Metastability of Amorphous Silicon

Historical Perspective and Real-Life Performance

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United Solar Ovonic

PV Module Reliability Workshop

Golden, CO

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Outline

- Staebler-Wronski effect and mitigation
- Flexible light-weight triple-junction laminates for roofing applications
- Outdoor behavior and energy yield
- Annual degradation
- Reliability
- How do we predict performance?
- Real life performance
- Summary

Staebler-Wronski Effect (1977)

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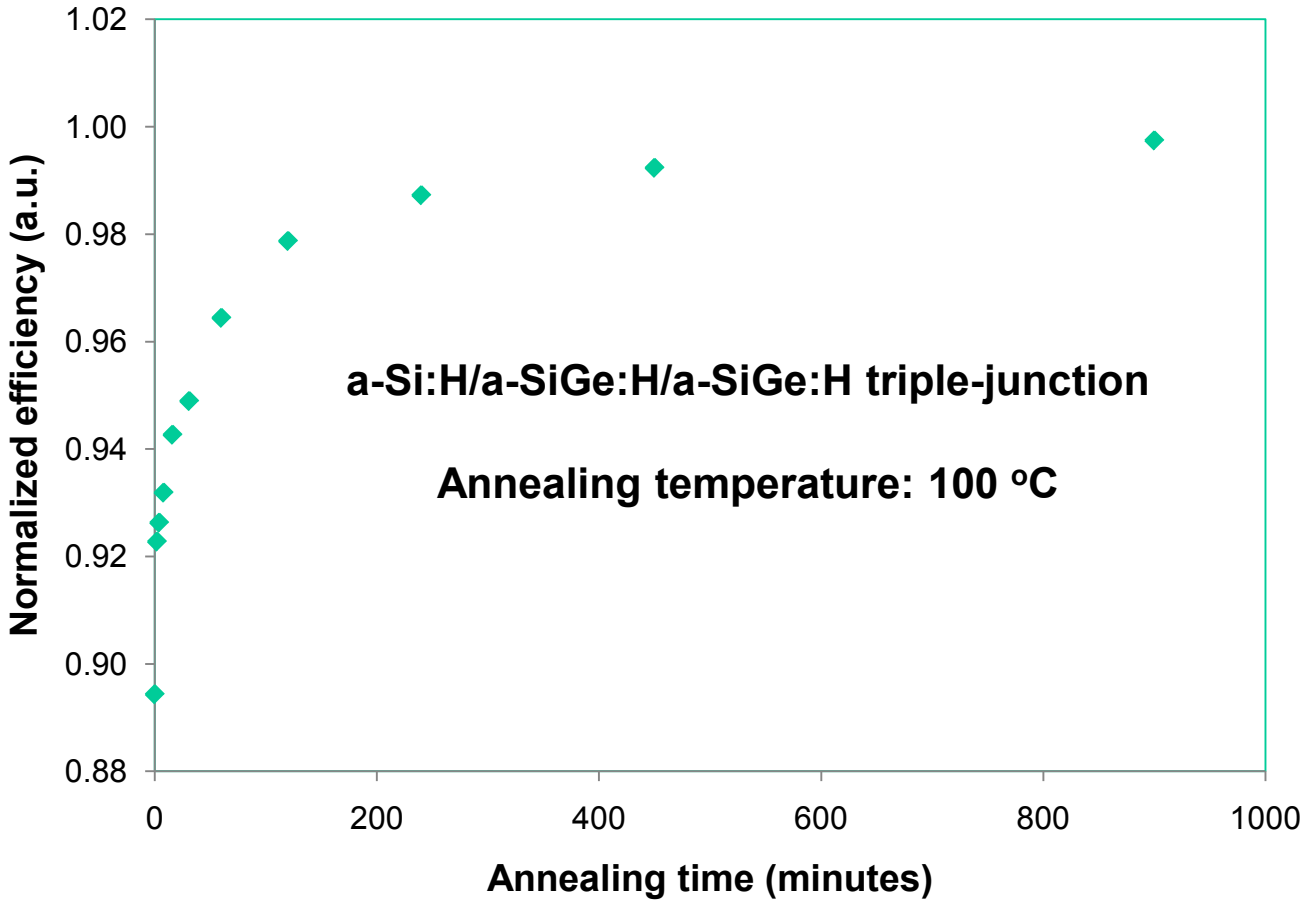
Reversible conductivity changes in discharge-produced amorphous Si[a)]

D. L. Staebler and C. R. Wronski

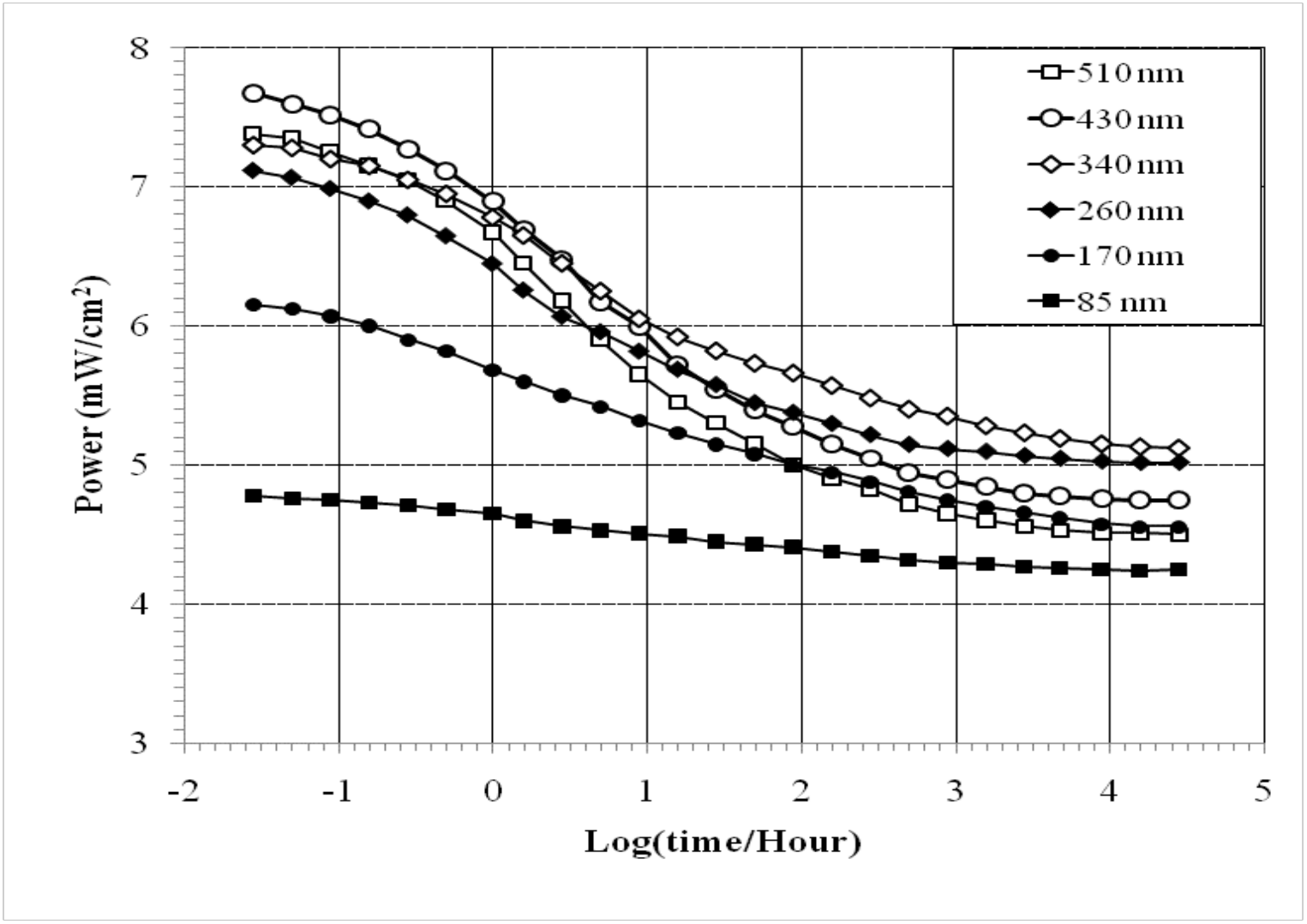
RCA Laboratories, Princeton, New Jersey 08540
(Received 9 May 1977; accepted for publication 17 June 1977)

A new reversible photoelectronic effect is reported for amorphous Si produced by glow discharge of SiH_4. Long exposure to light decreases both the photoconductivity and the dark conductivity, the latter by nearly four orders of magnitude. Annealing above 150°C reverses the process. A model involving optically induced changes in gap states is proposed. The results have strong implications for both the physical nature of the material and for its applications in thin-film solar cells, as well as the reproducibility of measurements on discharge-produced Si.

