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Cincinnati, Ohio

August 7–10, 2011

Photovoltaics Technology in the Federal Marketplace Part I: Understanding the Basics

Aug 9, 2011

Michael Quintana
Sandia National Laboratories

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

FEDERAL AGENCY SPONSORS

Outline of Presentation

- Background--Why PV in the US?
- What should you know about PV systems?—Cells, Modules, Inverters, BOS
- Where is PV used? Industry, Applications and Markets
- Summary

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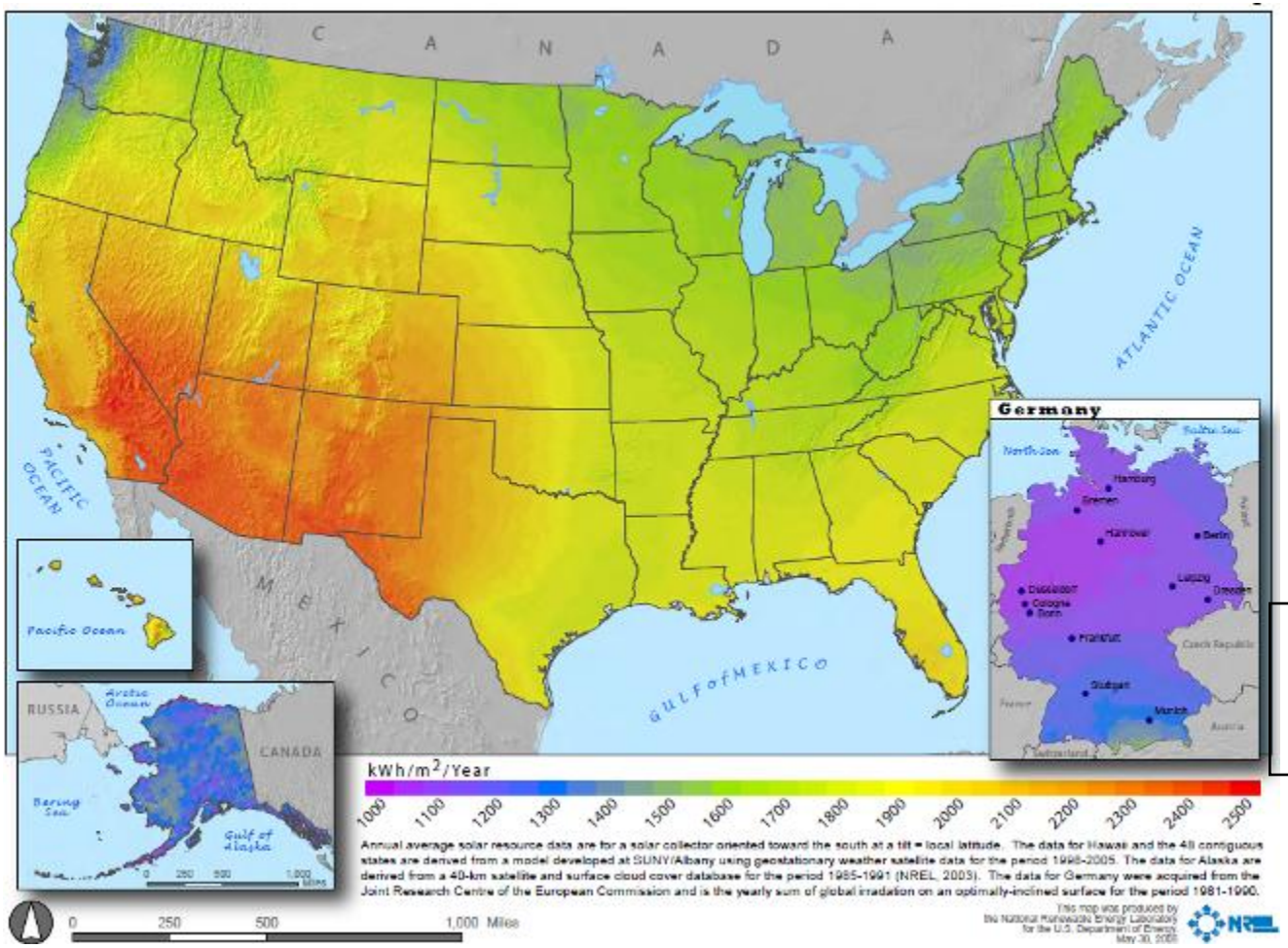
U.S. Has Great Opportunities for Increased Solar Energy Applications



All of the electricity in the U.S. could be provided using:

- Less than 2% of the land dedicated to cropland and grazing.
- Less than the current amount of land used for corn ethanol production.

2009 PV Installs
Germany: 3.87GW
US: 485MW

Germany has similar solar resource to Alaska!

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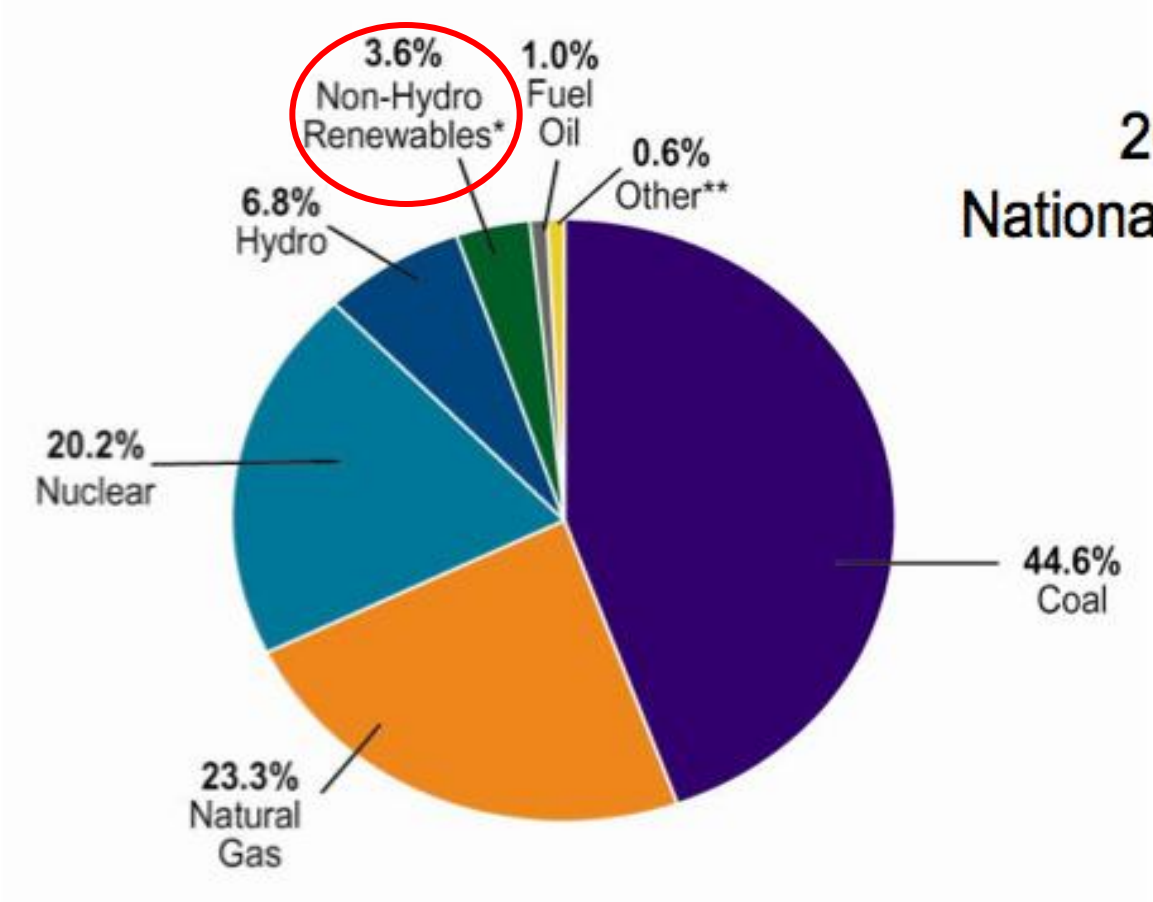
However, Solar Utilization is Still Not on the Map of Electrical Generation



2009 National Fuel Mix

*Includes generation by agricultural waste, landfill gas recovery, municipal solid waste, wood, geothermal, non-wood waste, wind, and solar.

** Includes generation by tires, batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, and miscellaneous technologies.

Sum of components do not add to 100% due to independent rounding.

Source: U.S. Department of Energy, Energy Information Administration, Power Plant Operations Report (EIA-923); 2009 preliminary data.

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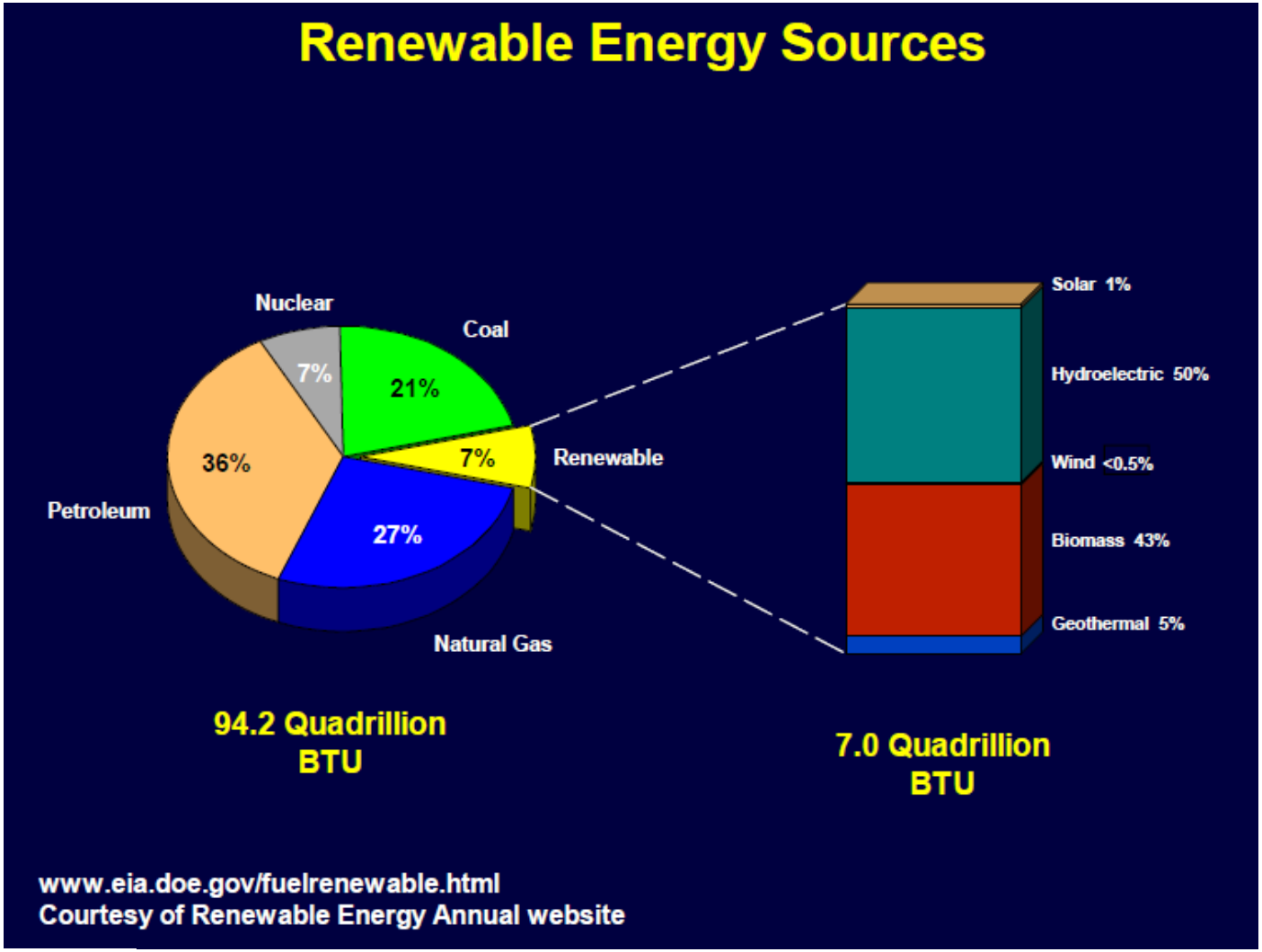
Where does PV fit within the Renewables Landscape?



