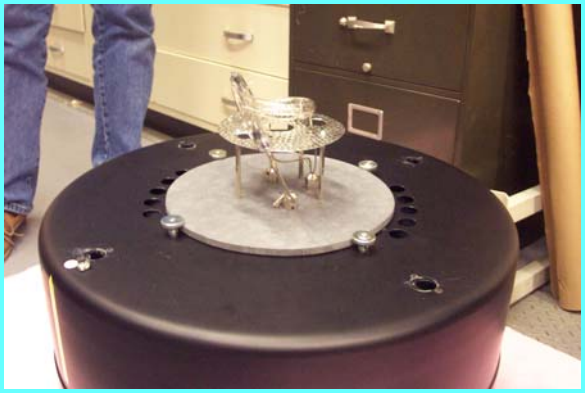
# Solar Simulator Components

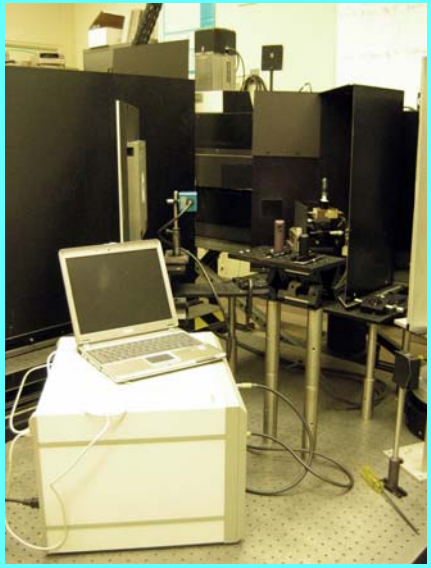


Optical Assembly

Shutter/Filter

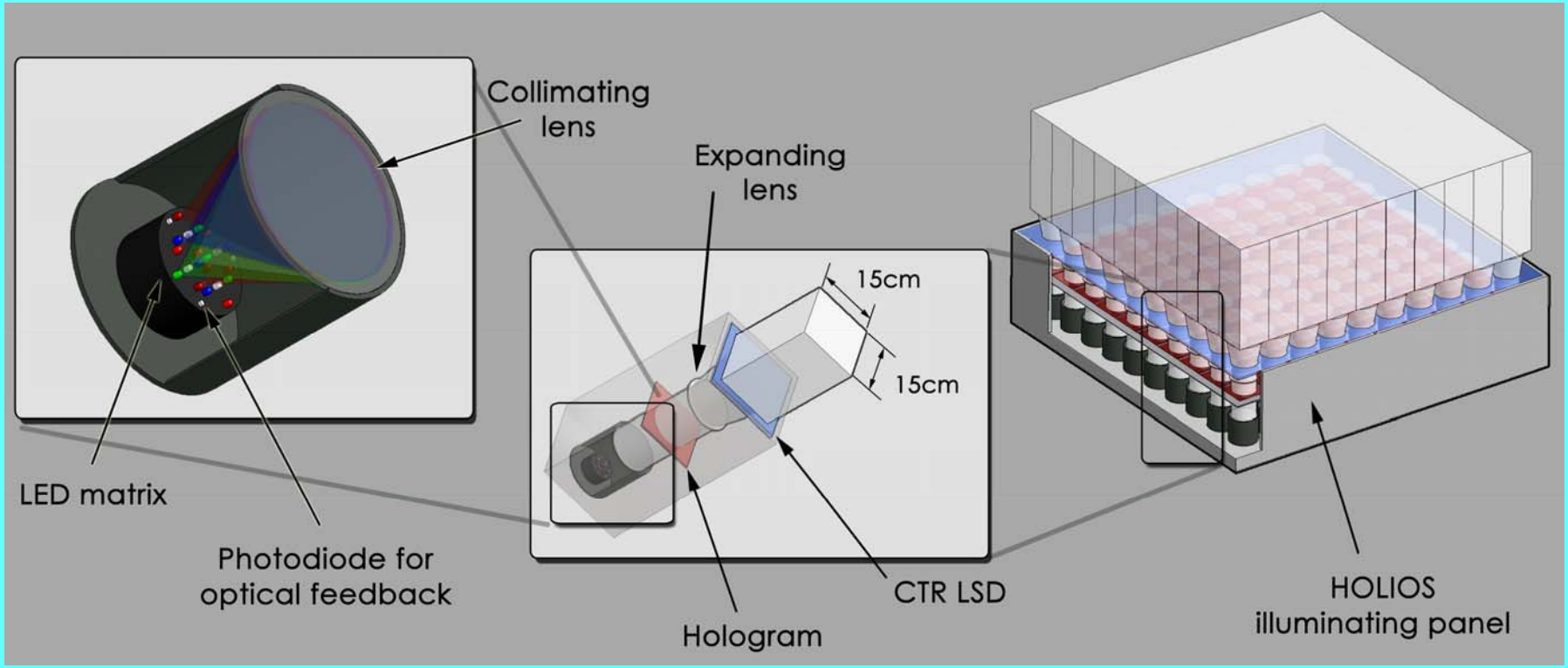


Xeon Lamp Assembly



Spectroradiometer

# Conceptual LED Simulator Design

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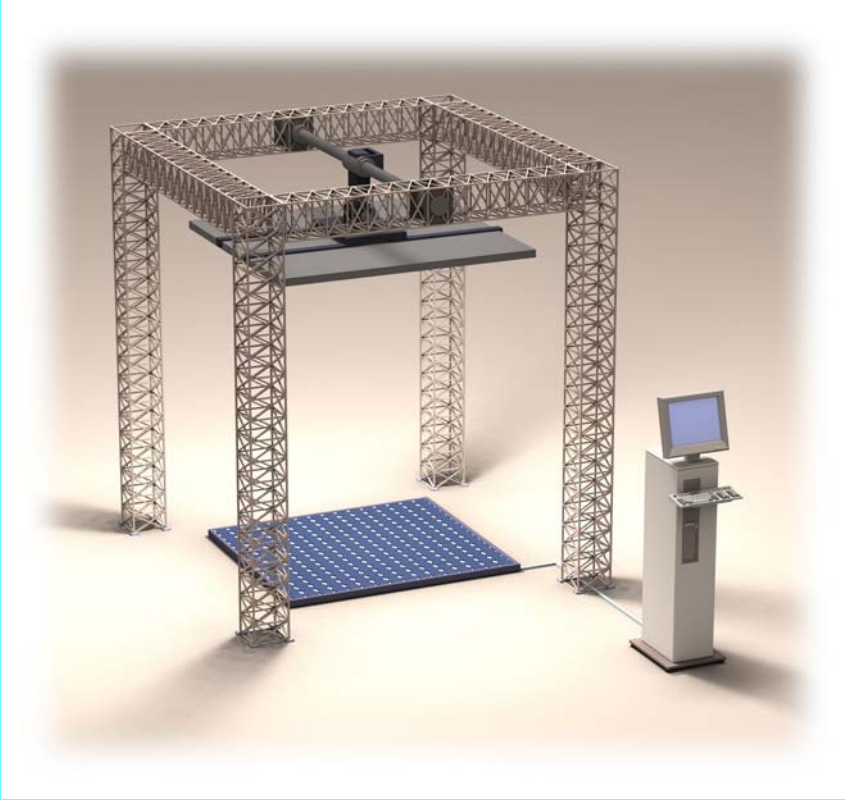
# Conceptual Design of LED Simulator



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# Summary

- Photovoltaic Industry is Experiencing Rapid Growth
  - 1998 - $1.5 billion
  - 2020 - $27 billion
- Building Integrated Photovoltaics
  - Distributed Energy Production
  - Architecturally Clean
- Barriers
  - High Initial Costs
  - Uncertainty in PV Module Power Ratings
  - Lack of Performance Data and Predictive Tools
- NIST's Program is Providing
  - Performance Data
  - Validated Performance Prediction Tools
  - Tools/Equipment/Procedures to Address Uncertainty Issues

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# Thank You for Attending!

## Enjoy the Tour

- Additional Information http://www.bfrl.nist.gov/863/heat_transfer_group/index.htm

My Dad and I after installing solar hot water system at my parents home. Provided hot water for the next 26 years!

**June 1978 – Suffolk, Va.**

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