SUNPOWER™

Module information for arpa-e ADEPT workshop, Washington, D.C. 2-8-2011

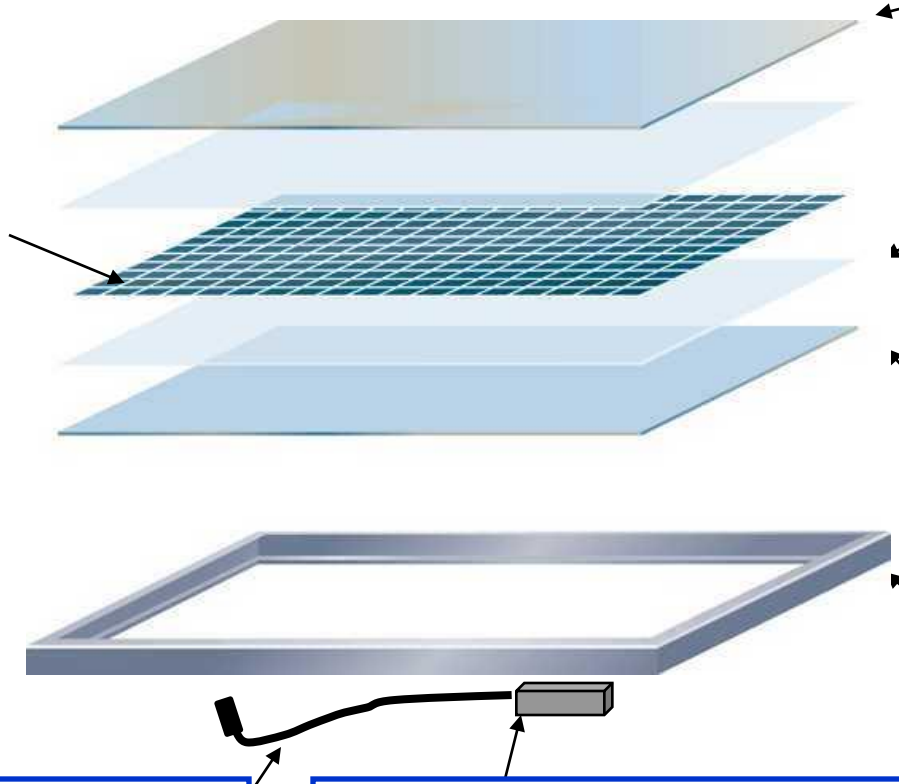
Doug Rose

SunPower Corporation

© 2011 SunPower Corporation

Common solar module construction

Stringed cells



Glass
Low iron AR/Non-AR (environmental protection, mechanical strength)

Encapsulant
EVA = Ethyl Vinyl Acetate (adhesive for cell, glass and backsheet)

Backsheet
TPE = Tedlar / Polypropylene / EVA (dielectric insolation, environmental protection)

Frame
(mechanical)

Wires/Connectors

Junction Box (electrical terminals, bypass diodes)

© 2011 SunPower Corp.

Very rough typical costs for standard modules

- Rough costs to simply give a sense for typical module conversion costs
  - Note: there is a big range, plus and minus, from these values
  - Includes labor, materials, labor, depreciation, overhead, yield

Step cost	$ for 1.65 m2 module	$/W for 14.5% effic. module (240W)
Cell interconnect + circuit formation	$10	$0.04
Glass/encapsulant/backsheet/ frame/packaging/test	$60	$0.25
Wires+connectors	$5	$0.02
Junction box	$8	$0.03
Diodes	$1	$0.004
	$84	$0.35

- Total module costs continue to fall
  - Trina in-house costs of $1.08/W in Q3'2010 (average 14%?, 180W?)
  - First Solar costs of $0.77/W in Q3'2010 (average 11.3%, 81W)

© 2011 SunPower Corp.

Other connection approaches

- SunPower all-back contact

- Day4 energy wire mesh

25th European Photovoltaic Solar Energy Conference and Exhibition /
5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spai

DAY4™ TECHNOLOGY FOR CONCEPTUALLY NEW PV MODULE PRODUCTIO

B. Sadlik, L. Rubin, V. Nebusov

Day4 Energy Inc., 8168 Glenwood Drive, Burnaby, BC, Canada
bsadlik@day4energy.com, phone: +1.604.296.0417, Fax: +1.604.678.6986
www.day4energy.com

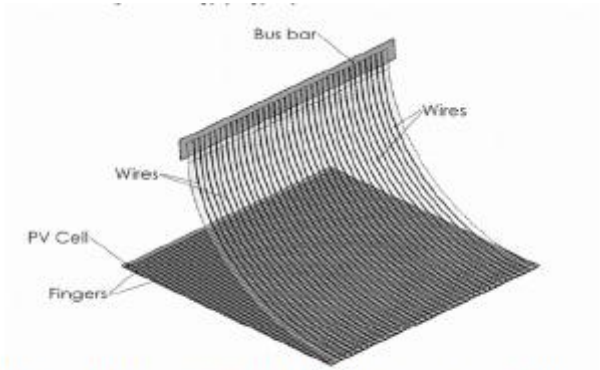
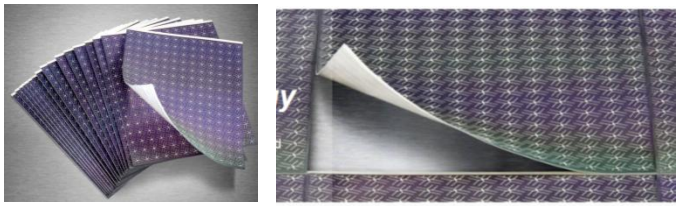


Figure 2: Placement of the Day4™ electrode on a PV cell.

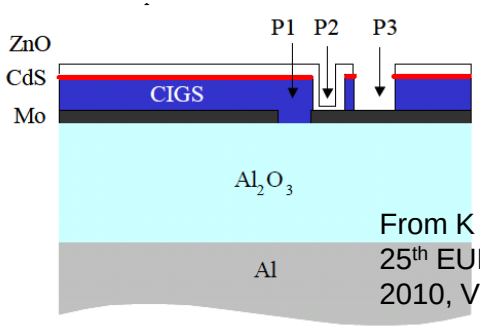
© 2011 SunPower Corp.

Some thin film examples

- Monolithic on glass
  - First Solar CdTe
  - Applied Materials a-Si
  - Solar Frontier CIGS
- Singulation then tile connect
  - NanoSolar
- Singulation then string like cSi cells
  - Global Solar
- Monolithic on foil then connect
  - Unisolar
  - Fuji
  - Ascent



Photos from Nanosolar.com



From K Moriwaki, et. al, 25th EUPVSEC, Sept 2010, Valencia, Spain

“Monolithic module assembly” with cSi

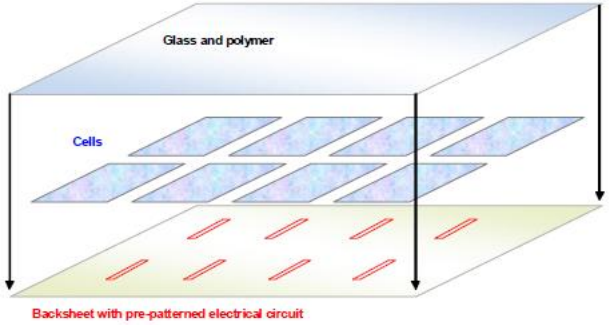
- Years of effort and progress, but not yet in large scale production

25th European Photovoltaic Solar Energy Conference and Exhibition /
5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain

– Applied Materials

DEVELOPMENT AND QUALIFICATION OF MONOLITHICALLY ASSEMBLED MODULES FOR BACK CONTACT PV CELLS

David H. Meakin*, James M. Gee, John Telle, William Bottenberg
Applied Materials, Inc.,
3535 Garrett Drive, Santa Clara, CA 95054 (USA), *Email: David_Meakin@amat.com



– ECN

module, which shows the placement of the different components, is given in Figure 2.