Effect of Thermal Annealing



Thick a-Si layer causes more degradation



Approaches for Improving a-Si cells

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- Improve materials using hydrogen dilution during film growth
- Incorporate light trapping in cell design
- Adopt multi-junction cell structures
- Rate products at their stabilized power

Effect of hydrogen dilution on a-Si cells

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Hydrogen dilution	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	Eff. (%)
Near-optimum	10.04	1.018	0.732	7.48
Optimum	*9.88*	*1.028*	*0.761*	*7.73*
On-the-edge	9.82	0.624	0.426	2.61
Over-the-edge	8.95	0.459	0.562	2.31

Effect of Hydrogen Dilution

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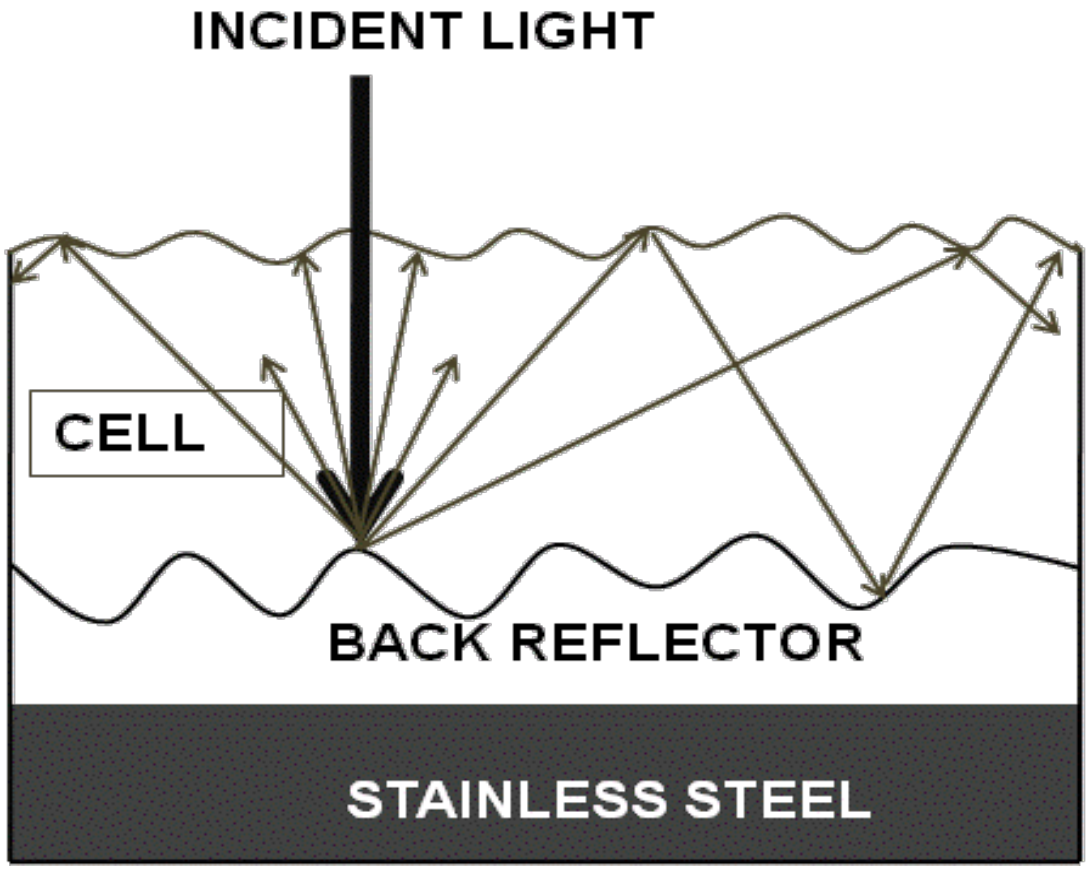
Description	State	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	Eff. (%)
a-Si, low dilution, 300 °C	Initial	12.3	0.94	0.65	7.5
	Degraded	11.6	0.91	0.55	5.8
a-Si, high dilution, 300 °C	Initial	11.6	0.96	0.68	7.6
	Degraded	11.2	0.94	0.61	6.4
a-Si, low dilution, 175 °C	Initial	11.4	0.96	0.64	7.0
	Degraded	9.5	0.91	0.46	4.0
a-Si, high dilution, 175 °C	Initial	10.9	1.00	0.69	7.5
	Degraded	10.5	0.97	0.60	6.1
a-SiGe, low dilution	Initial	17.6	0.72	0.55	7.1
	Degraded	14.9	0.64	0.41	3.9
a-SiGe, high dilution	Initial	18.0	0.74	0.59	8.0
	Degraded	16.3	0.69	0.45	5.1