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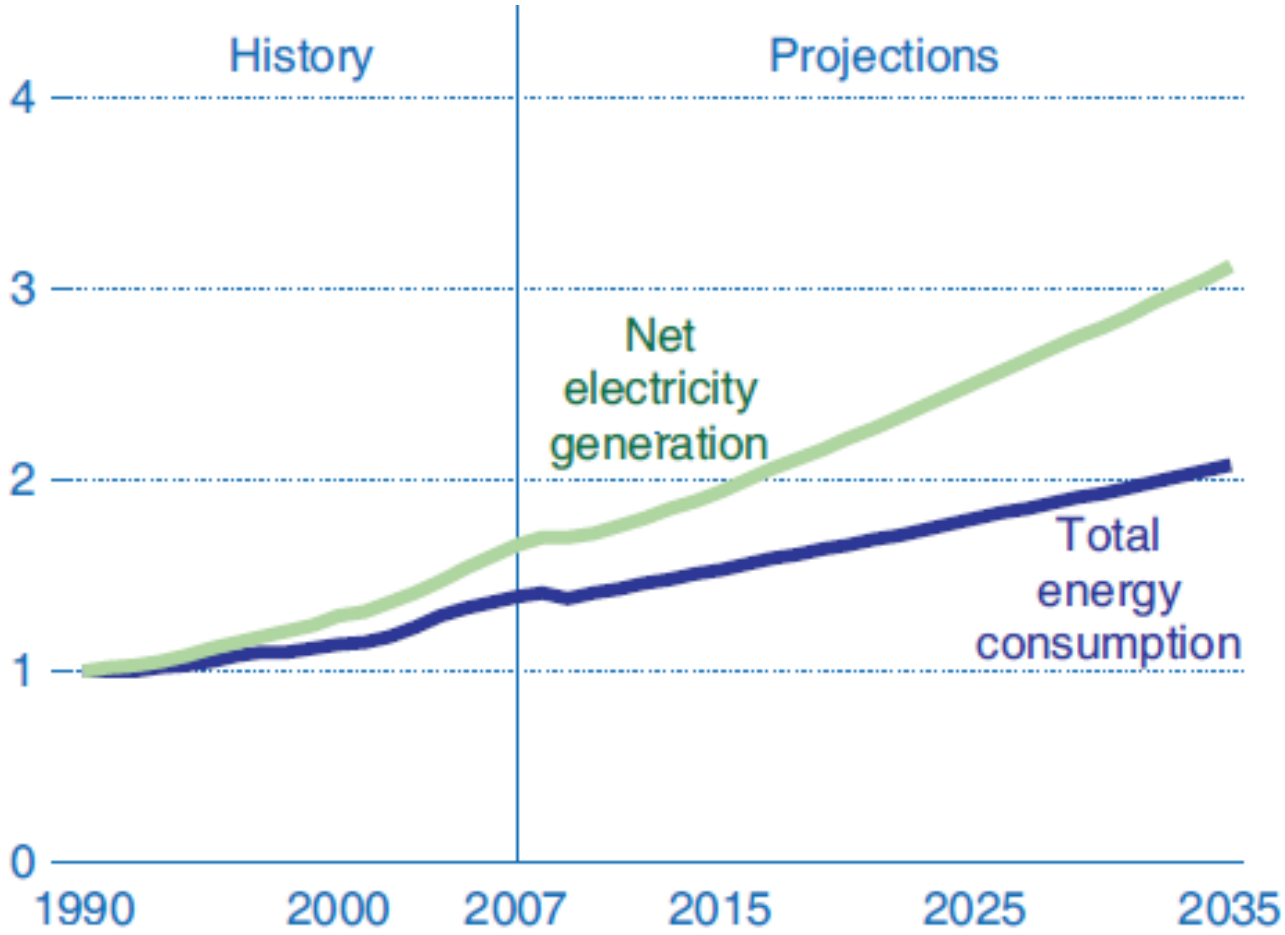
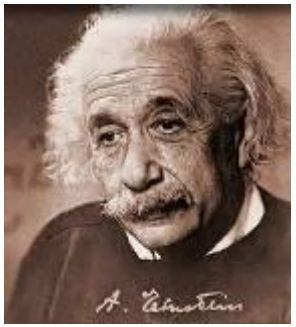
Growth in demand for electricity outpaces growth in total energy use throughout the projection period

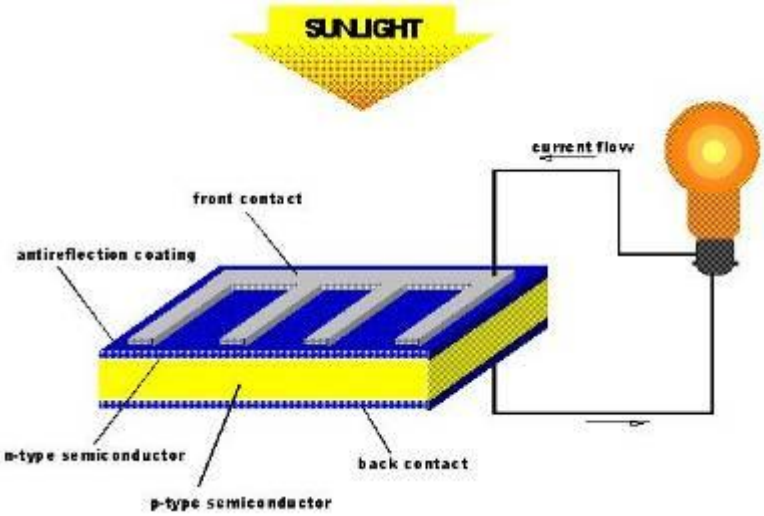


U.S. Energy Information Administration / International Energy Outlook 2010

What is The Photoelectric Effect?

- **1839: Edmond Bequerel, French physicist discovers photoelectric effect**
- **1904: Albert Einstein theoretically describes photovoltaic effect, for which he won the Nobel Prize in 1921**
- **1916: Robert Millikan practically demonstrates Einstein's theory**
- **1918: Jan Czochralski, Polish physicist discovers method of producing monocrystalline silicon – still in use today**
- **1941: first monocrystalline silicon cell produced**
- **1954: AT&T Bell Labs publishes reports on solar cells with 4.5% efficiency**





http://www.pvresources.com/en/history.php

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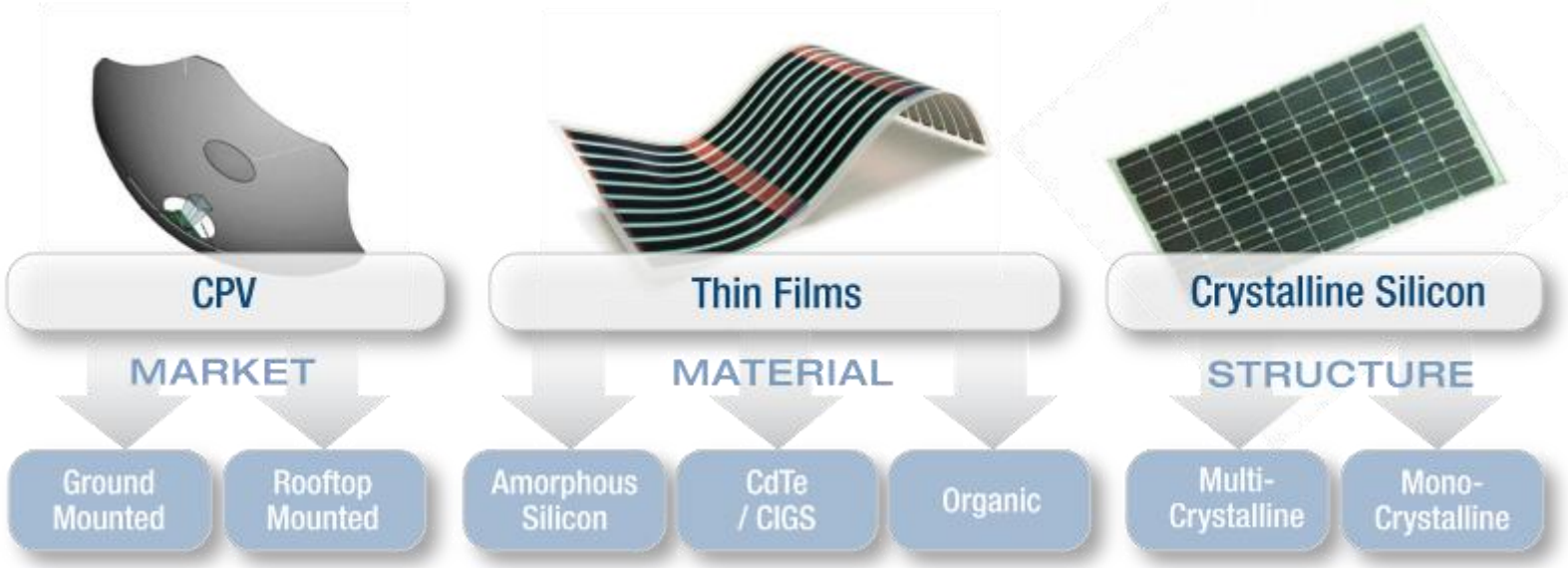
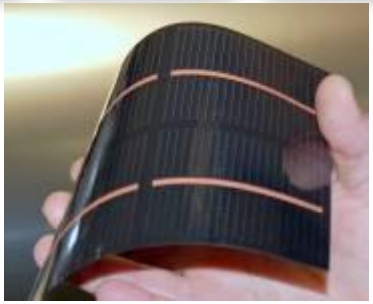
Government and Industry are Pursuing a Range of Promising PV Technologies



20x-100x

500x



$Cu(In,Ga)Se_2$ ~ 1-2 um

c-Si ~ 180 um

Slide courtesy Robert Margolis, NREL

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PV Conversion Technology Tradeoffs

Technology	Advantages	Disadvantages
Mono-Crystalline Silicon	Proven technology Higher Efficiency (22%)	High material usage
Poly-Crystalline Silicon	Proven technology Lower cost than mc-Si	Lower efficiency (13-16%) High material usage
Amorphous Silicon Thin Film	Proven roll-to-roll high throughput manufacturing Low materials usage	Low efficiency (~7%) High Cap-Ex Costs
CdTe Thin Film	Low manufacturing cost Low materials usage	Lower efficiency (~10%) Lifetime not demonstrated Glass required
CIGS Thin Film	High Thin Film Efficiency (~12-13%) Low materials usage	Currently expensive & difficult to manufacture Lifetime not demonstrated
Multi-junction– INGAS or III-V's	High efficiency (~36%) Very low material usage Space Quality	Expensive to manufacture Need for high tracking accuracy Expensive balance-of-system Thermal management issues
Organics (not yet commercial)	Very low cost to produce	Low efficiency (~4-6%) Unstable

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What does the PV Supply Chain look like?

Utility Transmission Grid and Its Customers

↑

System Owners and Power Purchase Agreements

↑

System Integrators/Developers—designed and installed systems

↑

System Components—modules, inverters, transformers, switches etc.

