Modules, Systems, and Reliability

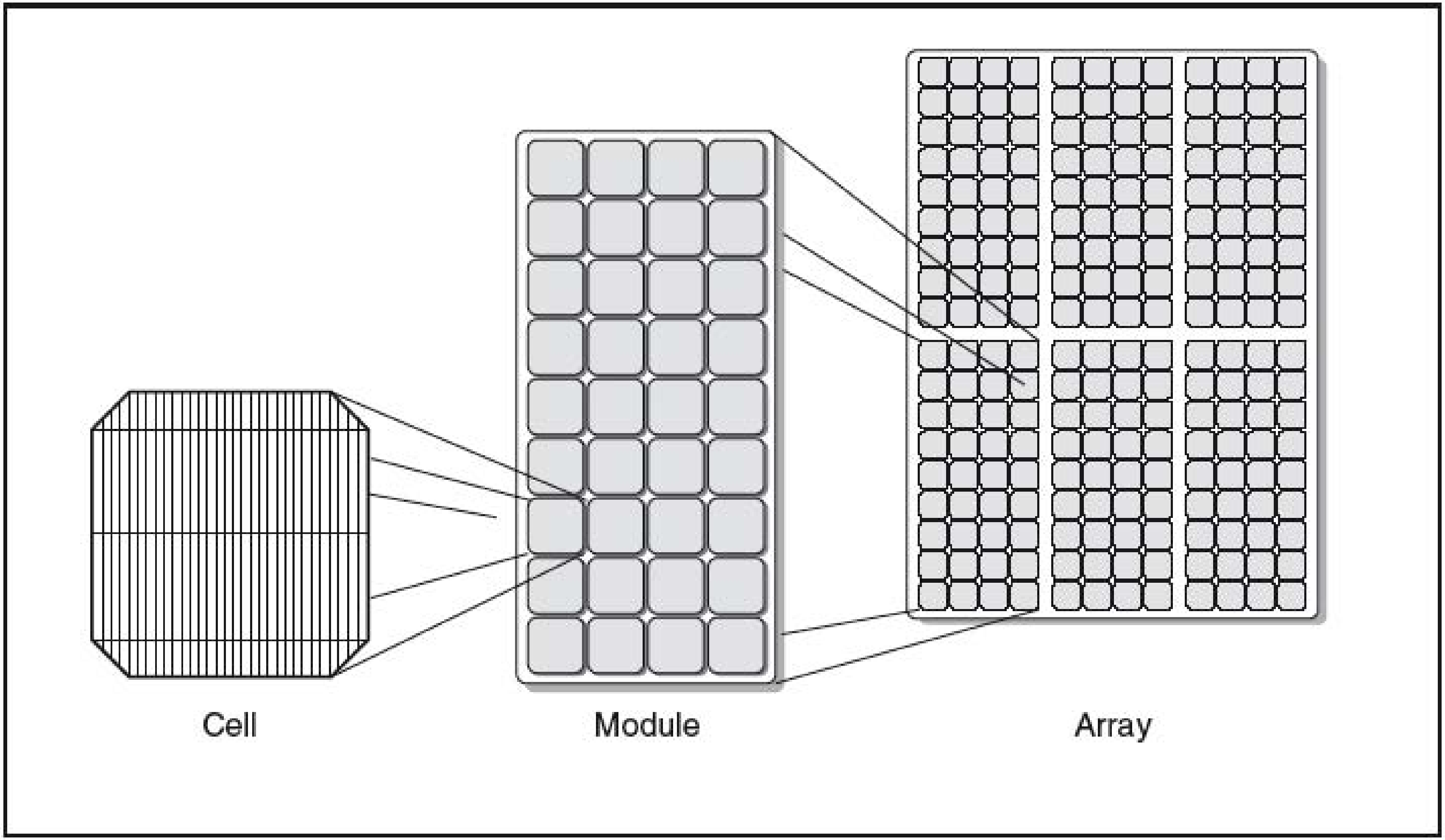
Lecture 17
MIT Fundamentals of Photovoltaics
2.626/2.627 – 11/10/2011

Prof. Tonio Buonassisi

Learning Objectives: Modules, Systems, Reliability

1. Describe how PV modules are manufactured.
2. Describe how PV module power output is affected by cell mismatch losses
3. Describe how microinverters and microelectronics can improve module performance output.
4. List the necessary tests a PV module must pass to ensure reliable multi-decade service life in the field, as well as the shortcomings of these tests.
5. Describe the differences between various types of PV systems: Grid-tied and stand-alone, tracking and non-tracking.
6. List major balance of system components.
7. Describe current consensus of life cycle analysis studies, and recycling of modules.