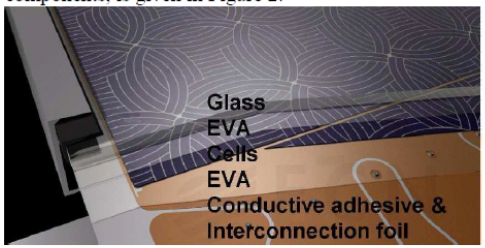


Figure 2: Illustrative image of the MWT module, showing the placement of the different components.

Module manufacturing is performed in our automated pilot line, a photo of the pilot line is shown in Figure 3.

To show the progress made with MWT the efficiency distribution on mc-Si cells from the last 7 years is depicted in Figure 4.

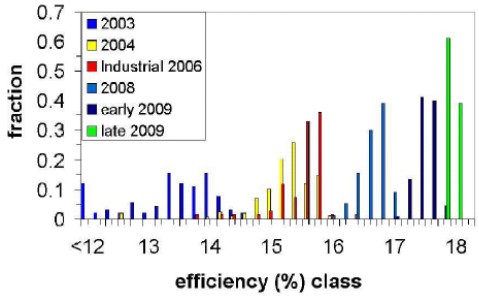
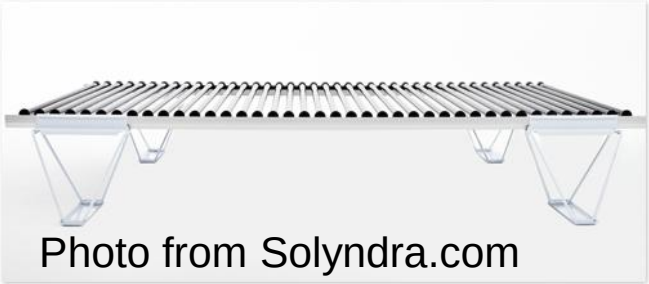


Figure 4: ECN-MWT efficiency throughout the years.

“Module” can include mounting approach

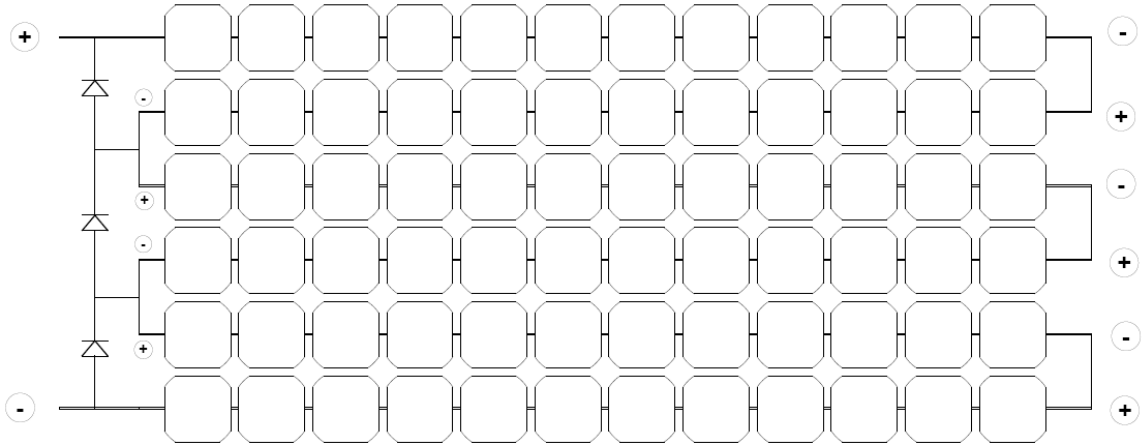
- SunPower T5 system
  - Integrated, non-penetrating roof mount
  - Fast installation
  - High density, low weight (2.4 lb/ft^2; 7 W_p/ lb)

- Solyndra and others have their own unique approaches



Bypass diodes

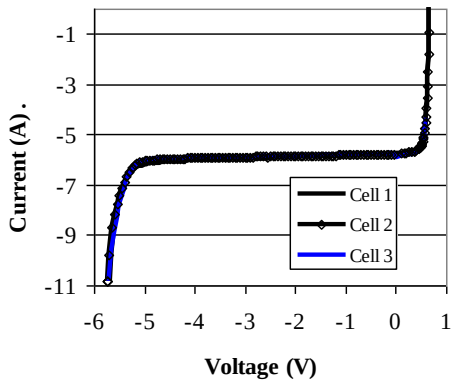
- By-pass diode in common modules:
  - Bypass diode will be in forward bias (and thus bypass the string) if string pair would otherwise be in reverse bias
  - For *some* modules, the diodes are needed to protect against hot spots (from localized shunting of high reverse-bias voltage) which could cause module damage
  - Diodes *can* be a major failure point if best practices are not followed
    - Poor quality diodes in hot conditions
    - Insufficient lightning protection



© 2011 SunPower Corp.

Many cell types have integrated bypass diode characteristics

- IV curve of a SunPower cell:
  - Uniform non-damaging reverse breakdown at ~-5.5V



United States Patent [19]
Swanson

[11] **Patent Number: 4,933,022**
[45] **Date of Patent: Jun. 12, 1990**

[54] **SOLAR CELL HAVING INTERDIGITATED CONTACTS AND INTERNAL BYPASS DIODES**

[75] Inventor: **Richard M. Swanson**, Los Altos, Calif.

Cells", *IEEE Transactions on Electron Devices*, vol. ED-31, No. 5, May 1984, pp. 661-664.
"Point-Contact Silicon Solar Cells", Interim Report, Stanford University, May 1983, EPRI AP-2589 Project 769-2.

(12) **United States Patent**
Armstrong et al.

(10) **Patent No.: US 6,690,041 B2**
(45) **Date of Patent: Feb. 10, 2004**

(54) **MONOLITHICALLY INTEGRATED DIODES IN THIN-FILM PHOTOVOLTAIC DEVICES**

(75) Inventors: **Joseph H. Armstrong**, Littleton, CO (US); **Scott Wiedeman**, Tucson, AZ (US); **Lawrence M. Woods**, Erie, CO (US)

(73) Assignee: **Global Solar Energy, Inc.**, Tucson, AZ (US)

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,323,719 A		4/1982	Green	
4,577,051 A		3/1986	Hartman	
4,759,803 A		7/1988	Cohen	
4,773,943 A	*	9/1988	Yamaguchi et al.	136/244
4,933,022 A		6/1990	Swanson	
5,248,346 A		9/1993	Fraas et al.	
5,252,139 A	*	10/1993	Schmitt et al.	136/251

United States Patent [19]
Yoshioka et al.

[11] **Patent Number: 5,580,395**
[45] **Date of Patent: Dec. 3, 1996**

[54] **SOLAR CELL WITH INTEGRATED BYPASS FUNCTION**

[75] Inventors: **Hideki Yoshioka**, Nara; **Tadashi Hisamatsu**, Kashihara, both of Japan

[73] Assignee: **Sharp Kabushiki Kaisha**, Osaka, Japan

3-12076
3-10274

Primary Ex
Attorney, A

United States Patent [19]
Green et al.