Light Trapping



Light Trapping Effect

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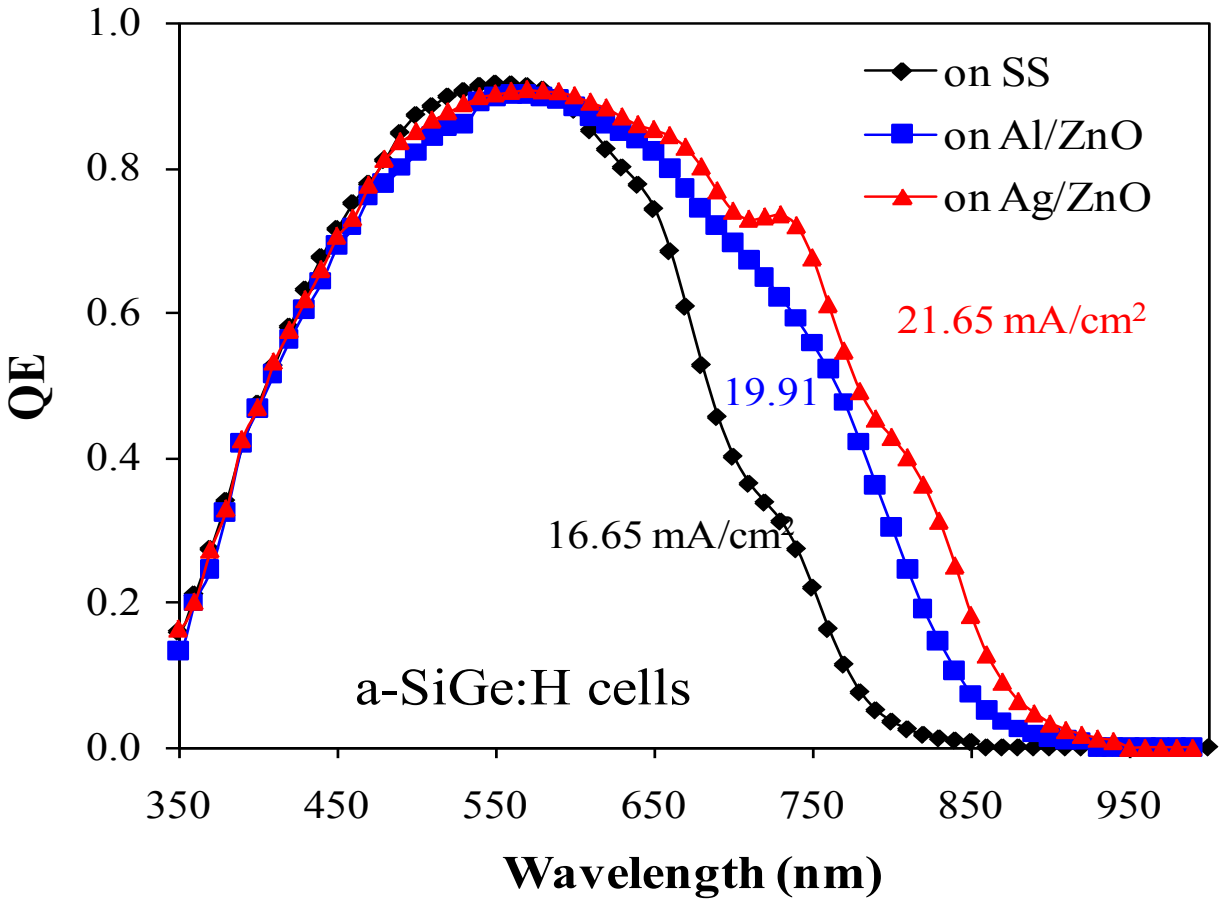
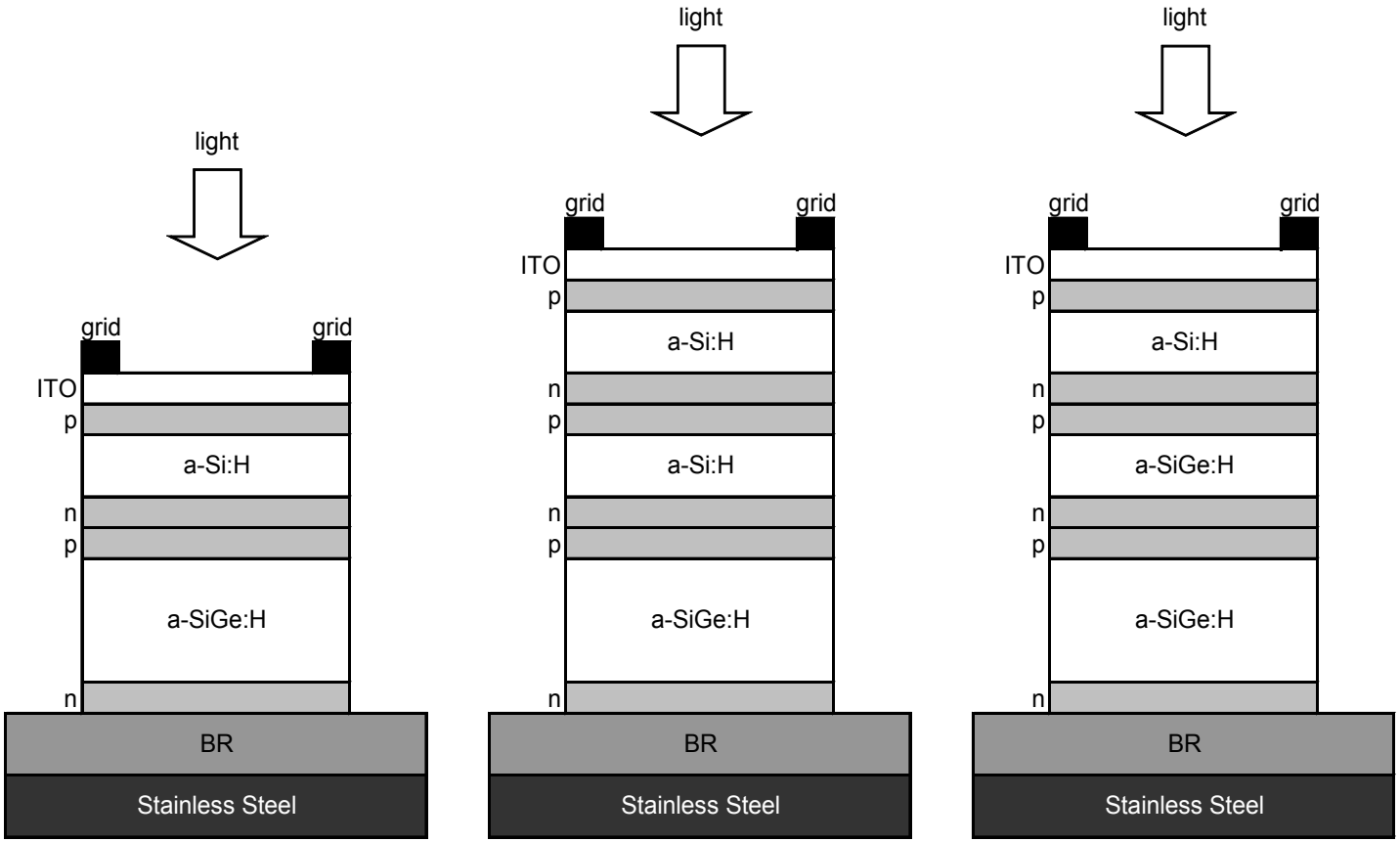
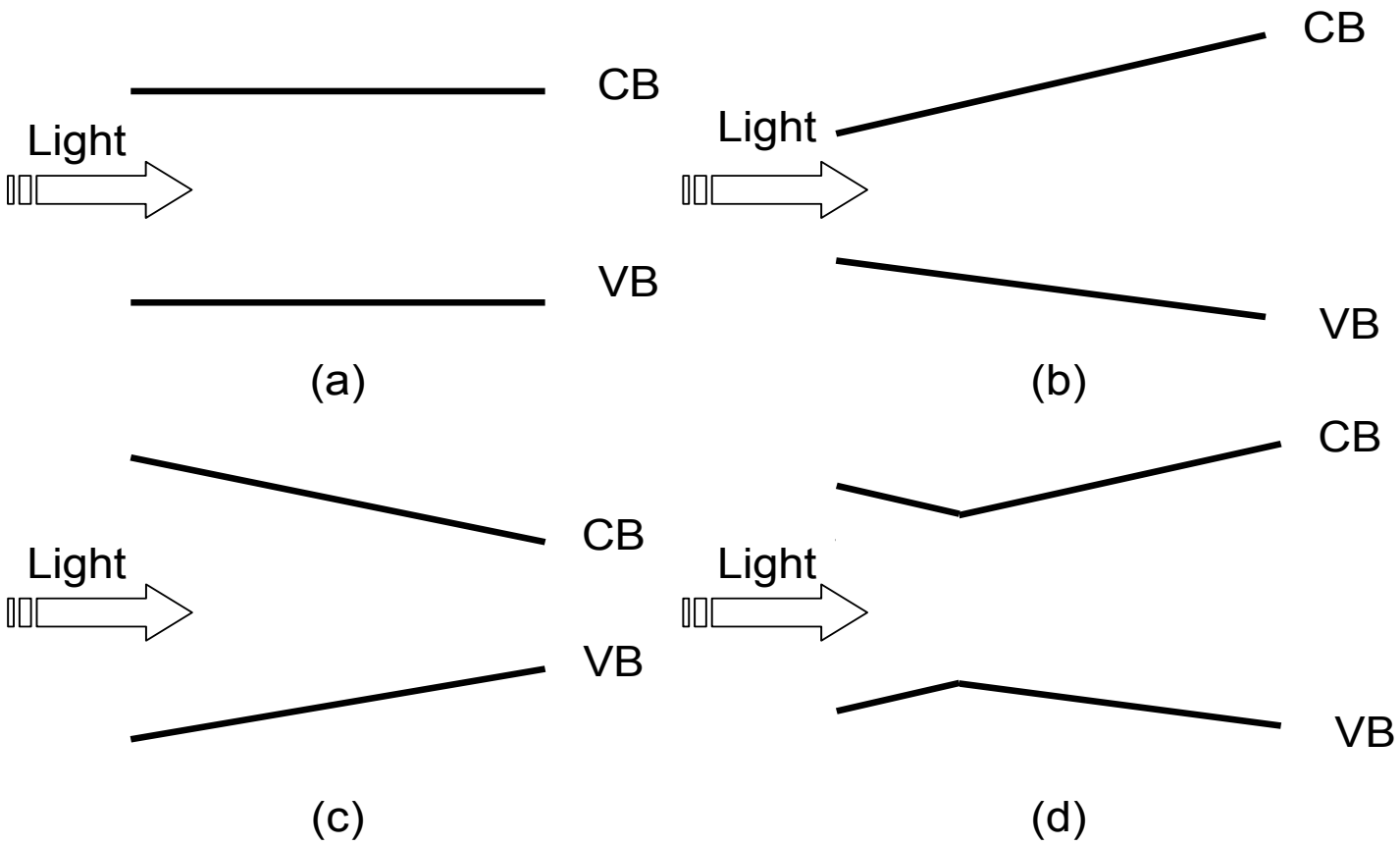
a-SiGe:H cell on ss, Al/ZnO, & Ag/ZnO