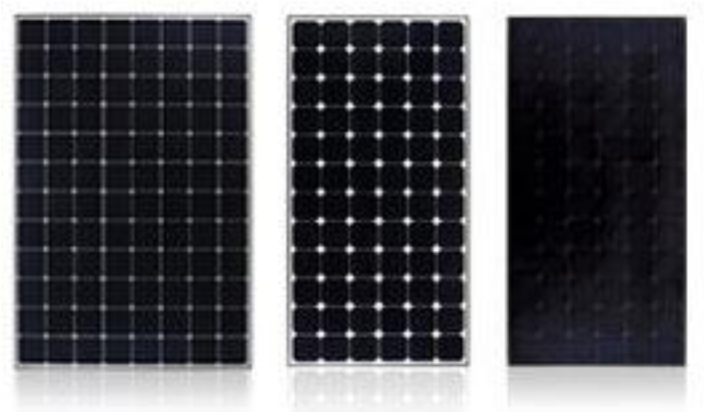
Definitions



Photovoltaic cells, modules and arrays *The building blocks of solar electricity are modular in nature, allowing great flexibility in applications.*

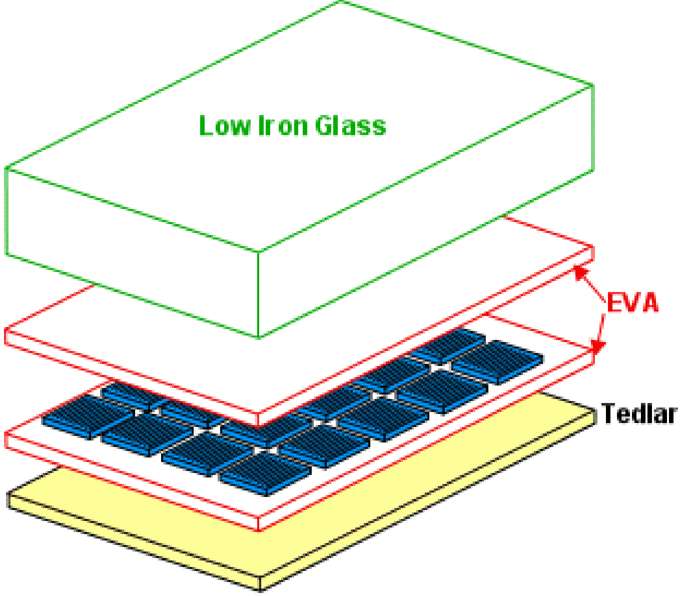
Solar Modules

- Modules require little maintenance
  - Water rinse 2-3 time/year
- Typically no moving parts
- Typical 20-30 year manufacturer warranty