↑

Processed components-- polymers, glass, silicon wafers, wire

↑

Materials—Silica, metals, rare earth metals, etc

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Outline of Presentation

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The PV Cell is the Basic Building Blocks

When exposed to sunlight cell will produce:

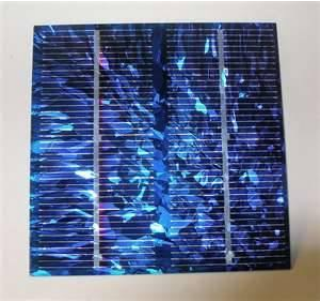
≈0.5 Volts dc

≈4.0 Amps dc

≈2.0 Watts

Connect multiple cells in series to creates a string

A PV module is one or more strings connected in parallel



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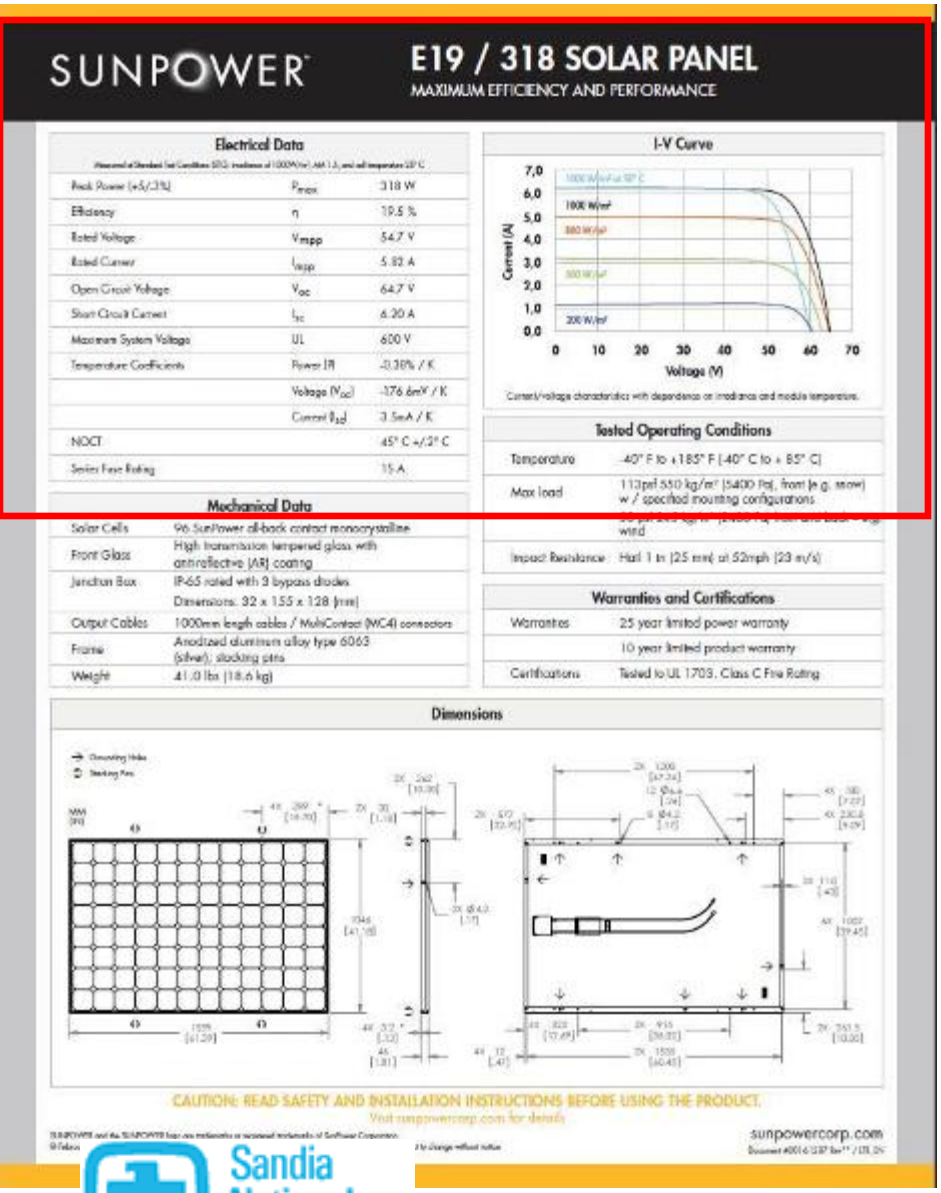
Photovoltaic Module Spec Sheets—Things To Take Note Of



SUNPOWER

E19 / 318 SOLAR PANEL

MAXIMUM EFFICIENCY AND PERFORMANCE

Electrical Data

Peak Power (+5/-3%)	P_{max}	318 W
Efficiency	η	19.5 %
Rated Voltage	V_{mpp}	54.7 V
Rated Current	I_{mpp}	5.82 A
Open Circuit Voltage	V_{oc}	64.7 V
Short Circuit Current	I_{sc}	6.20 A
Maximum System Voltage	UL	600 V
Temperature Coefficients	Power (P)	-0.38% / K
	Voltage (V_{oc})	-176.6mV / K
	Current (I_{sc})	3.5mA / K
NOCT		45° C +/-2° C
Series Fuse Rating		15 A

I-V Curve

Current (A) 7,0 6,0 5,0 4,0 3,0 2,0 1,0 0,0 — 1000 W/m² — 800 W/m² — 600 W/m² — 400 W/m² — 200 W/m² — 0 10 20 30 40 50 60 70 Voltage (V)

Current/voltage characteristics with dependence on irradiance and module temperature.

Mechanical Data

Solar Cells	96 SunPower all-back contact monocrystalline
Front Glass	High transmission tempered glass with antireflective (AR) coating
Junction Box	IP-65 rated with 3 bypass diodes Dimensions: 32 x 155 x 128 (mm)
Output Cables	1000mm length cables / MultiContact (MC4) connectors
Frame	Anodized aluminum alloy type 6063 (silver); stacking pins
Weight	41.0 lbs (18.6 kg)

Tested Operating Conditions

Temperature	-40° F to +185° F (-40° C to + 85° C)
Max load	113psf 550 kg/m² (5400 Pa), front (e.g. snow) w / specified mounting configurations 50 psf 245 kg/m² (2400 Pa) rear (e.g. wind)
Impact Resistance	Hail 1 in (25 mm) at 52mph (23 m/s)

Warranties and Certifications

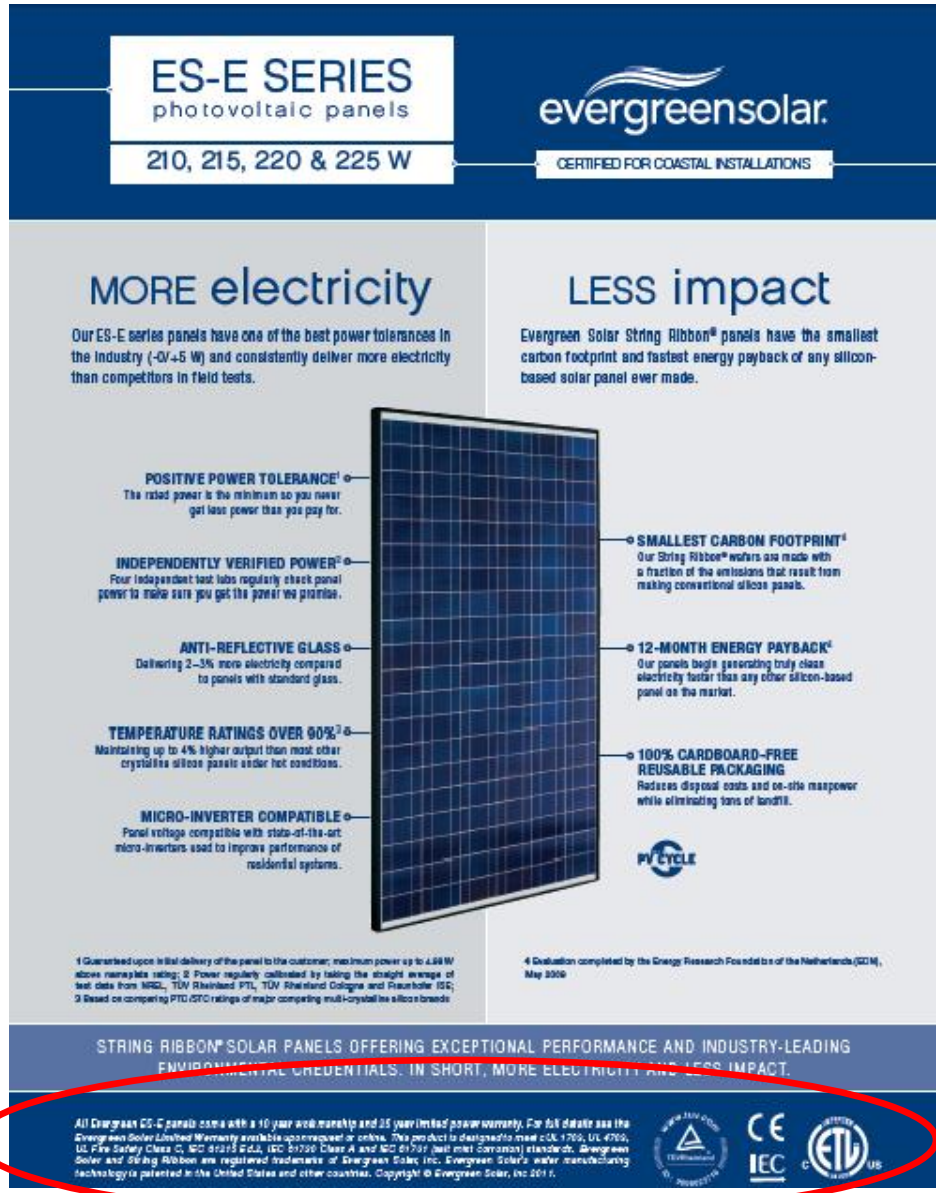
Warranties	25 year limited power warranty
	10 year limited product warranty
Certifications	Tested to UL 1703, Class C Fire Rating

Dimensions

CAUTION: READ SAFETY AND INSTALLATION INSTRUCTIONS BEFORE USING THE PRODUCT.

Visit sunpowercorp.com for details

sunpowercorp.com



ES-E SERIES

photovoltaic panels

210, 215, 220 & 225 W

evergreensolar.

CERTIFIED FOR COASTAL INSTALLATIONS

MORE electricity

Our ES-E series panels have one of the best power tolerances in the industry (-0/+5 W) and consistently deliver more electricity than competitors in field tests.

POSITIVE POWER TOLERANCE[1]
The rated power is the minimum so you never get less power than you pay for.

INDEPENDENTLY VERIFIED POWER[2]
Four independent test labs regularly check panel power to make sure you get the power we promise.

ANTI-REFLECTIVE GLASS
Delivering 2–3% more electricity compared to panels with standard glass.

TEMPERATURE RATINGS OVER 90%[3]
Maintaining up to 4% higher output than most other crystalline silicon panels under hot conditions.

MICRO-INVERTER COMPATIBLE
Panel voltage compatible with state-of-the-art micro-inverters used to improve performance of residential systems.

1 Guaranteed upon initial delivery of the panel to the customer; maximum power up to 4.99 W above nameplate rating; 2 Power regularly calibrated by taking the straight average of test data from NREL, TÜV Rheinland PTL, TÜV Rheinland Cologne and Fraunhofer ISE; 3 Based on comparing PTC/STC ratings of major competing multi-crystalline silicon brands

LESS impact

Evergreen Solar String Ribbon® panels have the smallest carbon footprint and fastest energy payback of any silicon-based solar panel ever made.

SMALLEST CARBON FOOTPRINT[4]
Our String Ribbon® wafers are made with a fraction of the emissions that result from making conventional silicon panels.

12-MONTH ENERGY PAYBACK[4]
Our panels begin generating truly clean electricity faster than any other silicon-based panel on the market.

100% CARDBOARD-FREE REUSABLE PACKAGING
Reduces disposal costs and on-site manpower while eliminating tons of landfill.

PV CYCLE

4 Evaluation completed by the Energy Research Foundation of the Netherlands (ECN), May 2009

STRING RIBBON® SOLAR PANELS OFFERING EXCEPTIONAL PERFORMANCE AND INDUSTRY-LEADING ENVIRONMENTAL CREDENTIALS. IN SHORT, MORE ELECTRICITY AND LESS IMPACT.

All Evergreen ES-E panels come with a 10 year workmanship and 25 year limited power warranty. For full details see the Evergreen Solar Limited Warranty available upon request or online. This product is designed to meet UL 1703, UL 4703, UL Fire Safety Class C, IEC 61215 Ed.2, IEC 61730 Class A and IEC 61701 (salt mist corrosion) standards. Evergreen Solar and String Ribbon are registered trademarks of Evergreen Solar, Inc. Evergreen Solar's wafer manufacturing technology is patented in the United States and other countries. Copyright © Evergreen Solar, Inc 2011.