Multi-junction cells using a-Si:H & a-SiGe:H

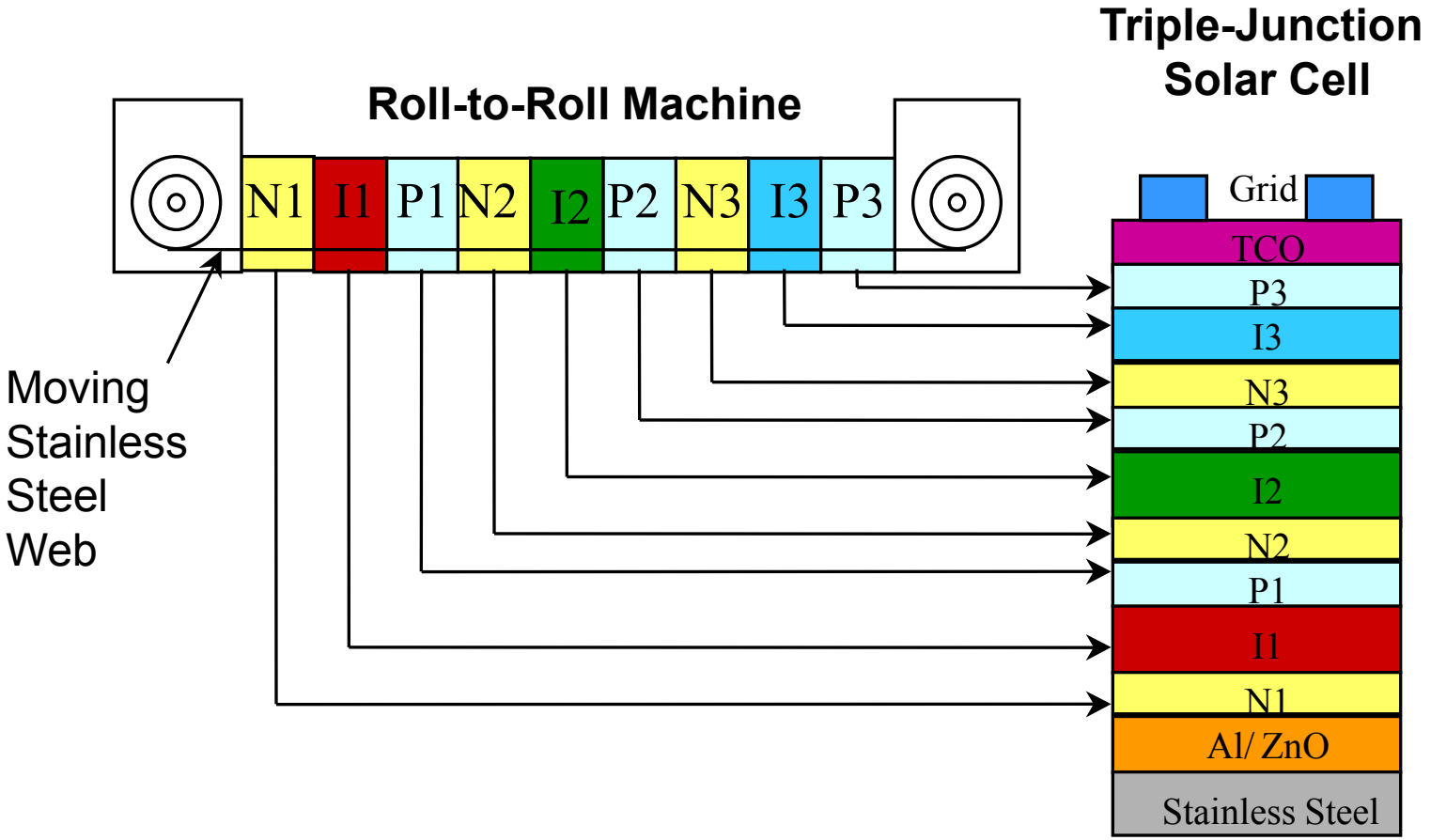


Ge profiling in a-SiGe:H cells



Manufacturing

ROLL-TO-ROLL DEPOSITION PROCESS



UNI-SOLAR Laminates are Unique

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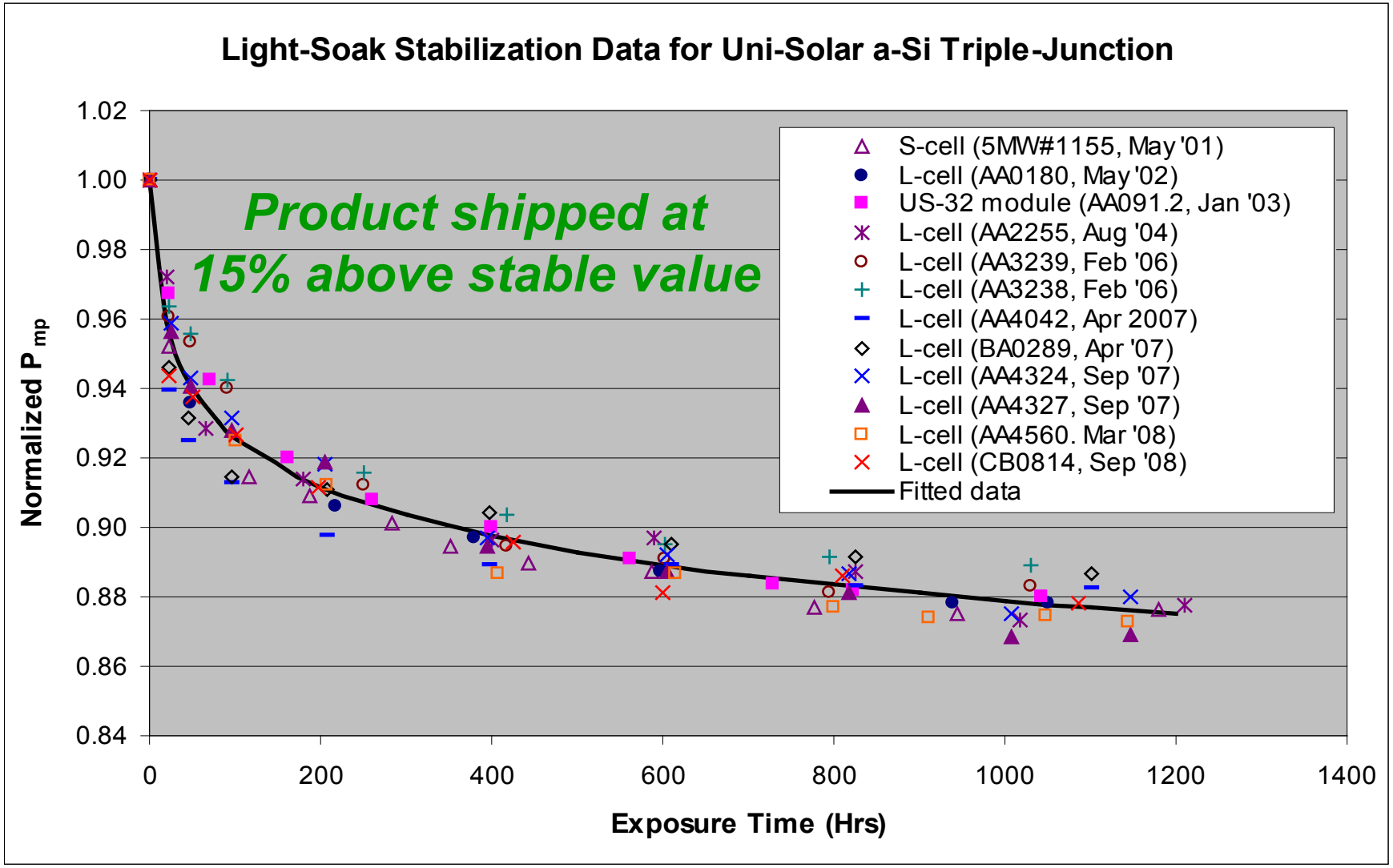
Conventional Solar Cells

UNI-SOLAR® Laminates

Historical indoor light-soak data



A DIFFERENTIATED PRODUCT

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Rome, Italy
Rome Trade Fair

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Commune St. Georges de Montaigu

A DIFFERENTIATED PRODUCT

UNI-SOLAR®

Coca-Cola Plant
Los Angeles, California

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Yuba City School District

Yuba City, California

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New 25MW Project with Enel Green Power

Buildings owned by CIS-Interporto di Nola in Italy

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The World's Largest Rooftop Installation
12MW - Zaragoza, Spain