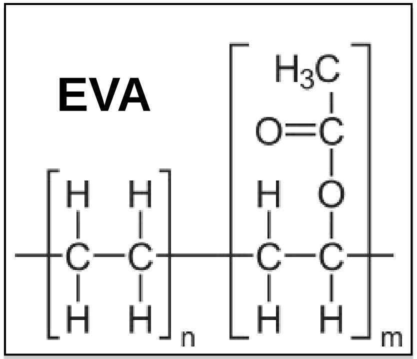
SunPower Modules

Solar PV Module DNA

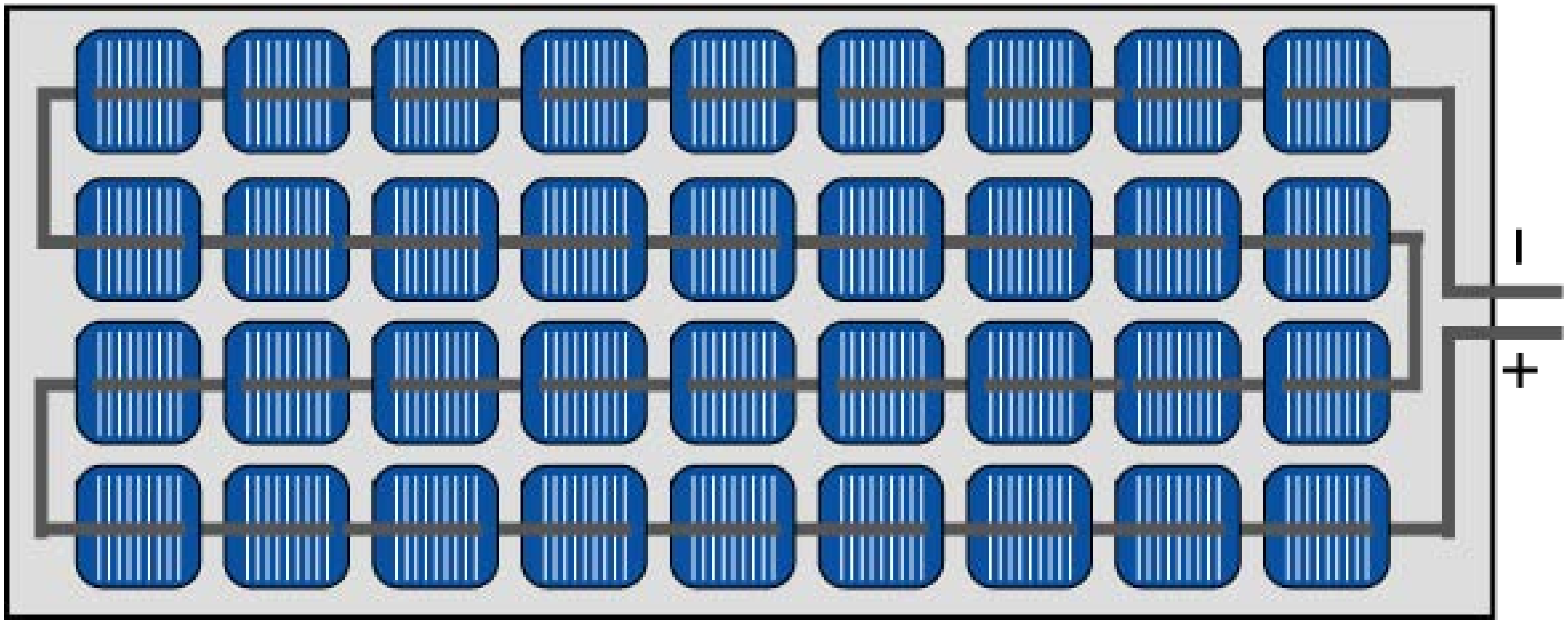


Source: PVCDROM

- Low-iron glass ensures good transmission of light.
- Ethyl Vinyl Acetate (EVA) flows at intermediate temperatures, encapsulating the cells. Thin film modules often use polyvinyl butyral (PVB), which is less reactive and has lower permeability than EVA.
- Tedlar forms an impenetrable back layer.
- Aluminum frame provides rigidity.
- Junction box provides electrical connections.



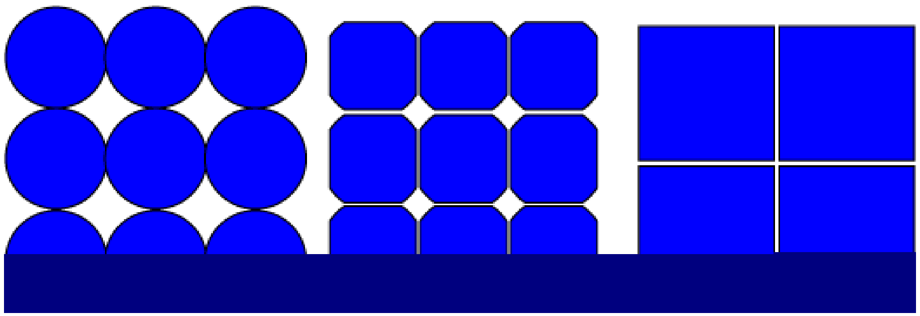
Module Circuit Design



 Source: PVCDROM

- For historical reasons, typical c-Si modules have strings of 36 cells connected in series, yielding a V_{mp} under operating conditions of 17-18V. This enables charging of a typical battery (≥15V). As grid-tied systems become more common, this voltage constraint is reduced.