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A Little Bit About Module Performance, Safety and Reliability

All of this information matters but most people immediately focus on:

- Efficiency
- Peak Power
- Rated Voltage/Current
- Certifications-IEC & UL
- Warranty
  - Warranty is not lifetime!
  - Two levels of warranty

Electrical Data

Measured at Standard Test Conditions (STC): irradiance of 1000W/m², AM 1.5, and cell temperature 25° C

Peak Power (+5/-3%)	P_{max}	318 W
Efficiency	η	19.5 %
Rated Voltage	V_{mpp}	54.7 V
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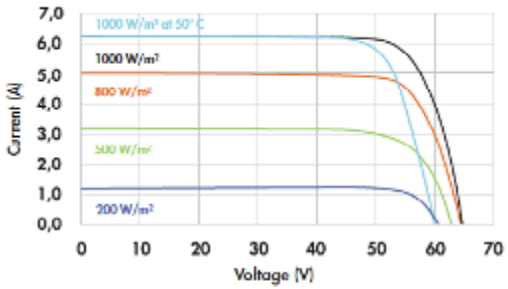
I-V Curve



Current/voltage characteristics with dependence on irradiance and module temperature

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The IV curve—A basic data point for a cell, module, and a string

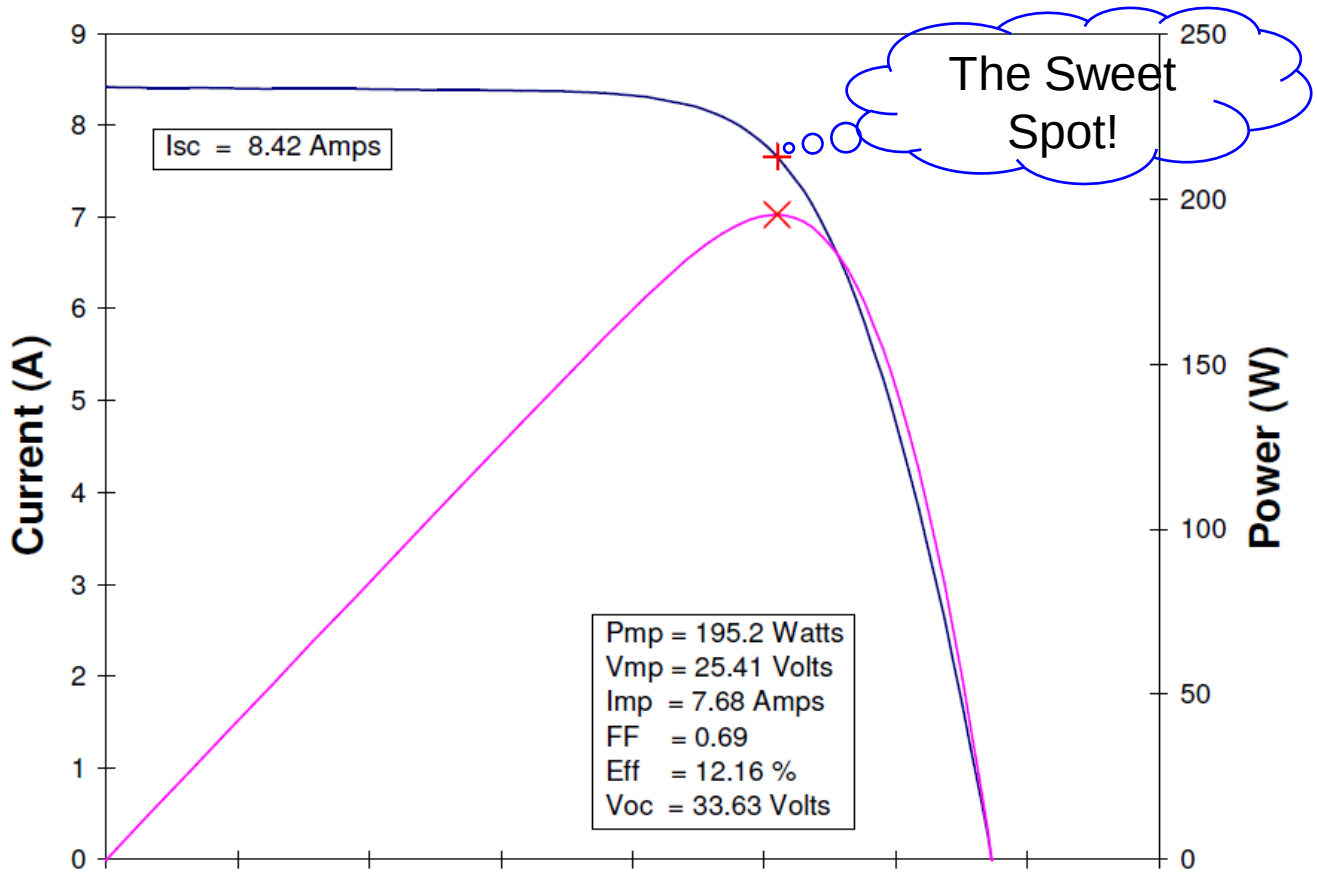
I_{sc}= short circuit current

V_{oc}= open circuit voltage

P_{mp}= max power

FF= fill factor

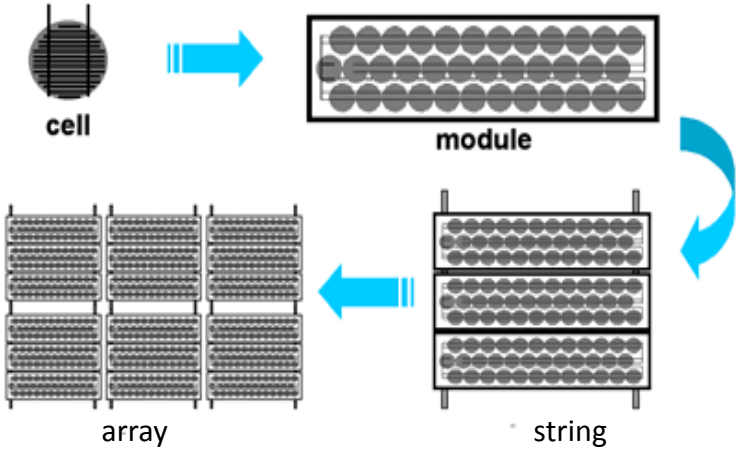
Eff= efficiency



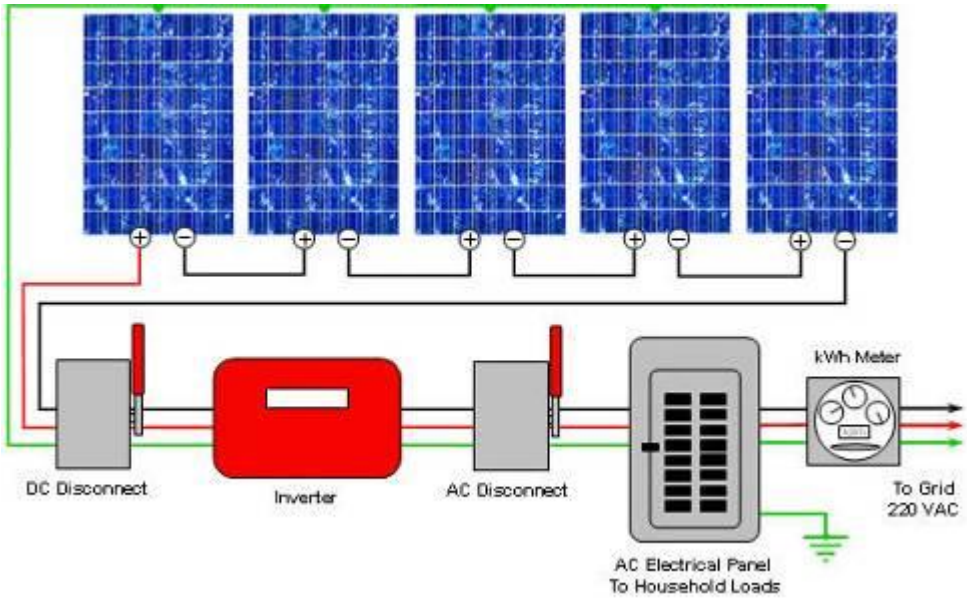
IV Curve

Power Curve

The Photovoltaic System Design



http://www1.eere.energy.gov/solar



www.creategreenhome.com

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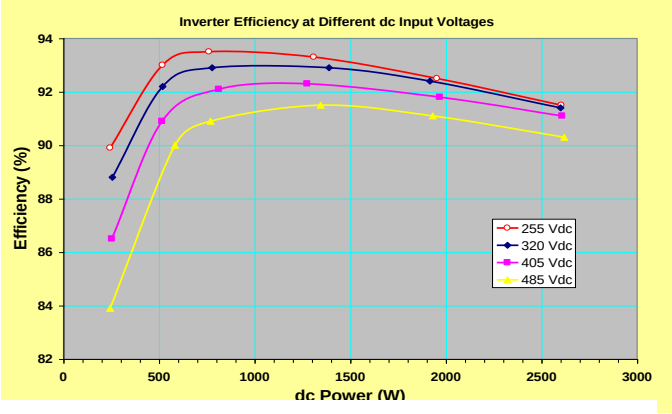
PV Inverters and Balance-of-Systems

- Convert DC to AC
- Available at module-scale (200W) up to 1 MW
- Principal hardware:
  - High power transistor bridges for conversion
  - Transformer for isolation of AC signal
  - Capacitors for signal smoothing
- Principal software:
  - Maximum Power Point Tracking (for optimum module utilization)
  - Anti-islanding (to detect grid loss)
  - Signal detection (turn on/off)
- Reliability: viewed as the weak link in the system
- Additional BOS: AC, DC disconnects; wiring, fuses, racks, meters, …
- Tracking systems can add 20-35% to energy production

Residential inverters and related disconnects/meters at Sandia's PV Systems Optimization Laboratory



Typical inverter efficiency plot (from SNL DETL)