[11] **Patent Number: 5,990,415**
[45] **Date of Patent: *Nov. 23, 1999**

[54] **MULTILAYER SOLAR CELLS WITH BYPASS DIODE PROTECTION**

[75] Inventors: **Martin Andrew Green**, Waverly; **Stuart Ross Wenham**, Menai Heights, both of Australia

[73] Assignee: **Pacific Solar Pty Ltd**, New South

5,248,346	9/1993	Fraas et al. .	
5,389,158	2/1995	Fraas et al. .	
5,461,002	10/1995	Safir	437/160
5,580,395	12/1996	Yoshioka et al.	136/255
5,609,694	3/1997	Asai	136/255
5,616,185	4/1997	Kukulka	136/255
5,665,175	9/1997	Safir	136/255
5,797,998	8/1998	Wenham et al.	136/255

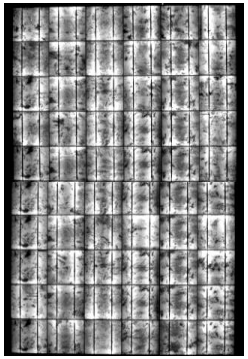
FOREIGN PATENT DOCUMENTS

© 2011 SunPower Corp.

Power electronics as fix for module problems?

- At $2/W system, 2% energy boost worth ~$0.04/W
- Larger problems must be fixed very cheaply to compete against other technologies which do not have the problem
  - For example, results of SunPower tests of two manufacturers modules using a high accelerated life test of damp heat with bias

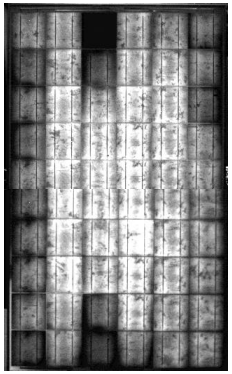
Electroluminescence images show damaged cells around the perimeter, where leakage current to the frame is highest.

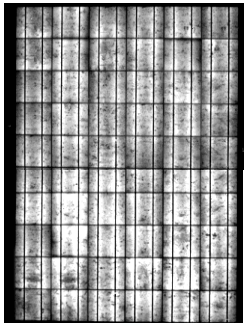


Manufacturer #1

Power loss

Sample 1: -12%
Sample 2: -23%

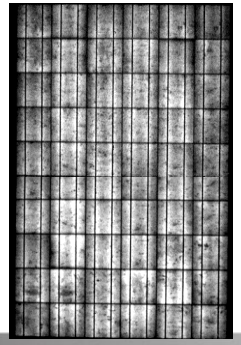




Manufacturer #2

Power loss

Sample 1: -3.2%
Sample 2: -4.4%

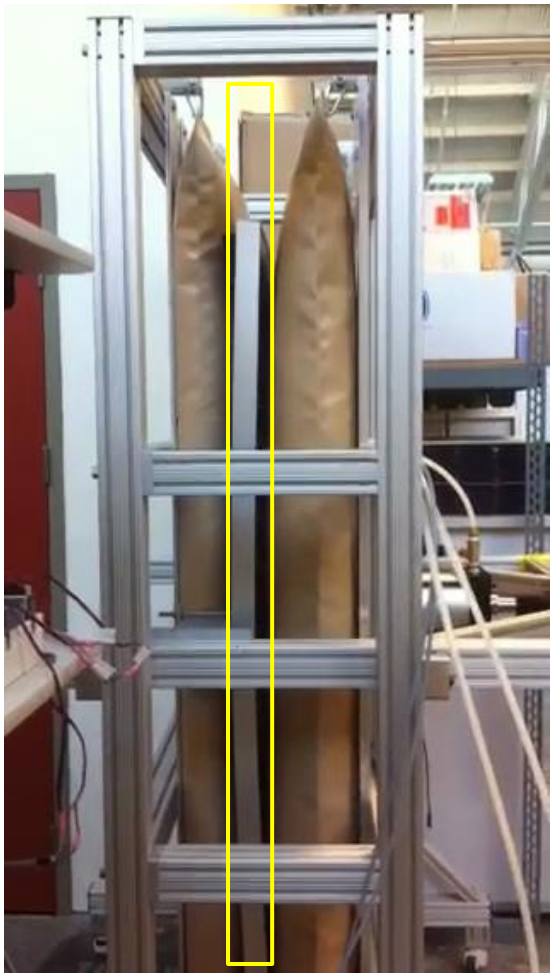


© 2011 SunPower Corp.

Cracked cell problems?

Dynamic Load HALT:

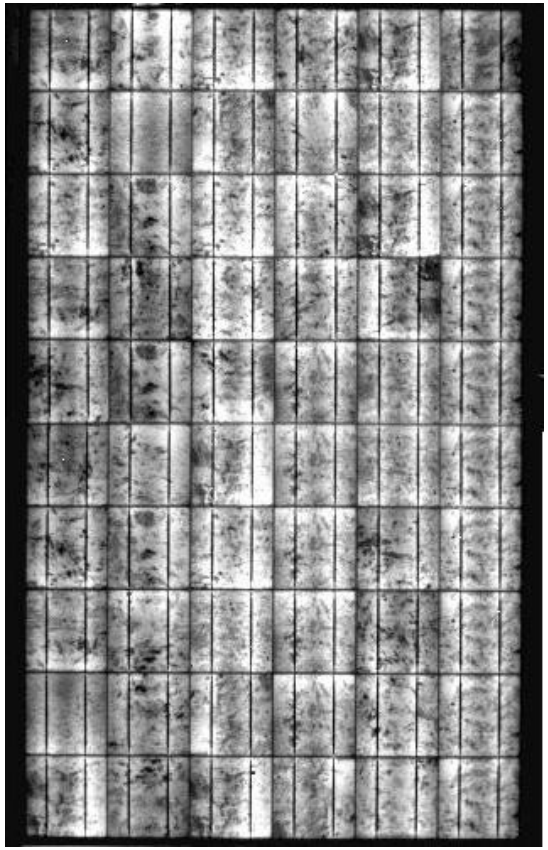
- 1,000 alternating cycles of +/-2400 Pa (standard wind load), then 4 temp. cycles -40 to 60C



© 2011 SunPower Corp.