Uni-Solar
PRODUCT FEATURES

Higher Energy Yield (kWh/kW)

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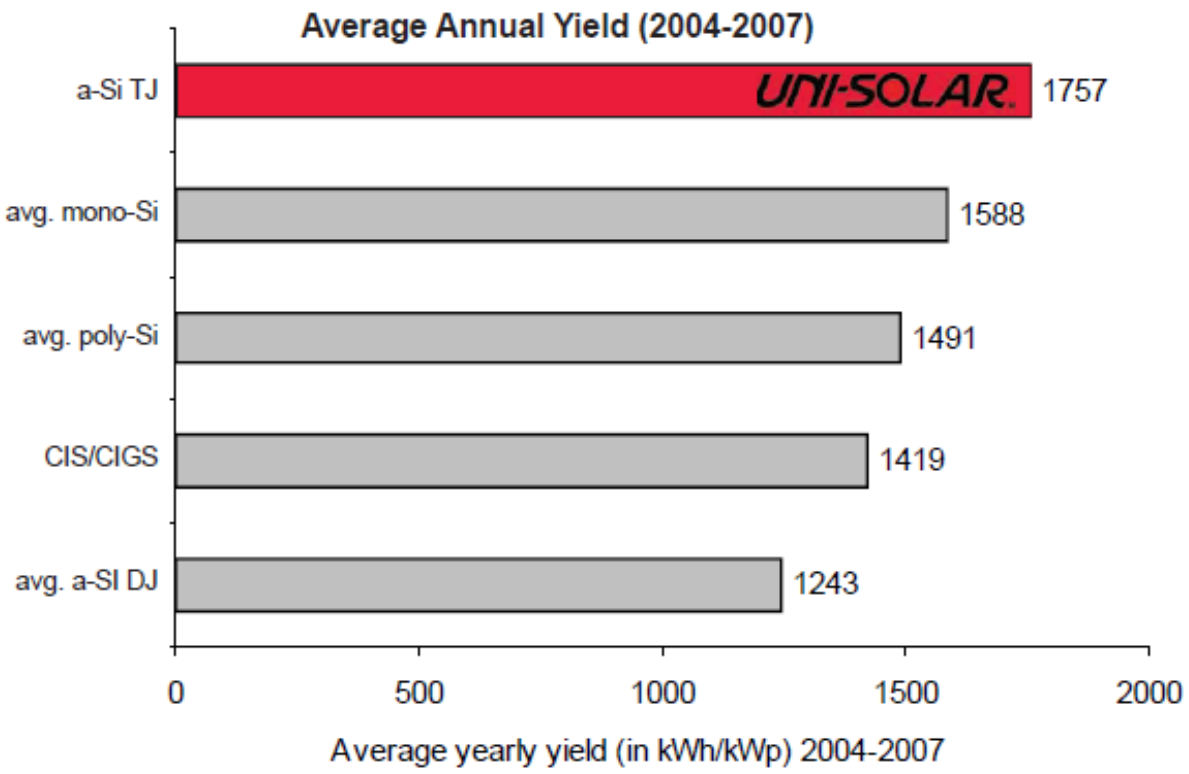
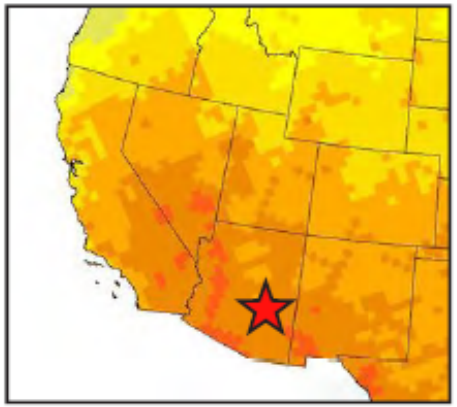
Site: Tucson, Arizona, USA
Source: Tucson Electric Power, Arizona, USA





USO Surplus versus:
Avg. mono-Si: +11%
Avg. poly-Si: +18%
CIS/CIGS: +24%
Avg. a-Si: +41%

Higher Energy Yield (kWh/kW)

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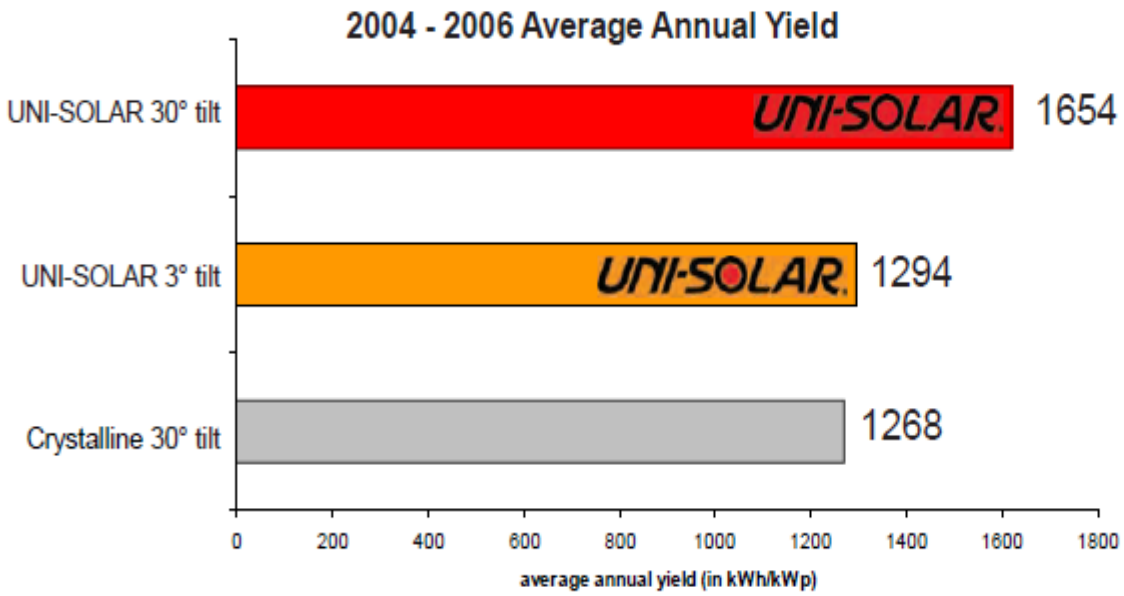
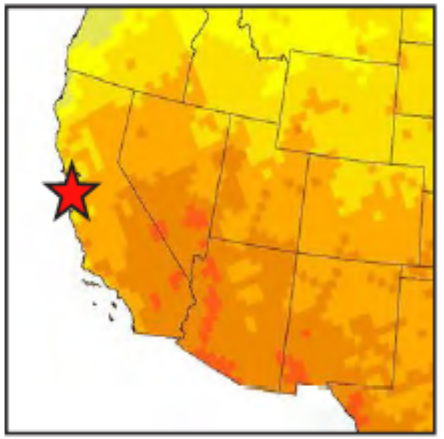
Site: Santa Cruz, California, USA
Source: Solarquest Report





USO 30° Tilt Surplus versus:
USO 3° Tilt: +28%
Crystalline 30° Tilt: 31%

Higher Energy Yield (kWh/kW)