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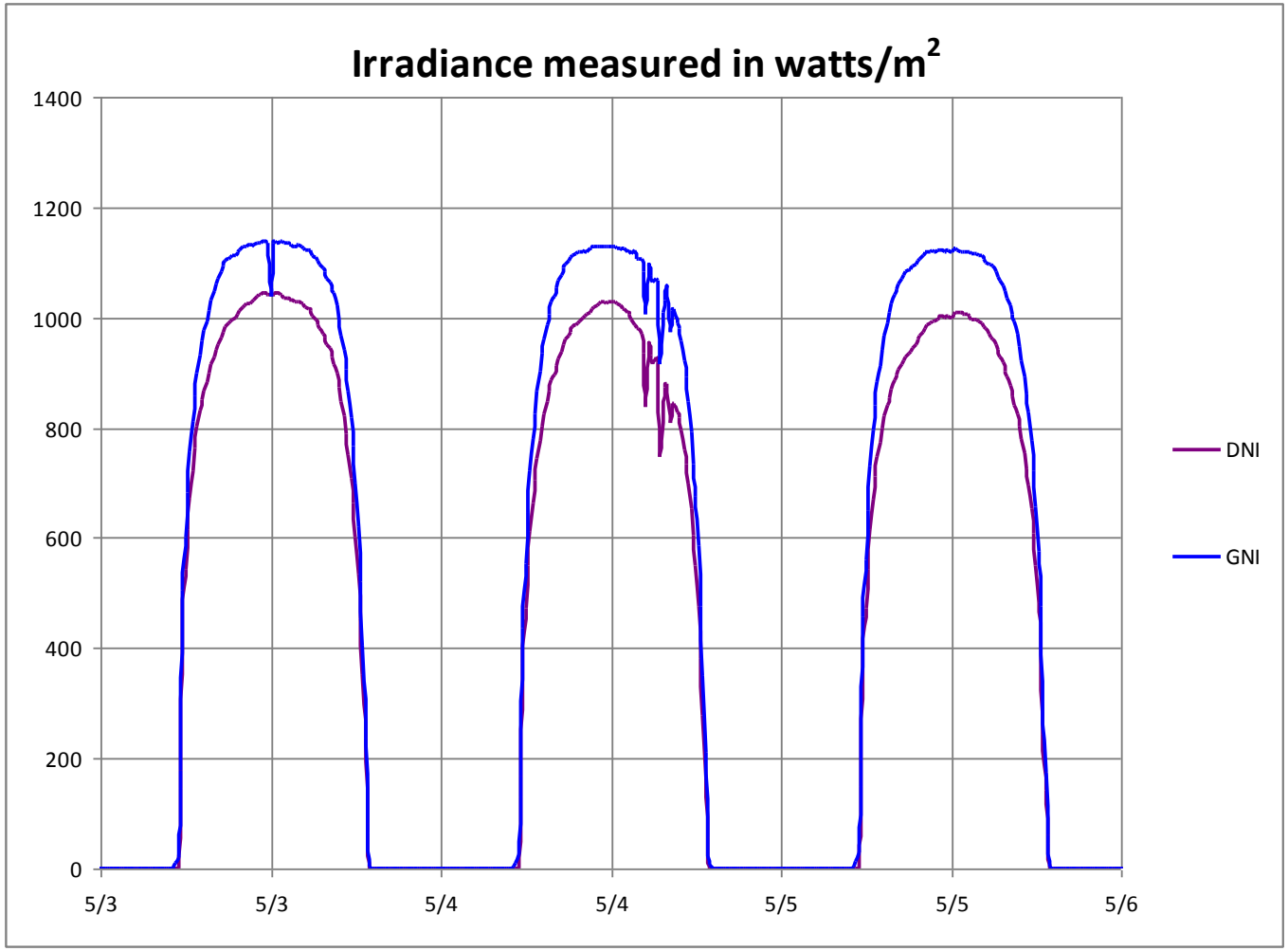
Irradiance (solar energy) measured on 3 consecutive days



Energy output from a PV system follows roughly the same contour when a system is properly designed.

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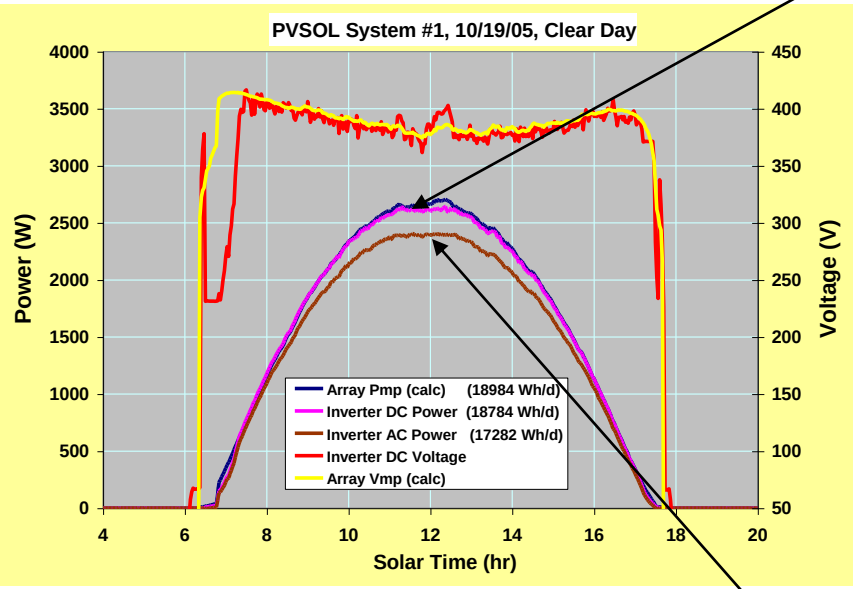
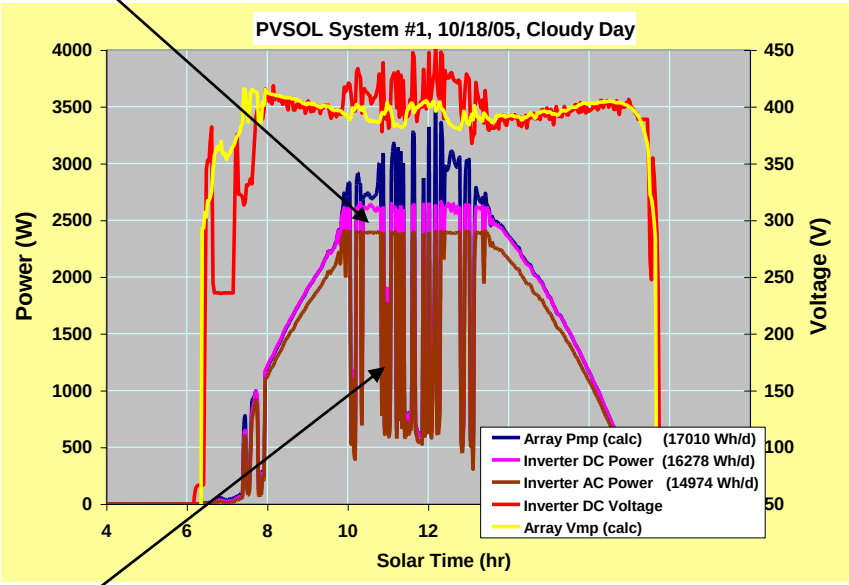
Examples of Clear vs. Cloudy Day Power Generation

Predicting Behavior is Important

Modeled vs Measured dc Power





Measured ac Power

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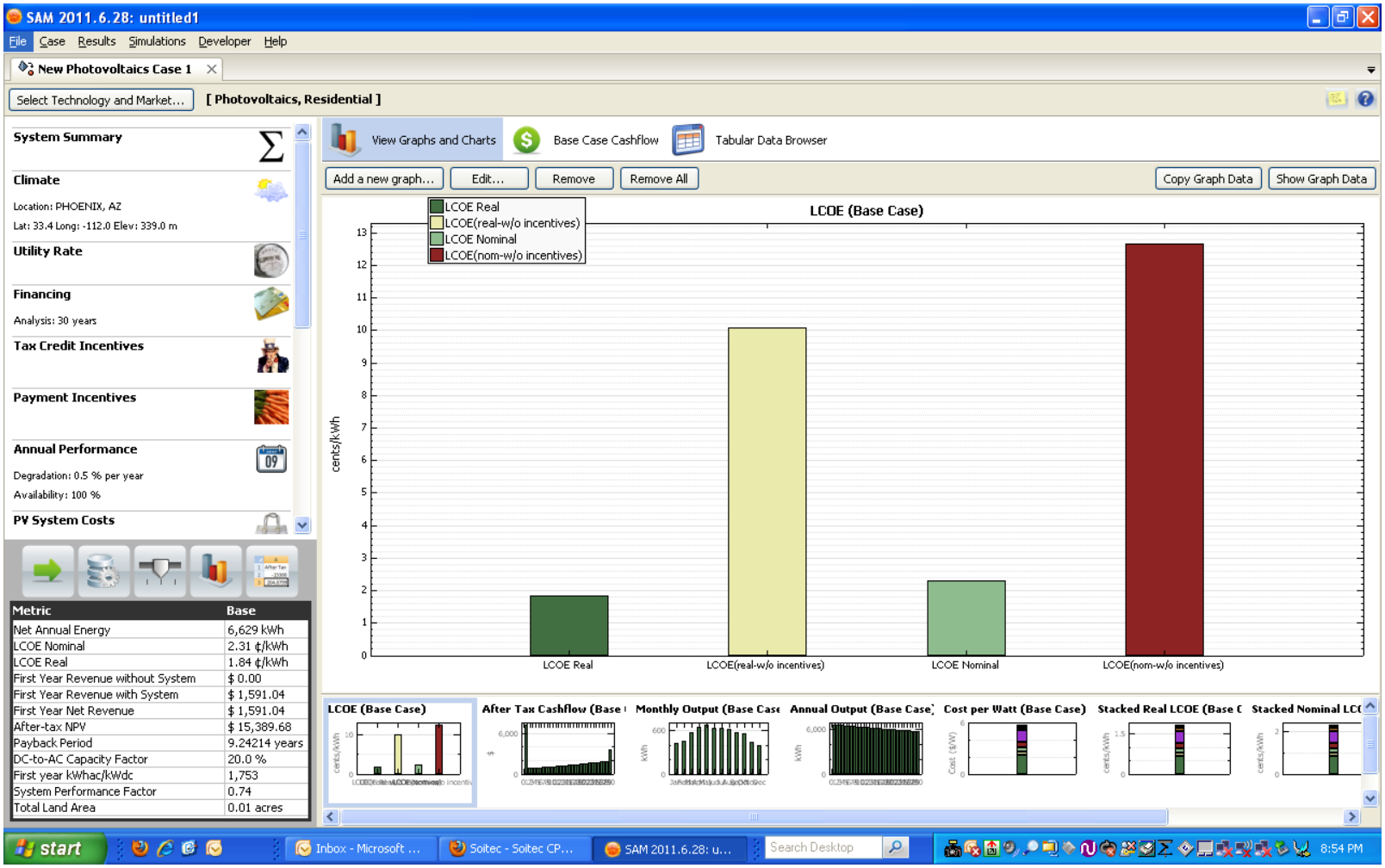
Decision Making? DOE's Solar Advisor Model (SAM) Helps By Applying Performance, Climate, Utility Rate, Tax Incentives and More



https://www.nrel.gov/analysis/sam/

There are several commercial models on the market also

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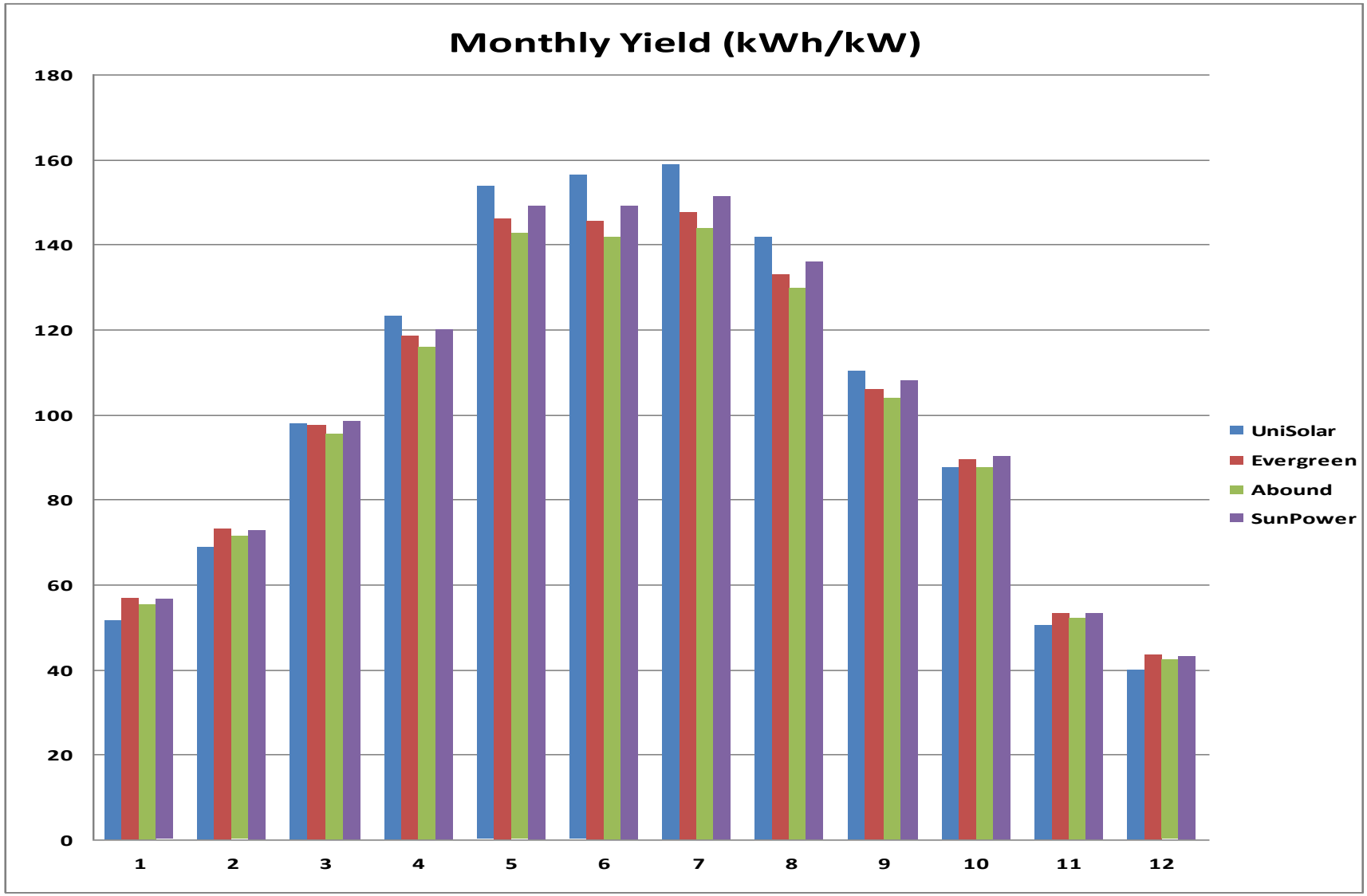
One Product of SAM is an Annual Energy Prediction