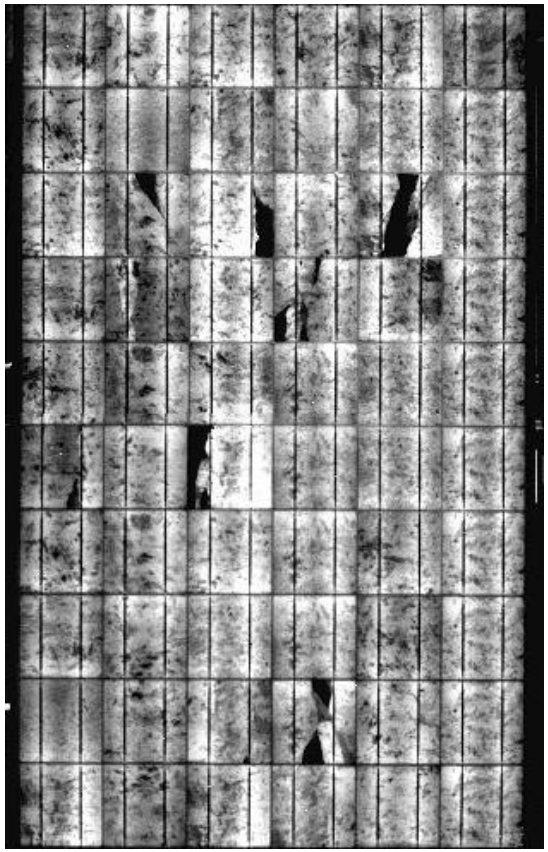
Dynamic load HALT

Initial



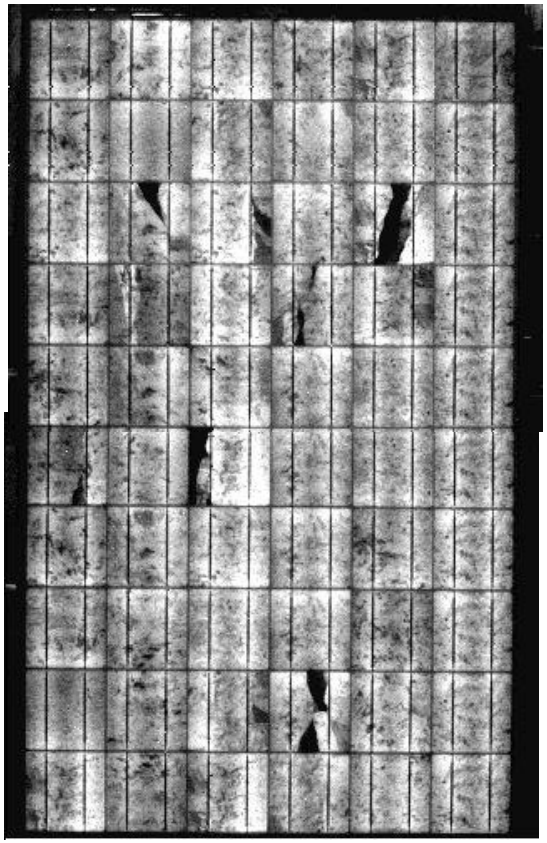
223.9W

After 1000 load cycles



-2.1%

After 4 temp cycles

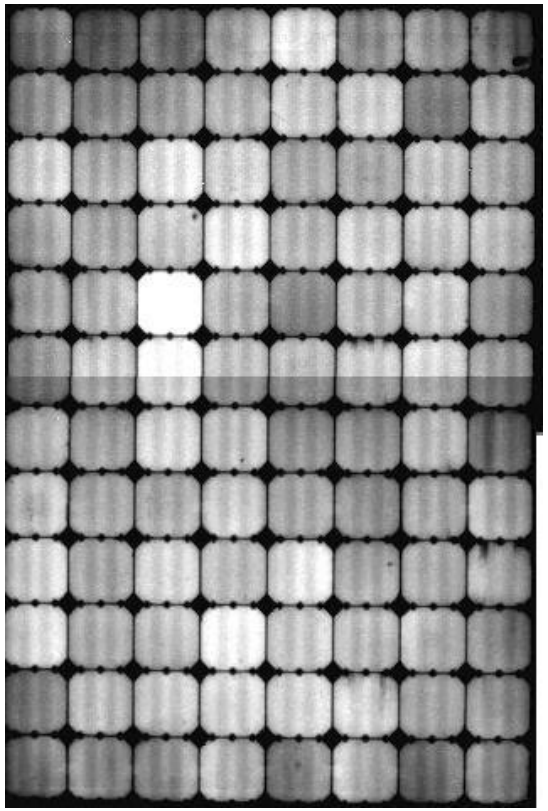


-3.4%

© 2011 SunPower Corp.

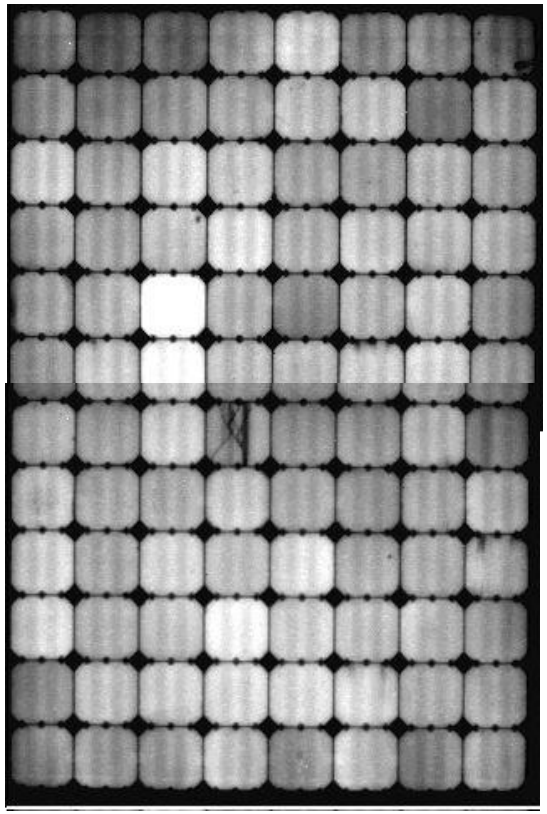
Dynamic load HALT - SunPower 145µm-thick cells