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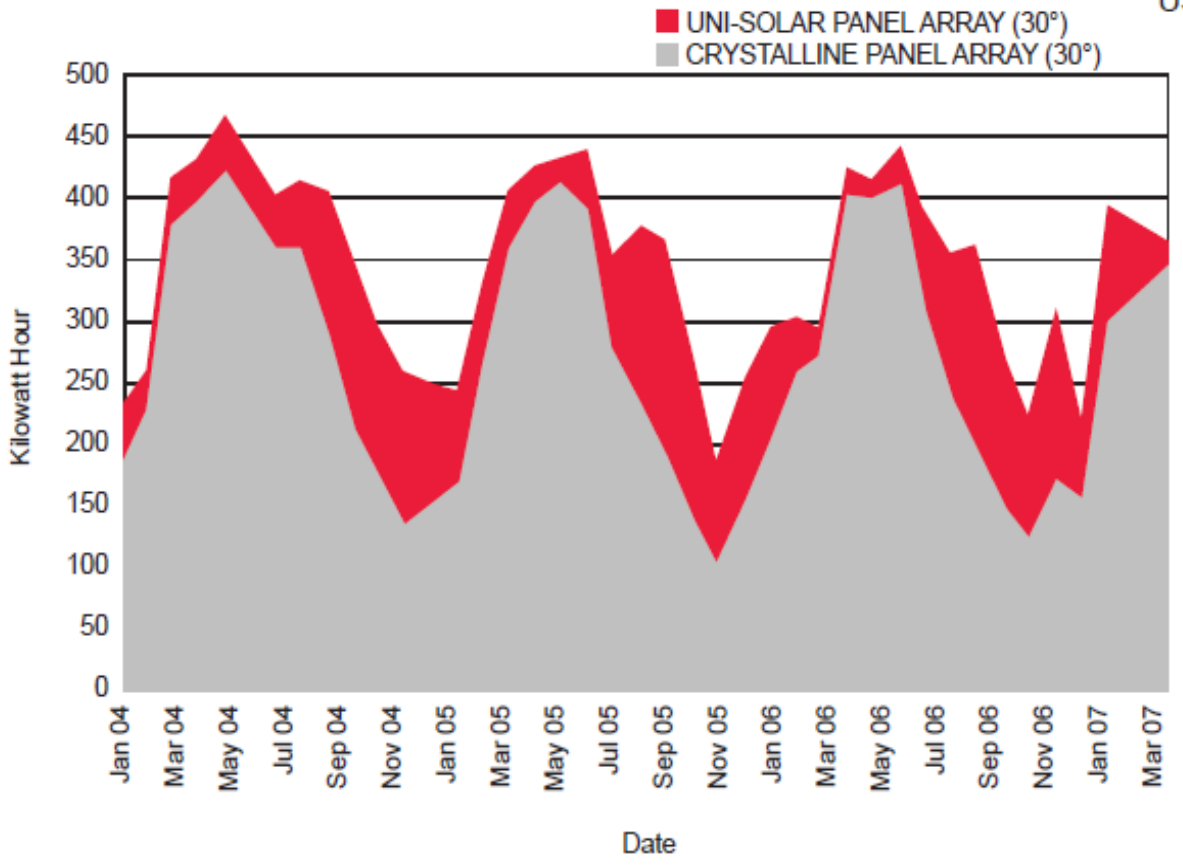
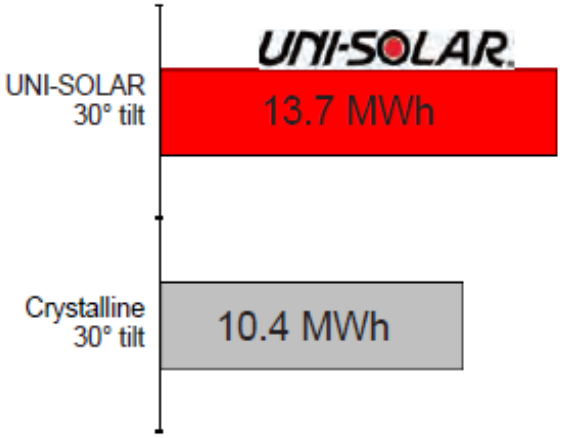
Santa Cruz Test Site
Energy Production Performance Summary



Cumulative Power Production
November 2003 - March 2007
USO Surplus versus Crystalline: +31%



Higher Energy Yield (kWh/kW)

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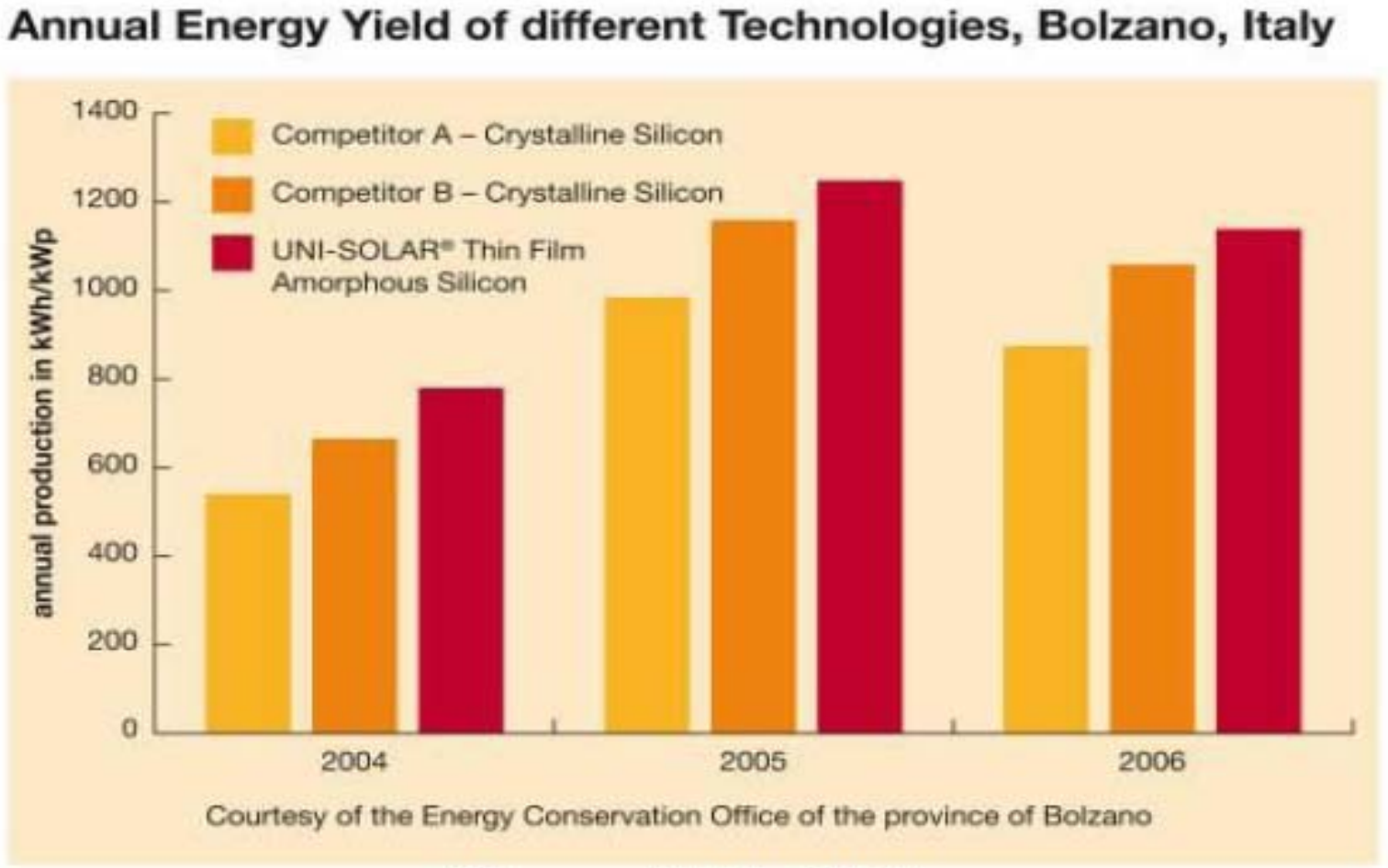
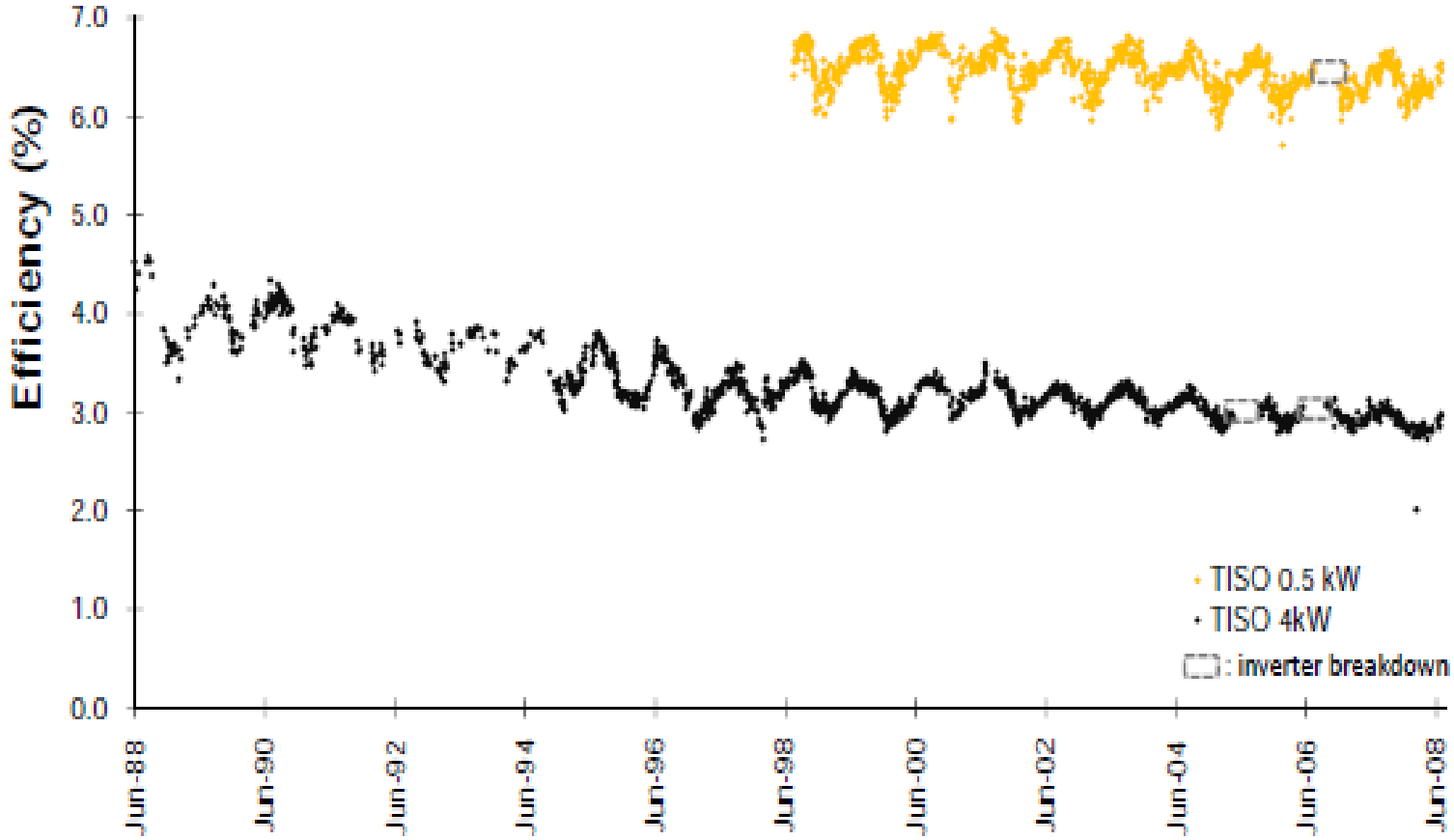