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Performance and Reliability Factors

Climate

- Temperature
- Humidity
- Ultra-violet light
- Rain
- Wind
- Snow
- Ice

Location

- Soiling
- Shading
- Clouds
- Flora & Fauna
- Lightning

Design

- Grid stability
- Incident angle
- Component selection
- Interface with surroundings

Early System Scoping Considerations

Needs

- System loads
- Load profile
- Cut annual consumption
- Expectations
- Peak shaving
- Carbon footprint
- Technology interest

Location

- Climate
- Roof mount
- Roof health
- Ground mount
- Existing infrastructure
- Shading
- Aesthetics
- Utility requirements
- Jurisdictional needs
- Engineering requirements
- System of systems?

Budget/Cost

- Initial costs
- Lifetime
- Warranties
- O&M budget
- Technology
- Infrastructure
- Installation
- Ancillary costs
- Infrastructure
- Third-party ownership

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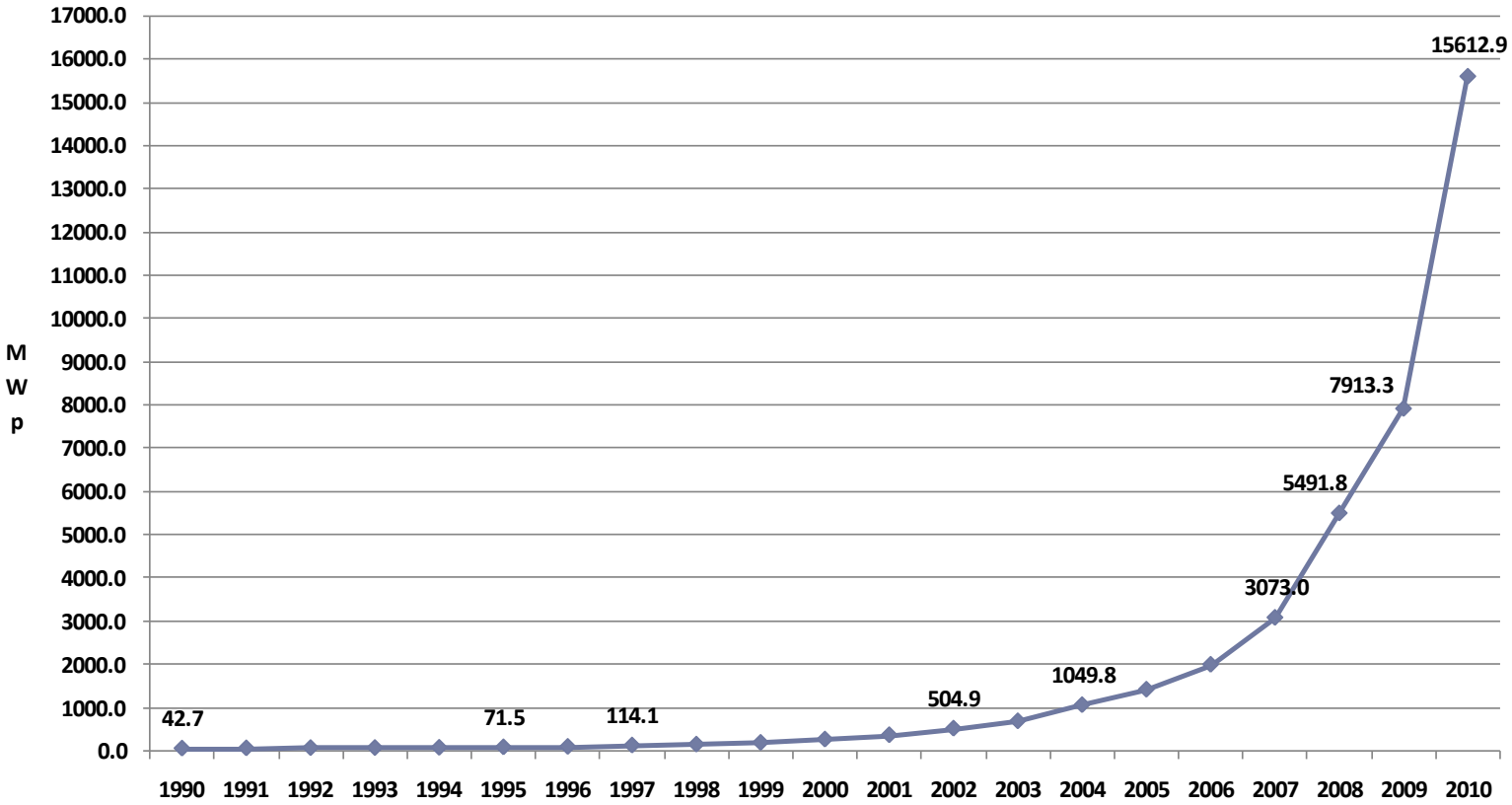
Industry Growth: 1979 to 2009



20 year compound annual growth: 34%, five year CAGR to 2010 estimated at 62%

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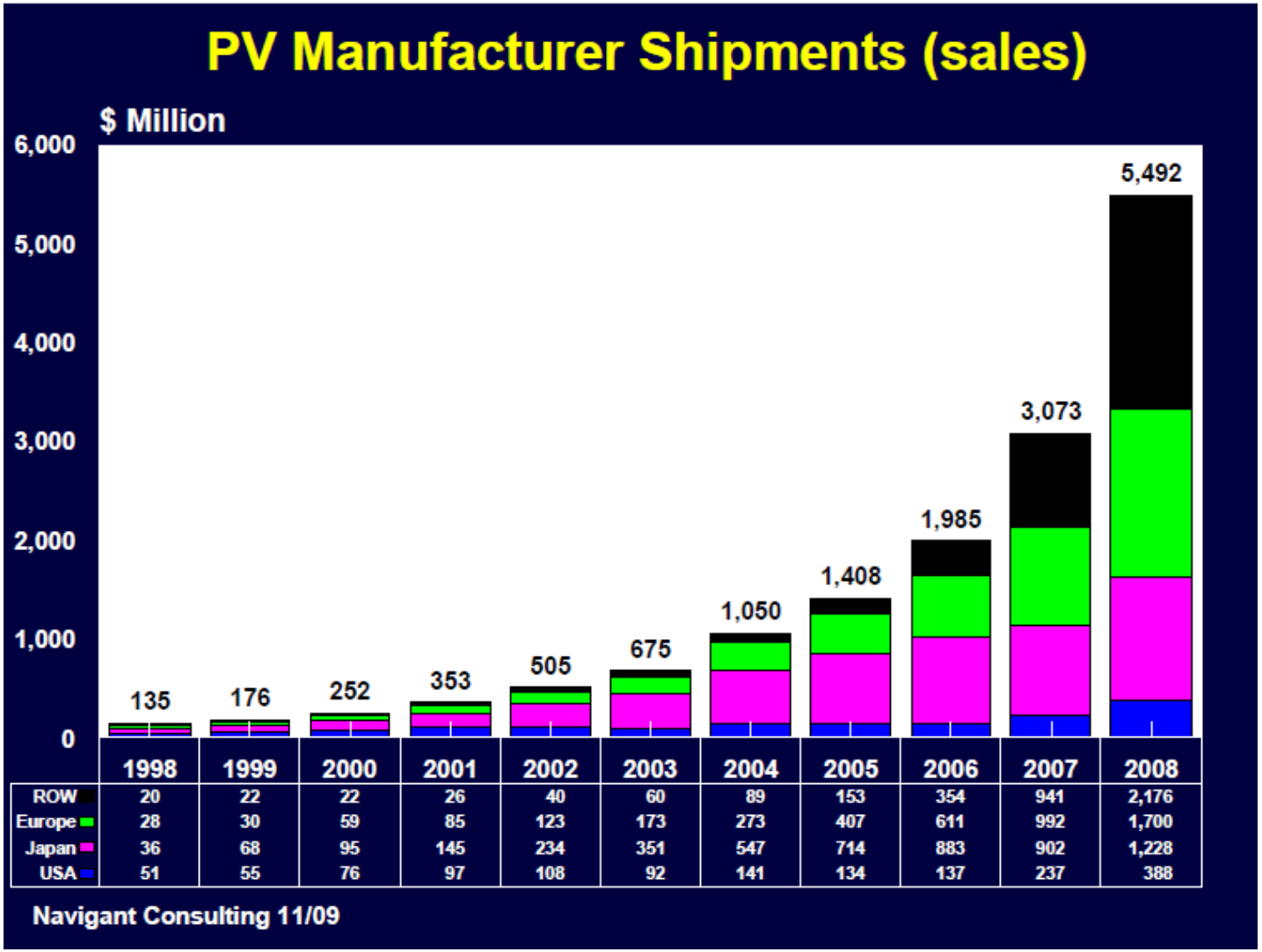
US Manufacturing is slowly growing



	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
ROW	20	22	22	26	40	60	89	153	354	941	2,176
Europe	28	30	59	85	123	173	273	407	611	992	1,700
Japan	36	68	95	145	234	351	547	714	883	902	1,228
USA	51	55	76	97	108	92	141	134	137	237	388