Initial



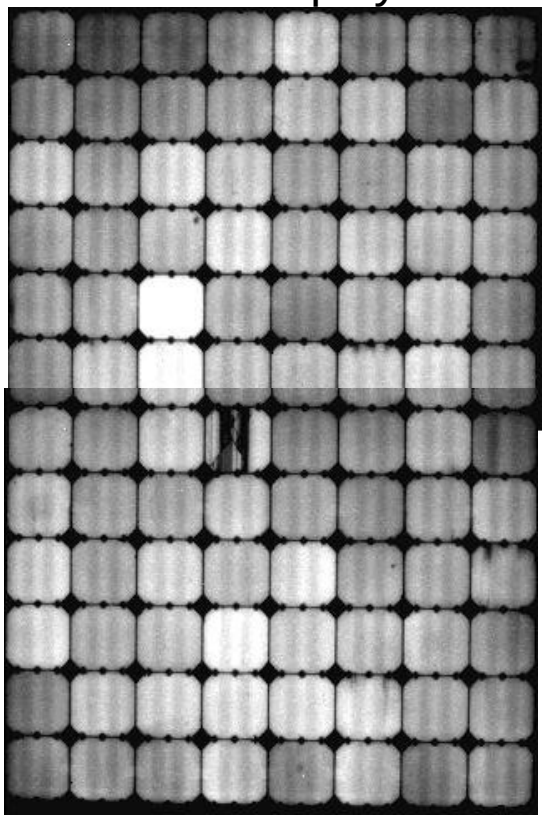
305 W

After 1000 load cycles



+0.5%

After 4 temp cycles



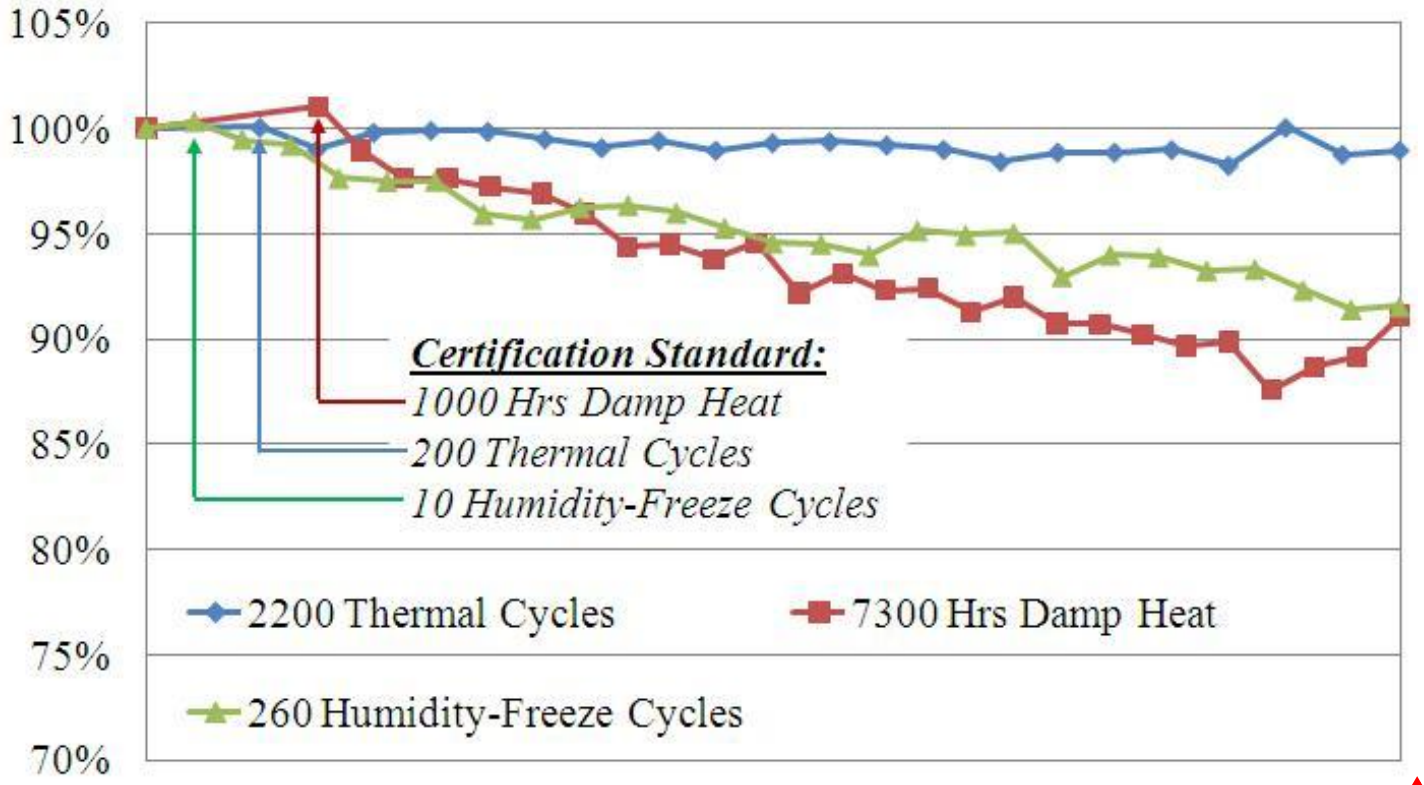
-0.7%

SunPower all-back-contact cells: cell cracked, but very little power difference

© 2011 SunPower Corp.

What are “state-of-the-art” modules?

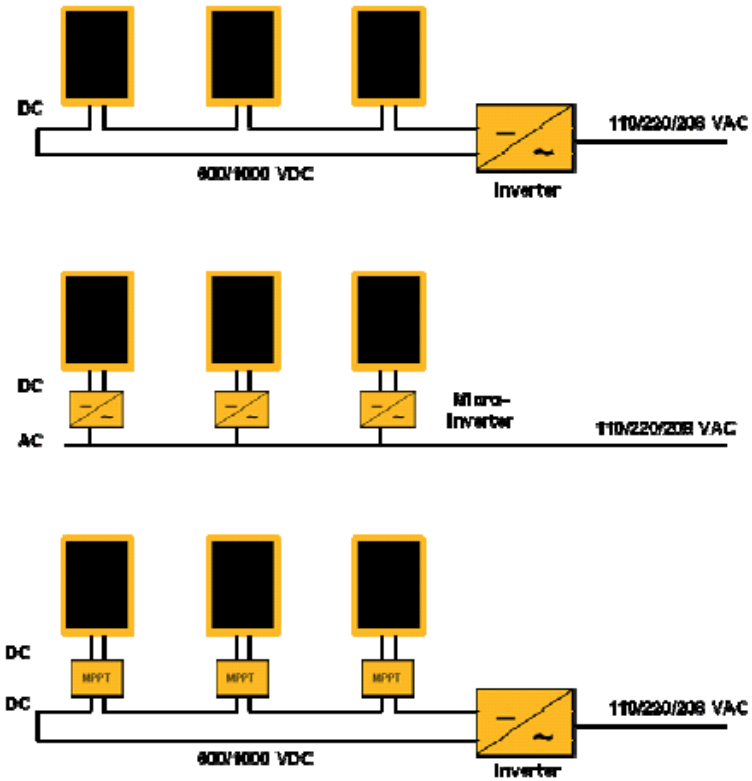
SunPower back-contact-cell modules: long-term testing example



Thermal cycling: 22X cert. std.
Humidity freeze: 26X cert. std.
Damp heat: 7.3X cert. std.

© 2011 SunPower Corp.

Residential inverter approaches



String Inverter – Traditional

- Serial DC connectivity – same current thru array circuit, with increasing voltage
- MPPT function across multiple strings/ modules impacting total energy harvest
- String inverter CEC efficiency ~ 95%
- High DC voltage, safety concern

Micro-Inverter

- Parallel AC connectivity – same voltage thru array circuit, with increasing current
- MPPT per module to maximize power output
- Efficiency: most MI's worse than transformer string inverters, Enphase exception at 95% CEC, TL string inverters with 1% advantage.
- Reduces voltage level, arc fault concerns

DC-DC Series

- Serial DC connectivity – same voltage thru array circuit, with increasing current
- MPPT function per module to maximize aggregated power, active only when needed
- Efficiency: MPPT box at 99.5% + string/ central inverter at typical level, up to 97% CEC
- High DC voltage, longer DC runs increase chance of arc fault, but capable manual shut off

Inverters and junction boxes are high on pareto of field failure rates

© 2011 SunPower Corp.

AC modules and MPP trackers

- AC and MPP manufacturers and some 3rd party studies have shown data with significant energy gains for some applications

- Some 3rd party studies show small gains for most applications, even with shade

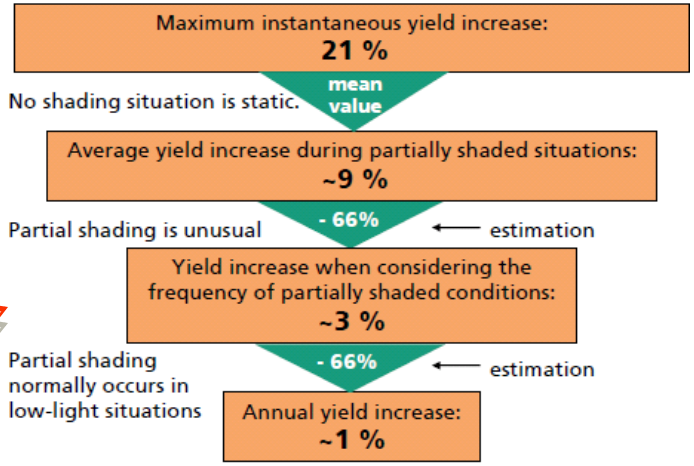


Figure 5: Example estimation of annual yield increase through the use of module-MPPT by balancing partial shading losses.