More kWh/kW

Long Term Behavior (single vs. triple junction)



Annealing effect improves summer performance

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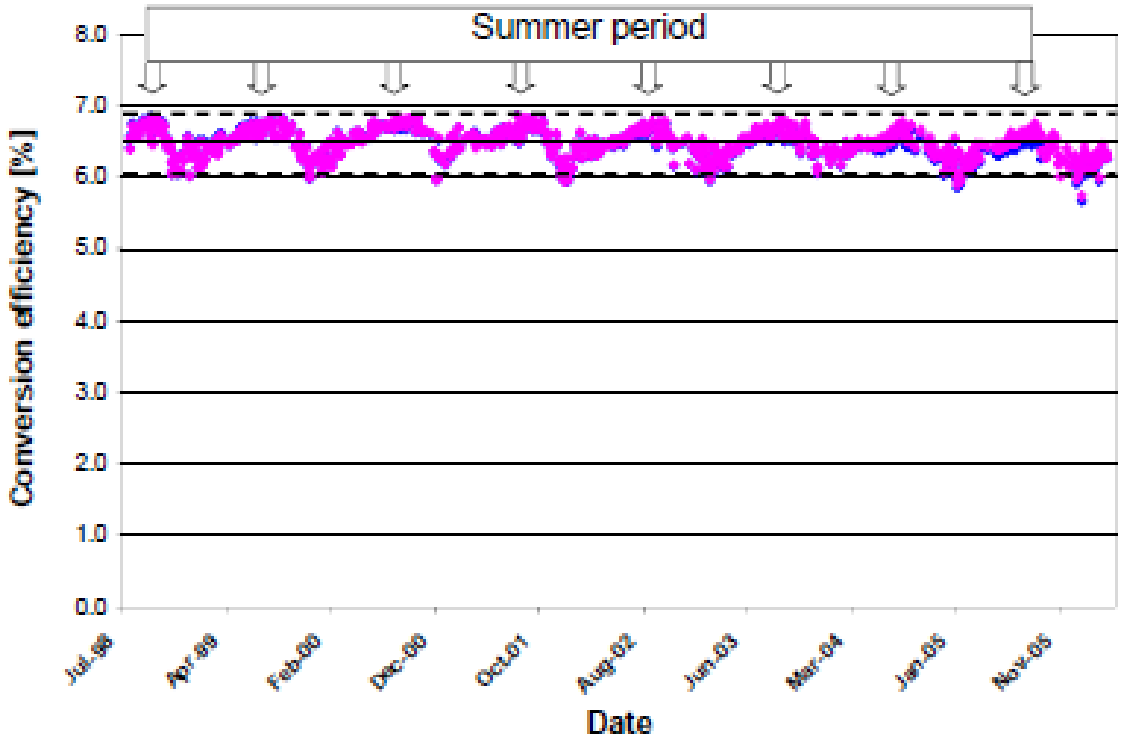
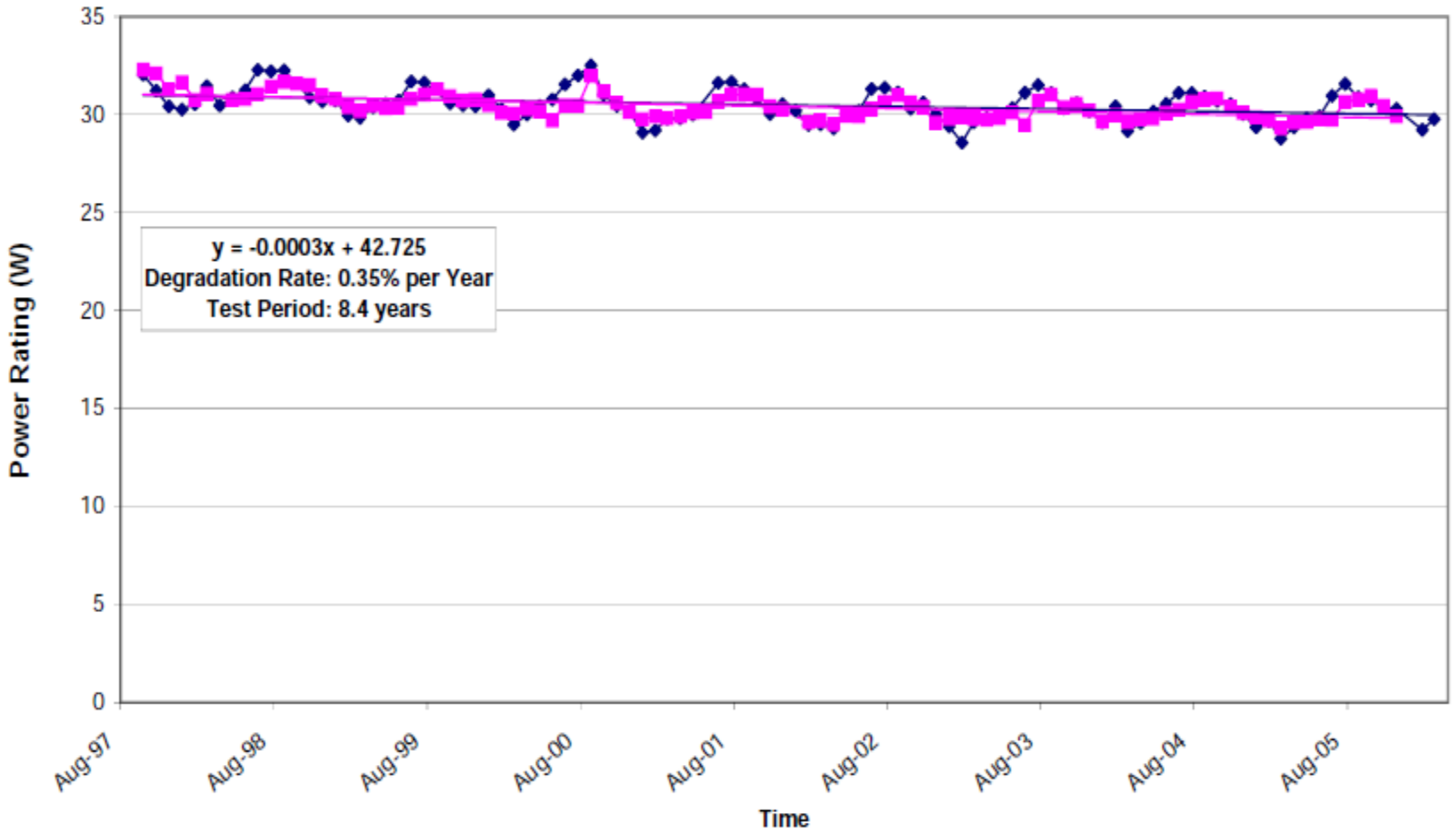
Results in Switzerland