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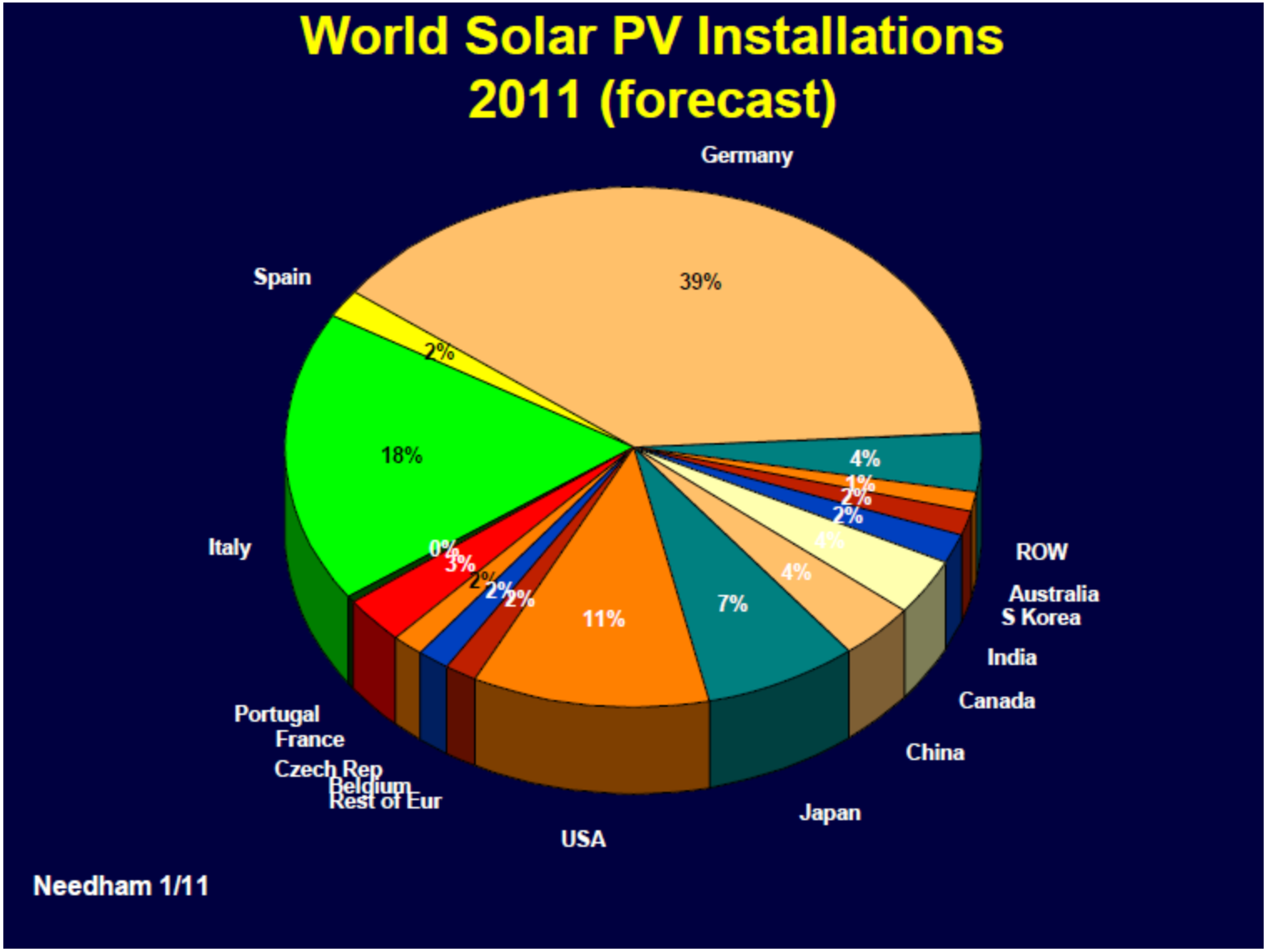
Who is buying Photovoltaic Systems?



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A little about system costs

- Everybody worries about first costs-$/W!
- Lifetime, O&M, and degradation are not well understood
- Levelized of Cost of Electricity (LCOE)= Total lifecycle cost/Total lifetime energy production($/kwh).
- Everybody understands ¢/kilowatt-hour

$$\frac{\text{Initial Investment} - \sum_{n=1}^{N} \frac{\text{Depreciation}^{n}}{(1+\text{Discount Rate})^{n}} \times (\text{Tax Rate}) + \sum_{n=1}^{N} \frac{\text{Annual Costs}^{n}}{(1+\text{Discount Rate})^{n}} \times (1\text{-Tax Rate}) - \frac{\text{Residual Value}}{(1+\text{Discount Rate})^{n}}}{\sum_{n=1}^{N} \frac{\text{Initial kWh/kWp} \times (1 - \text{System Degradation Rate})^{n}}{(1 + \text{Discount Rate})^{n}}}$$

SunPower 14 Aug 2008

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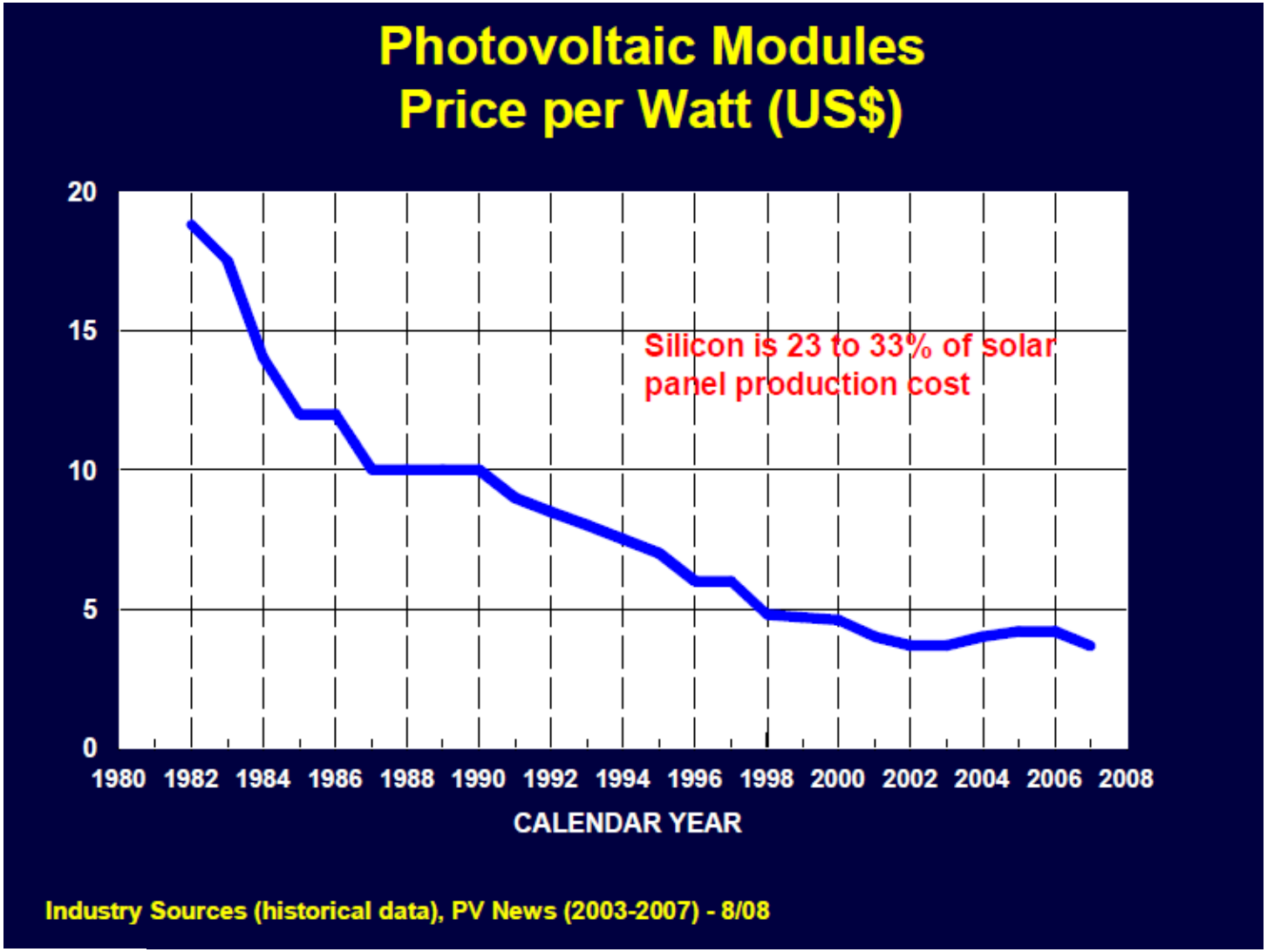
Costs/Prices are steadily declining!



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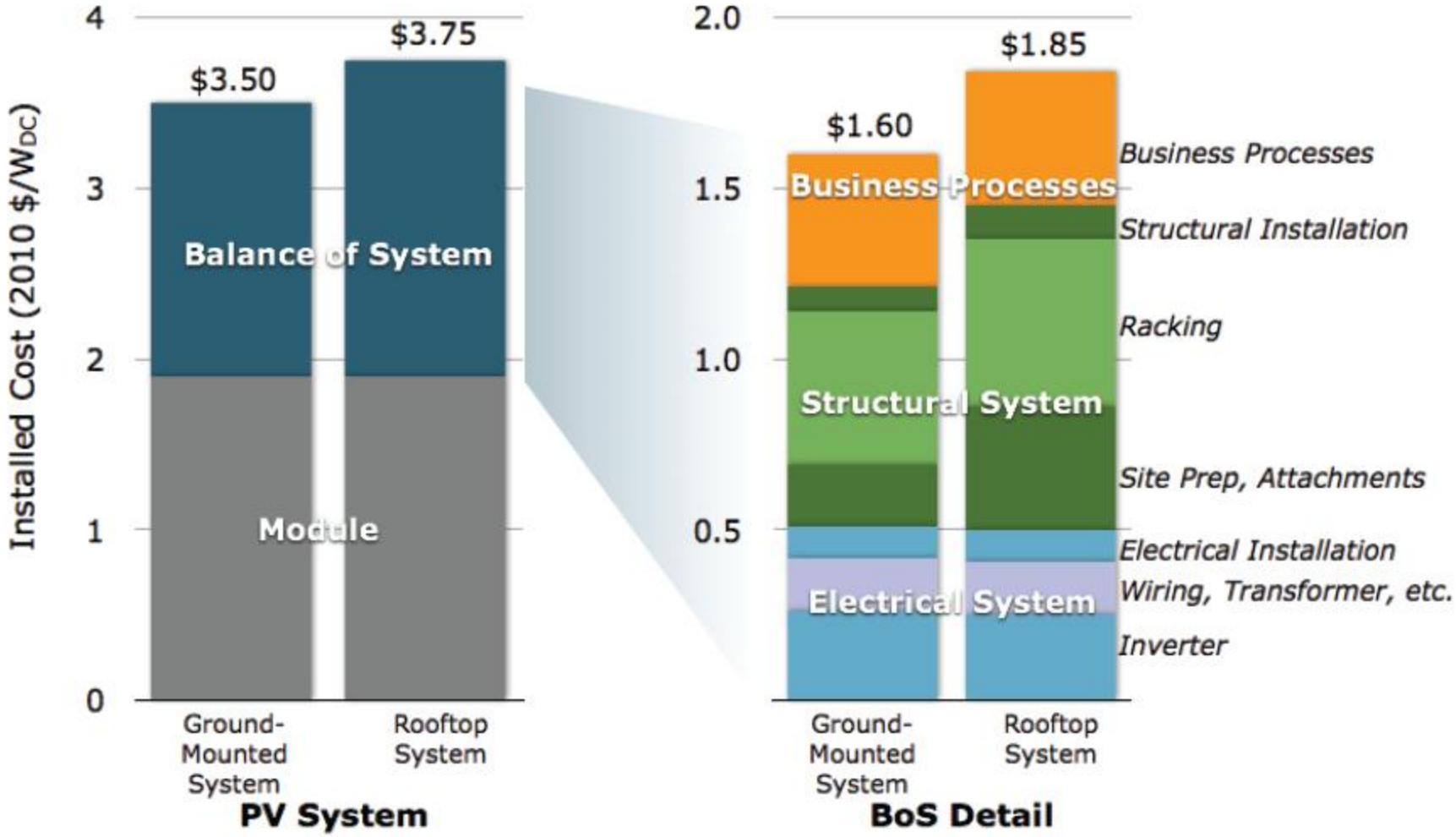
Cost Breakdown of Conventional U.S. PV Systems ca. 2010