LIGHT AND SHADOW – WHEN IS MPP-TRACKING AT THE MODULE LEVEL WORTHWHILE?

Rogalla S., Burger B., Goeldi B., Schmidt H.
Fraunhofer-Institute for Solar Energy Systems ISE
Heidenhofstraße 2, 79110 Freiburg, Tel. 0761 4588-5454, Fax: - 9911
soenke.rogalla@ise.fraunhofer.de, www.ise.fraunhofer.de

25th European Photovoltaic Solar Energy Conference and Exhibition /
5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain

Literature

- Samples for this presentation taken solely from 25th PVSEC to illustrate availability of information

25th European Photovoltaic Solar Energy Conference and Exhibition /
5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain

The peer reviewed version of this paper is published in the journal Progress in Photovoltaics http://wileyonlinelibrary.com/journal/pip

MODULE INTEGRATED ELECTRONICS - AN OVERVIEW

Burger B., Goeldi B., Rogalla S., Schmidt H.
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstraße 2, 79110 Freiburg, Tel. 0761 4588-5237, Fax: -9237
bruno.burger@ise.fraunhofer.de, www.ise.fraunhofer.de

ABSTRACT: PV module integrated electronics is becoming more and more important. There are a lot of different tasks and applications for module integrated electronics, such as: operational displays, data monitoring, theft protection, safety shut down, reduction of mismatch losses [1], DC/DC conversion and DC/AC conversion. This paper gives an overview of the products that are available today.

Comment

- When considering the goals and approaches for power electronics, use the right benchmark:
  - Costs are dropping very rapidly
    - Grid-parity-driven growth in 2013-5 will accelerate cost reductions (costs without subsidies lower than avoided costs in more and more locations around the world)
    - Major companies with large research budgets involved
  - Both low cost and high performance are required
  - Look for ways to provide additional value to the grid
  - System costs can be higher when the *value* of the system is higher (e.g., on a residential roof)

Closing comment: PVDock

- SunPower, SolarBridge, and Tigo formed PVDock SIG (Special Interest Group) to encourage the development of a standard mechanical and communications interface that would enable a module supplier to swap out a variety of power electronics (ACPV, DC/DC, Diodes, Fire shut off switch, …).
- SunPower recommends a broader participation, and funding, for the PVDock SIG

Note: PV-Dock™ is a registered trademark of SolarBridge

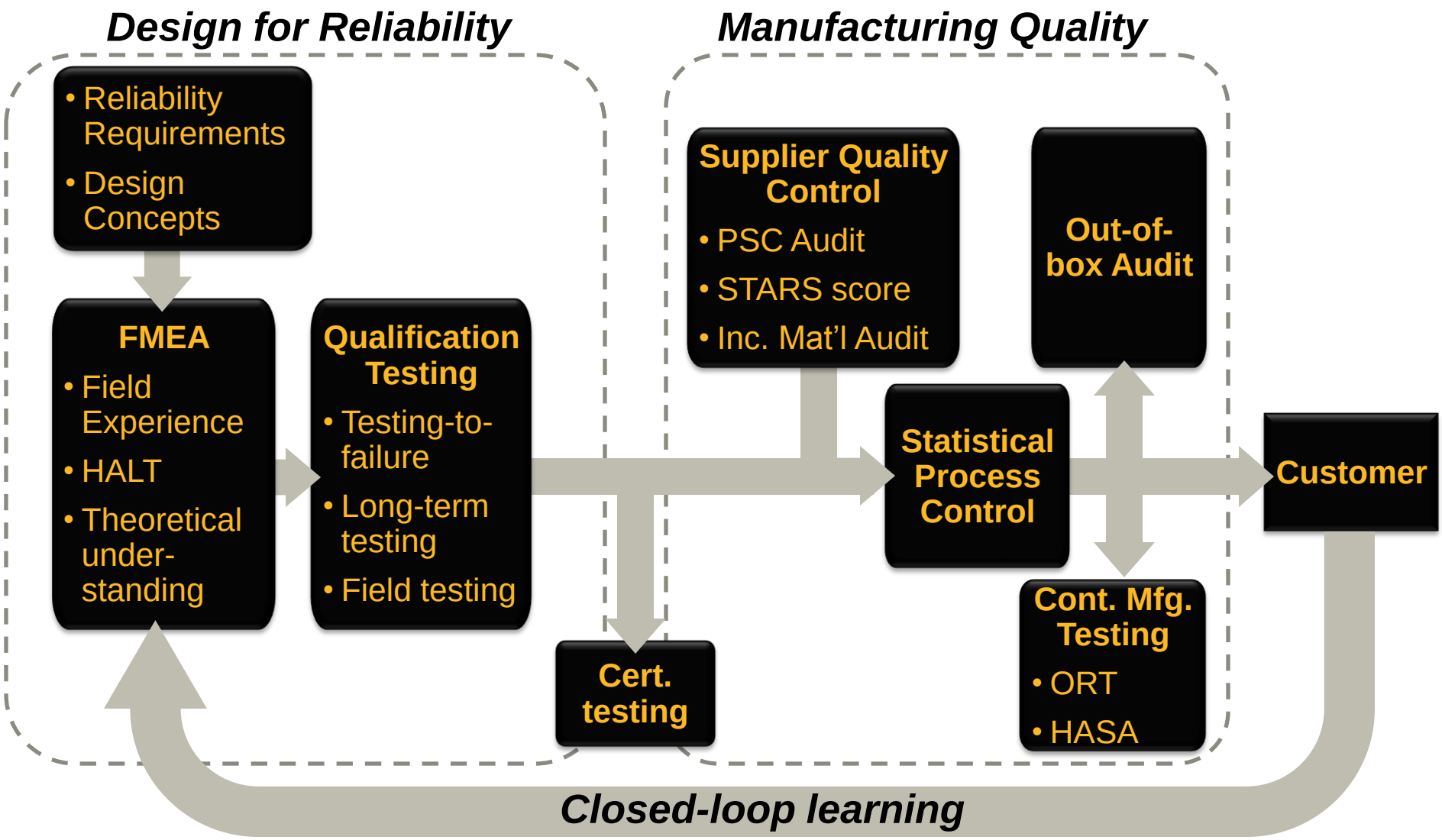
SunPower announcement at: http://www.prnewswire.com/news-releases/sunpower-forms-pvdock-special-interest-group-with-power-conversion-manufacturers-104480409.html

www.sunpowercorp.com

Thank You

© 2010 SunPower Corp.