Site: Lugano, Switzerland
Horz. Irradiance: 1234 kWh/m2
Tilt: 30°
Size: 0.5 kWp
Inverters: Dorfmueller
Installed Year: 1998
Source: TISO – ISAAC Institute - SUPSI – University of Ticino, Switzerland

UNI-SOLAR modules typically show their peak in efficiency during SUMMER periods, opposite to crystalline modules. This is due to the annealling effect of a-Si, which gradually improves the conversion efficiency in the warm period of the year.

Long Term Degradation, Golden, CO (1997 – 2006)



Long Term Degradation Studies

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3rd party studies on Triple Junction installations

Location	Climate	Test Institute	Size	First Year	Data Range	Annual Degr. (%/Yr)
Golden, CO, USA	Hot & Dry	NREL	0.032 kWp	1997	1997-2006	0.39
Juelich, Germany	Temperate	KfZ-Juelich	0.032 kWp	1998	1998-2004	0.14
Lugano, Switzerland	Temperate	TISO-ISSAC	0.5 kWp	1998	1998-2007	0.33
Freiburg, Germany	Temperate	ISE-Freiburg	2 kWp	2001	2002-2007	0.10
Cocoa, FL, USA	Hot & Humid	FSEC	1.2 kWp	2003	2005-2007	0.58
Golden, CO, USA	Hot & Dry	NREL	1.2 kWp	1998	1998-2004	0.98
Average Degradation Rate: 0.42% per year Weighted Average Degradation Rate: 0.49% per year						

- *UNI-SOLAR* products have been extensively tested for long durations at third party sites
- The degradation rates are: 0.42% per year average; 0.49% per year weighted average

Long-term Degradation

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What causes the 0.3% -- 1% annual degradation?

- **EVA yellowing?**
- **Dirt?**
- **Contacts?**

Reliability

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- **What causes the field failure?**

  Accelerated tests, such as IEC 61646, has improved reliability significantly

- **Manufacturing defects**
  - **Contacts**
  - **Shunts**
  - **Poor encapsulation**
- **Improper installations**
- **Manufacturers and installers need to be more vigilant**

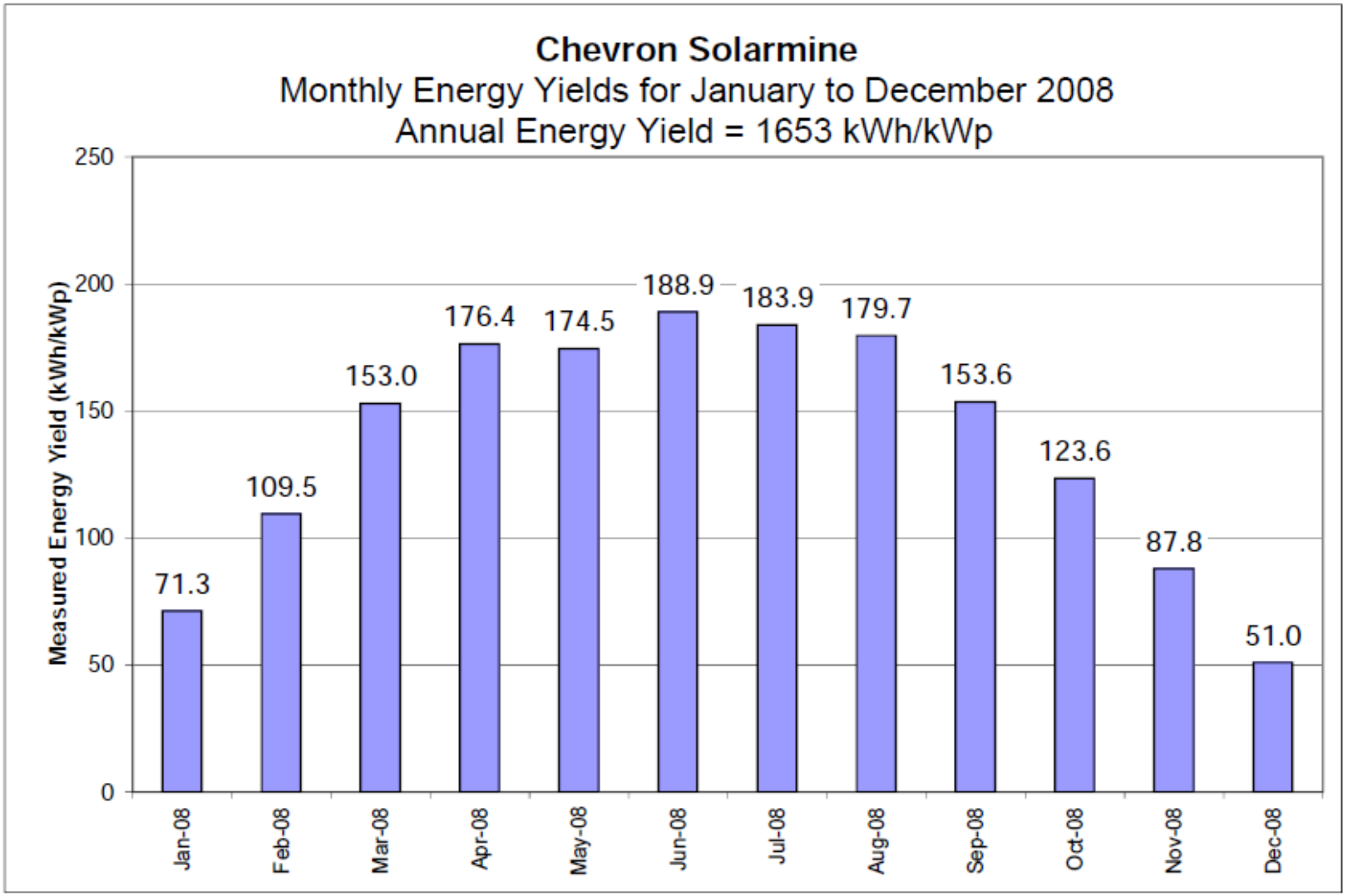
Predict System Performance

- SAM
- PVSYST
- None considers the annealing effect
- Real life temperature dependence is flat rather than -0.2%/ ^{O}C

Chevron Solarmine, California

Chevron Solarmine
Fellows, CA (near Bakersfield)
614 kWp

Real Life Data



Models

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	PVWATTS Energy Yield (kWh/kW_p)	PV*SOL Energy Yield (kWh/kW_p)	PVSYST Energy Yield (kWh/kW_p)	Measured Energy Yield Chevron Solarmine Jan. 2008 to Dec. 2008 (kWh/kW_p)
Tilt: 20°	1457	1669	1629	1653
Losses	• Soiling: 5% • Mismatch: 2% • Spectral & Climate: 0% • Diode: 0.5% • Cable: 3%	• Soiling: 2% • Mismatch: 2% • Spectral & Climate: 1% • Diode: 0% • Cable: 2%	•Soiling: 2% •Mismatch: 2% •Spectral & Climate: 1% •Diode: 0% •Cable: 2%	-

Used default values for PVWATTS

Summary

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- Staebler-Wronski effect is reversible upon thermal annealing
- The triple-junction structure with high quality material results in improved module performance featuring higher kWh/kW
- Reliability has been much improved; 25 year warranty is being offered
- Long-term degradation still exists and needs better understanding
- Performance prediction should include thermal annealing to reflect real-life conditions