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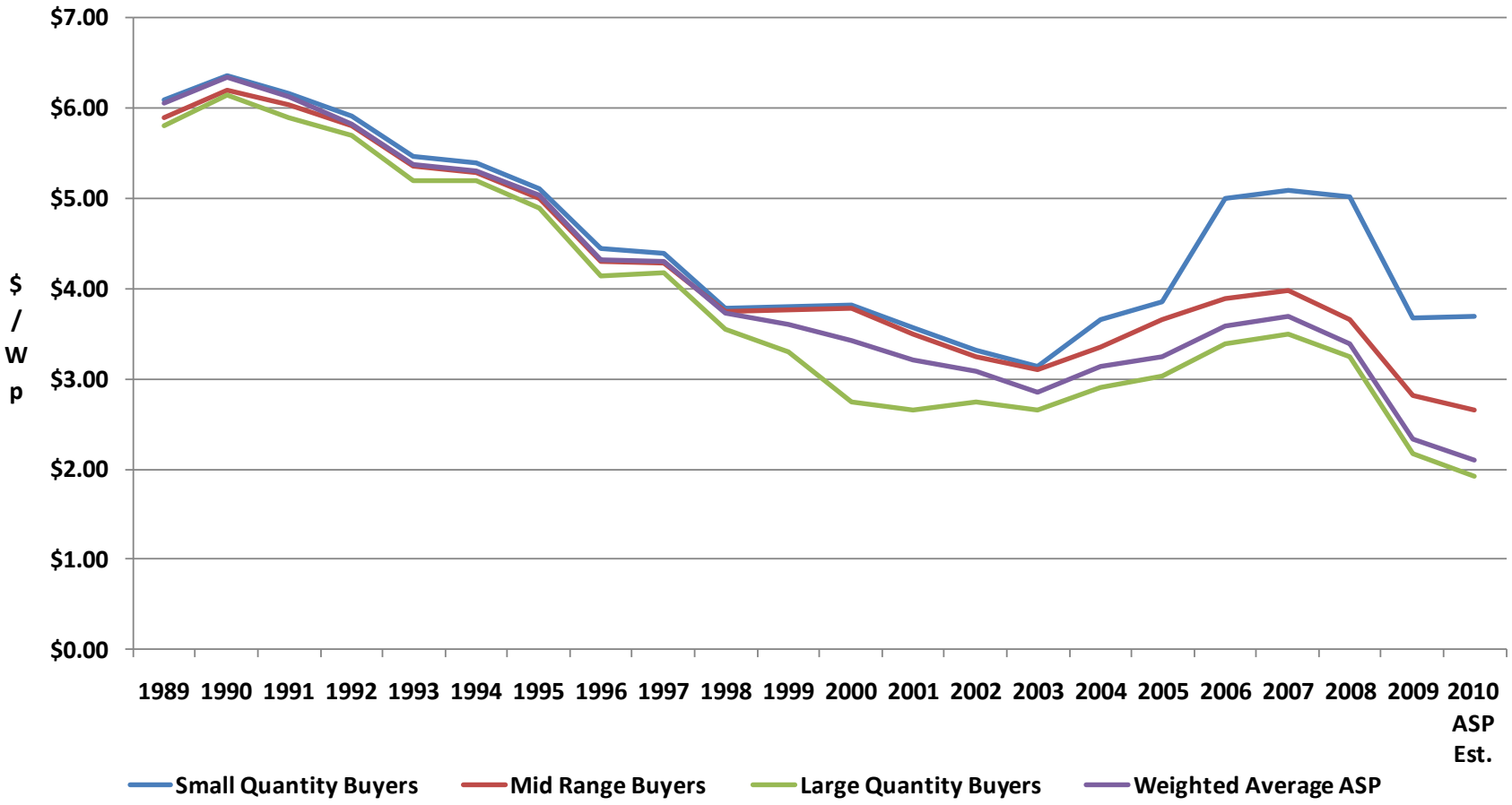
Rocky Mountain Institute Solar PV BoS Design Charrette 2010

Expect a Volume Price Influence



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Photovoltaic Systems Applications

Residential

Forest City Military Communities Plans to Install PV on 2300 homes in Hawaii starting in 2010 (courtesy FCHC)

Commercial-rooftop scale

Otay Mesa Border Crossing, San Diego: 274kW PV installed by GSA (courtesy SolarCity)

Building Integrated PV

Architecturally integrated as part of building structure

Utility-scale

PV Plant in Germany

Government Sector

Denver Federal Center

…and Off-Grid

Solar Tent courtesy of Iowa Thin Films

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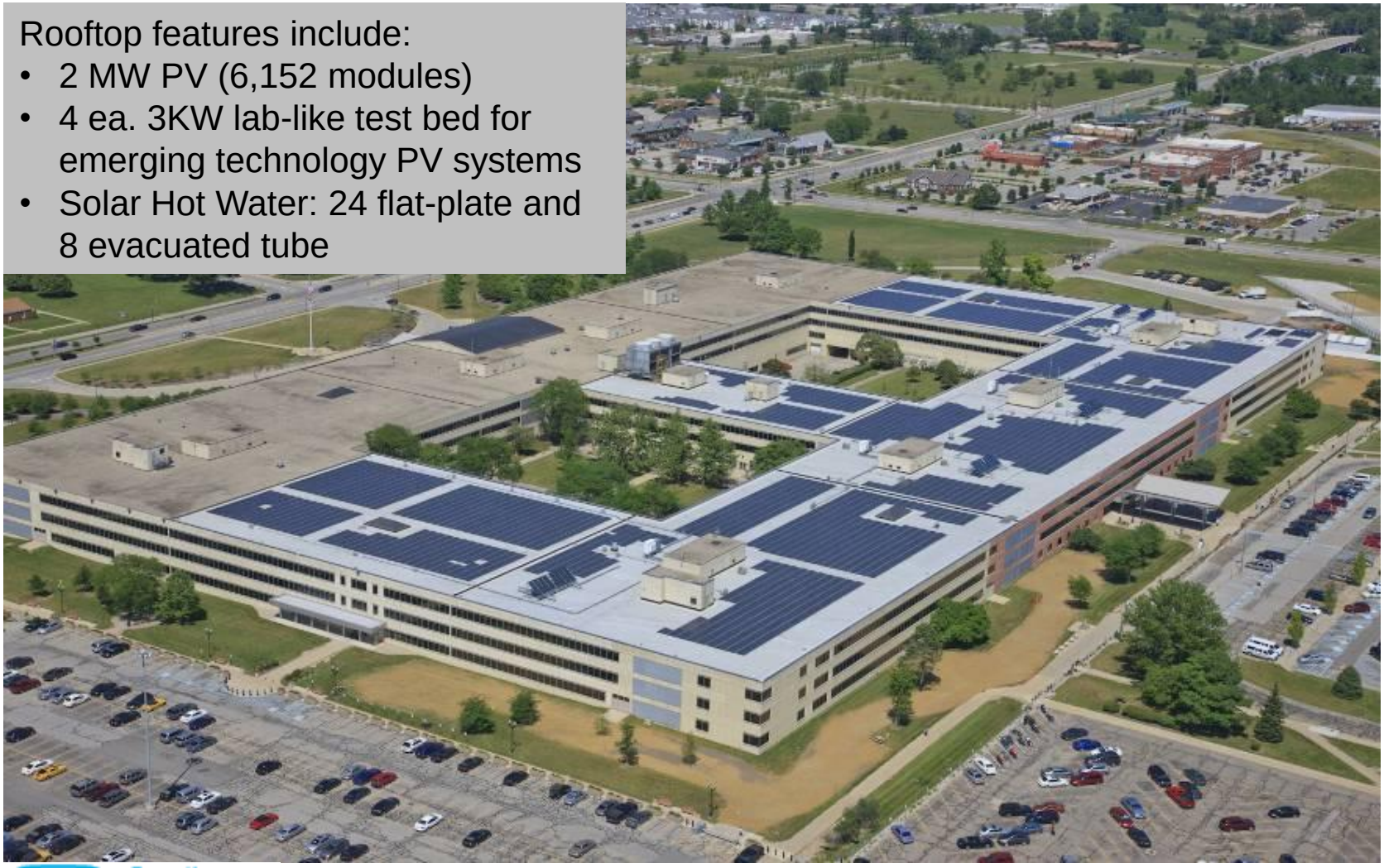
General Services Administration PV System Emmett Bean Federal Center, Ap 2010

Rooftop features include:

- 2 MW PV (6,152 modules)
- 4 ea. 3KW lab-like test bed for emerging technology PV systems
- Solar Hot Water: 24 flat-plate and 8 evacuated tube



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Emmett Bean Federal Center PV System

In the beginning…

PV Evaluation test-bed

2MW+ self-ballasted PV system

Lab-level meteorological system

Utility-Scale Projects Are Big Growth in US

World's largest plants (~80MW) in Canada, Europe
Current plans in US for 100's of MW

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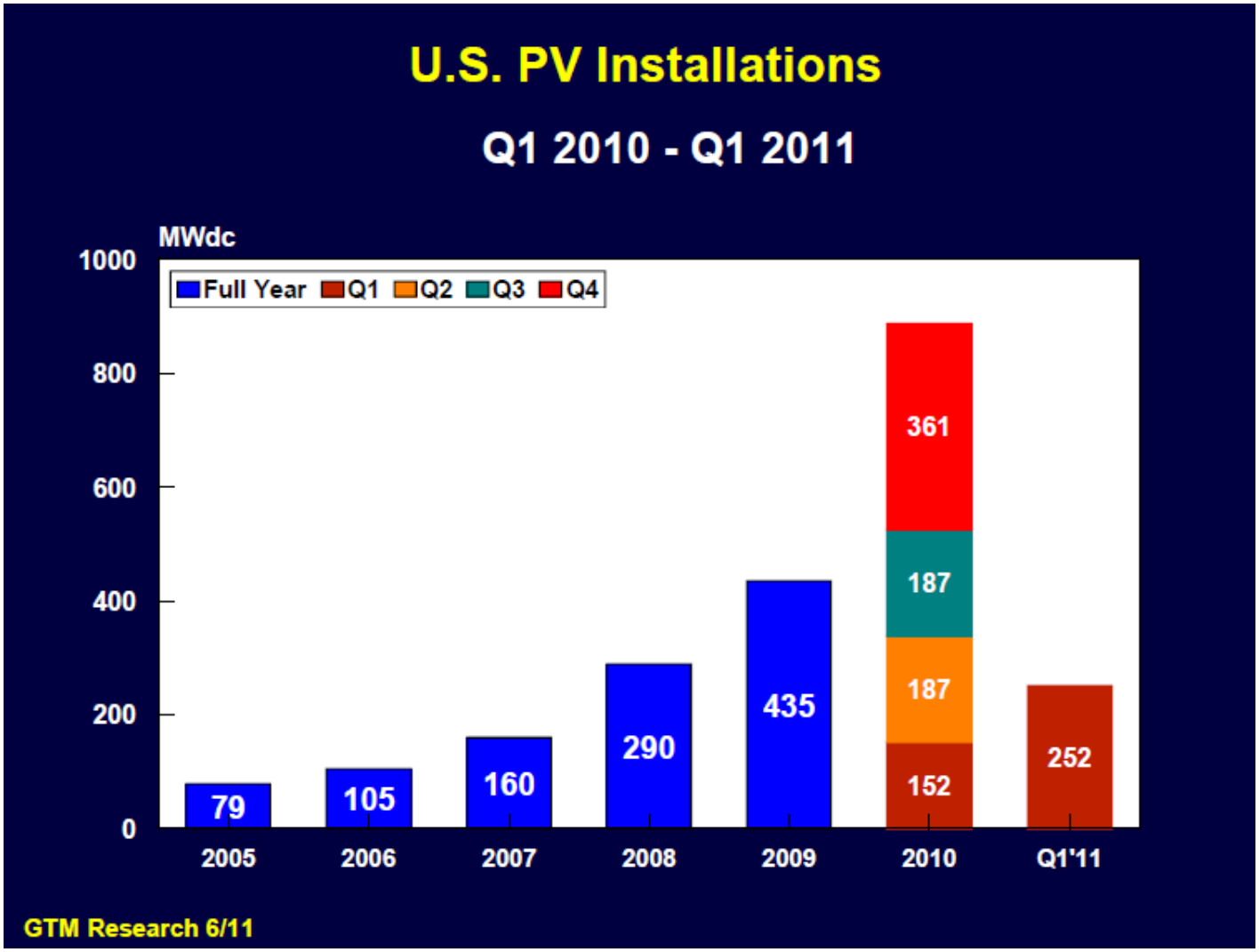
US Market for PV is very brisk right now!



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Outline of Presentation

- Background--Why PV in the US?
- What should you know about PV systems?—Cells, Modules, Inverters, BOS
- Where is PV used? Applications and Markets
- Summary

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Summary

- United States is very rich in the fuel that makes PV work—there is not likely to be shortage any time soon!
- PV is a “maturing technology” that presents cost, performance, and reliability competitive with many energy generation technologies.
- Growth is occurring for many reasons but the single biggest reason is confidence.

Committing to adoption is only the beginning!

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