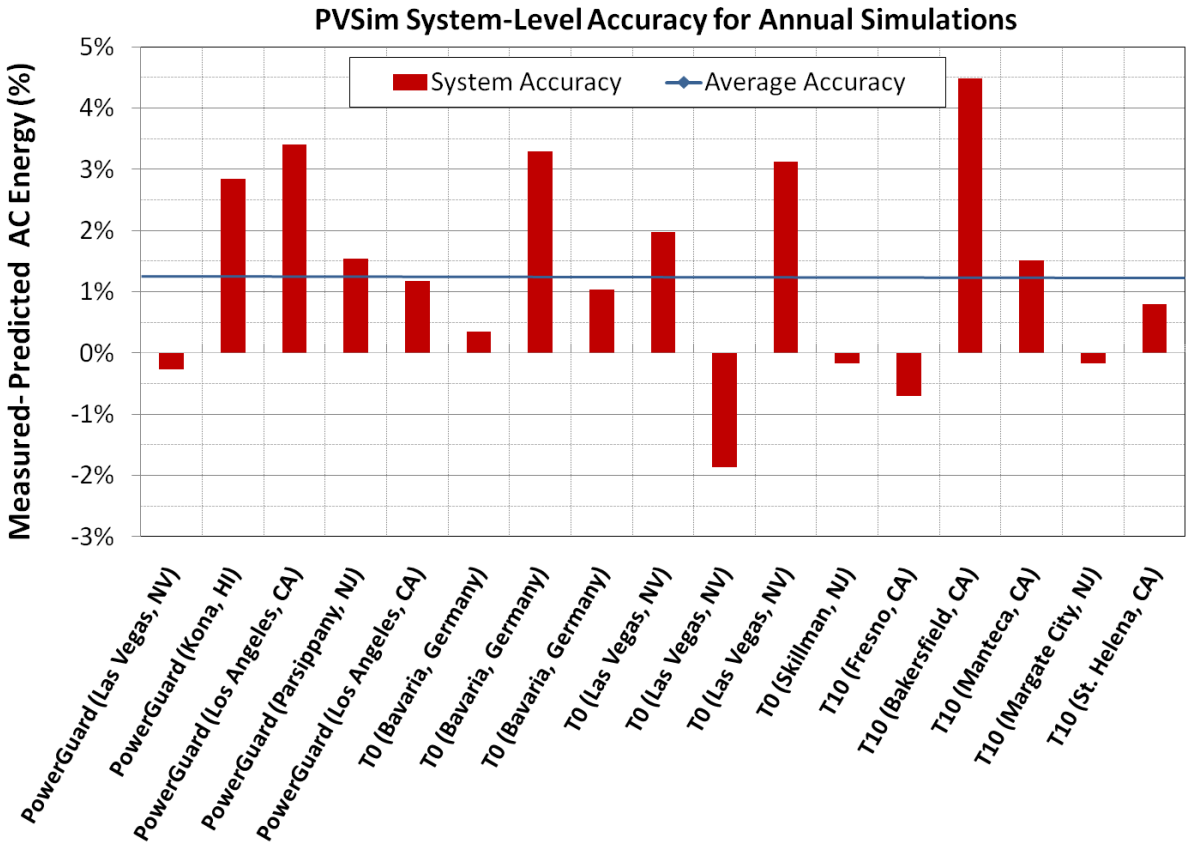
Deploying high-reliability PV Modules: Overall Process



© 2011 SunPower Corp.

SunPower simulation tool

- PVSim provides accurate prediction of energy production:
  - Standard deviation of error in actual vs. predicted for 17 large systems across broad range of locations and mounting approaches **= 1.3%.**
  - Actual energy delivery is 1.2% higher than predicted

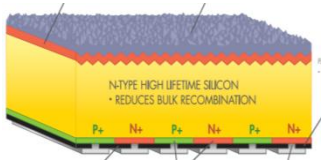


Powerguard = flat fixed mount
T0 = horizontal 1-axis tracked
T10 = 10° fixed tilt
T20 = 20° tilt 1-axis tracked

© 2010 SunPower Corp.

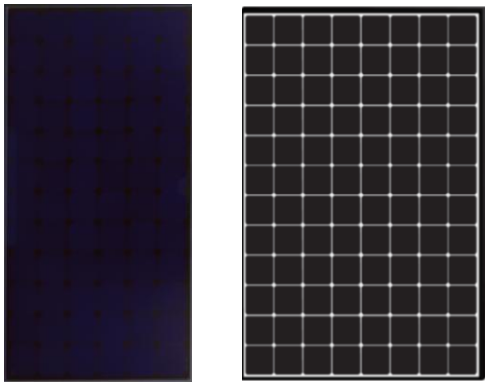
SunPower Products

> 22% efficiency all-back contact cell

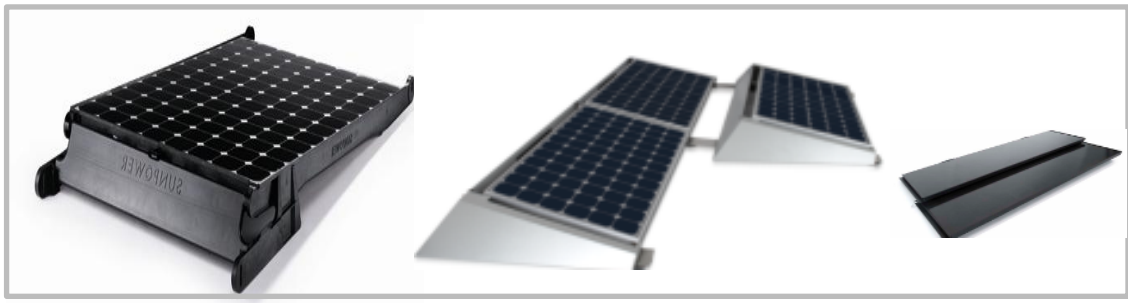


Panels

225 W **318 W**



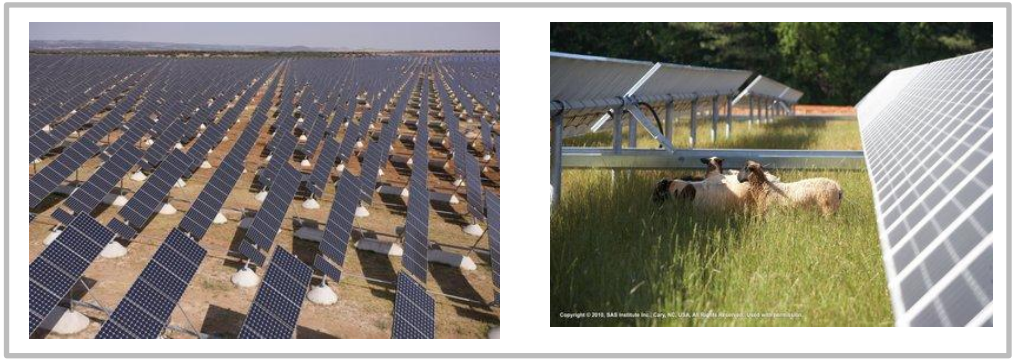
Roof top and roof integrated solutions



Monitoring

Trackers

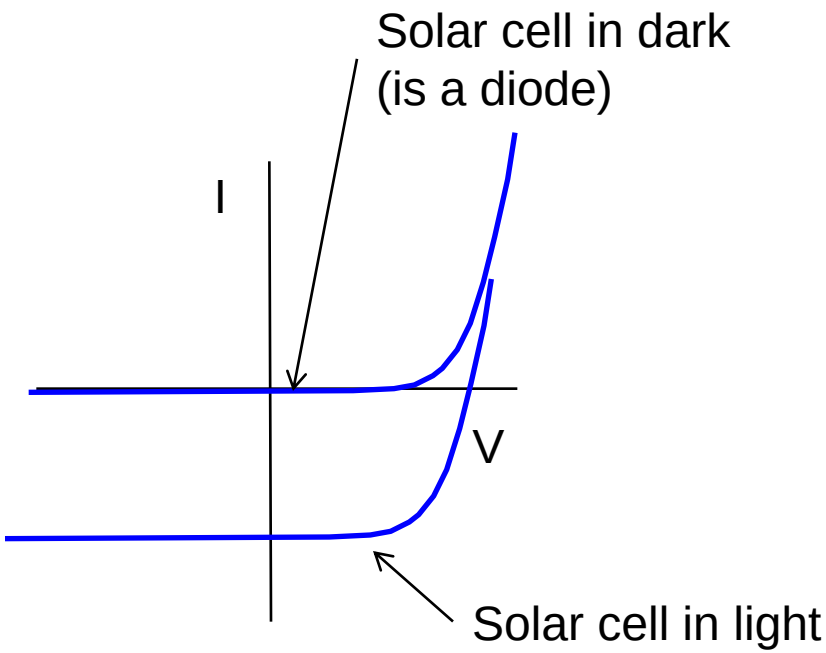
Power Plants



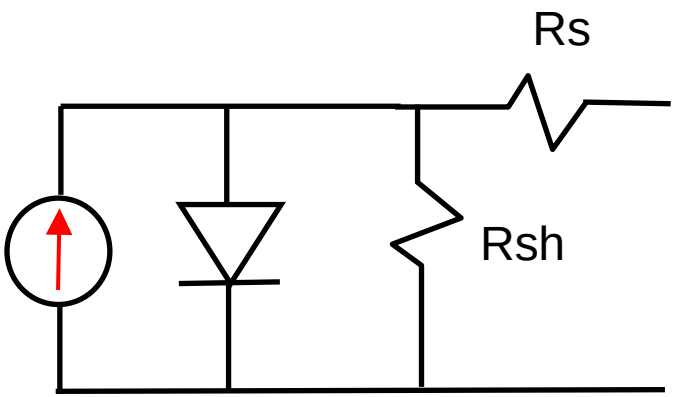
© 2010 SunPower Corp.

Solar cell equivalent circuit

I-V curve

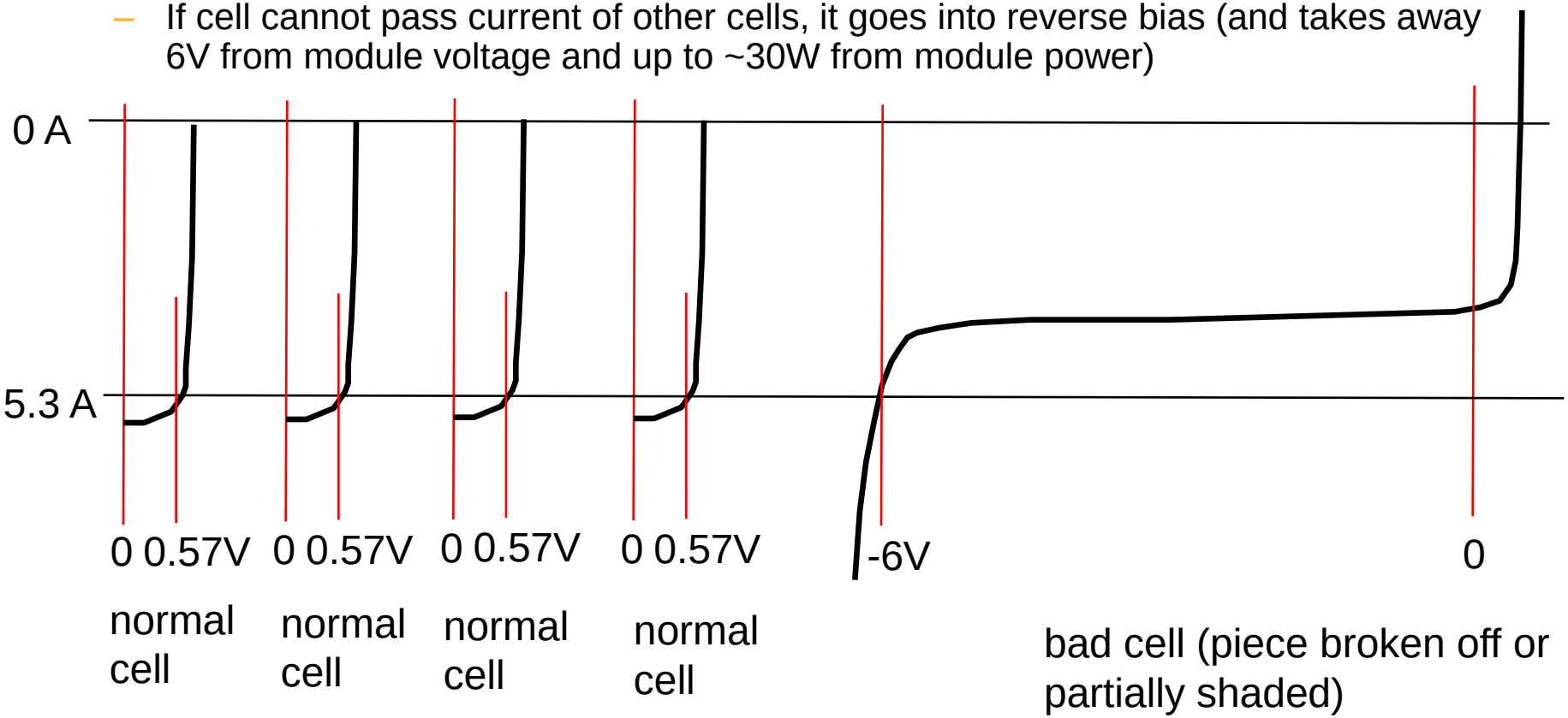


Cell equivalent circuit



Cells in a module

- Cells in a module:
  - All cells are in series
  - If cell cannot pass current of other cells, it goes into reverse bias (and takes away 6V from module voltage and up to ~30W from module power)



Designed for Roof Compatibility & Longevity

Molded frame, mounting system and deflectors

Engineered polymer exceeds stringent 30-yr design-life requirement.

- GE engineered material 20% glass-filled polyphenylene & polystyrene blend.
- Excellent dimensional stability and high impact resistance
- Very low creep behavior, even at elevated temperatures
- Hydrolytic stability: lowest water absorption of all engineering thermoplastics
- Decades of real life field exposure: electrical enclosures, automotive parts, sprinkler heads, water pumps, roof tiles, solar water heaters, PV modules

© 2009 SunPower Corp.
© 2011 SunPower Corp.

Performance

Huge driver for cost of PV-generated energy

Confidence in the energy production and O&M estimates very strongly affects selling price and **financing rates**

$$\textbf{LCOE} = \text{NPV}\left[\frac{\text{Total System Installed Costs + O\&M Costs}}{\text{Energy produced}}\right]$$

Energy / rated W

- Environmental conditions
- Mounting (tracking, tilt,…)
- System design
- Module type

System availability

(uptime)

System Quality and Reliability

- System Lifetime
- Degradation rates
- Failure rates

LCOE ≡ Levelized Cost of Energy
NPV ≡ Net Present Value
Total system costs includes cash flow impact of financing
O&M ≡ Operation and Maintenance

© 2011 SunPower Corp.

Cost of PV-generated energy

- Levelized-cost of energy (LCOE) is *one* analytical tool. A simplified version:

$$\text{LCOE} \approx \frac{\text{Total Costs}}{\text{Energy produced}} \approx \frac{\text{Total System Installed Costs + NPV (O\&M Costs)}}{\text{Sunlight Collection x Conversion Efficiency}}$$

* Note: Some calculations use the Net Present Value (NPV) of the energy produced

Energy produced = Rated power x Capacity Factor

- LCOE calculation using cash flows:

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

Financing terms have a very large impact on LCOE. Influences on them include:

- Availability of capital, assumption for inflation, perception of risk

© 2009 SunPower Corp.
© 2011 SunPower Corp.