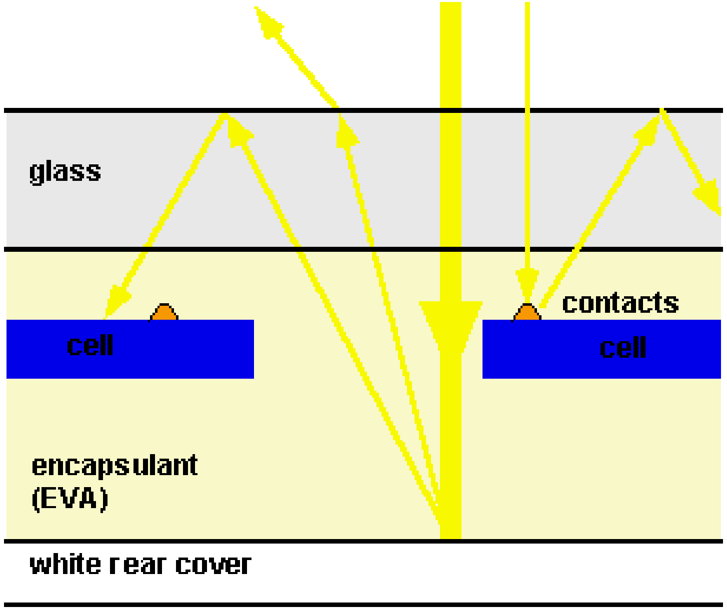
Packing Fraction in Modules



Courtesy of PVCDROM. Used with permission.

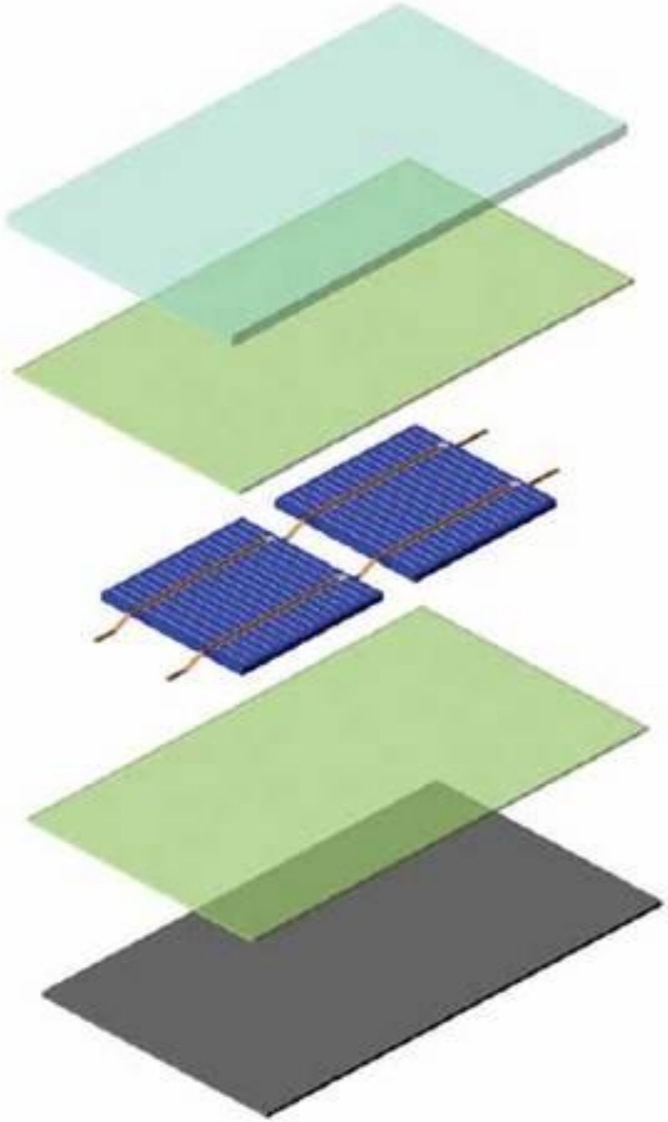
Source: PVCDROM

Light Concentration in Modules with Low Packing Fraction



- Higher packing fraction lowers glass, encapsulant costs per watt peak.
- Lower packing fraction increases optical concentration.

Solar Module Technology Trends: Cheaper, Better Materials



Transparent Front Surface (Glass Replacement)

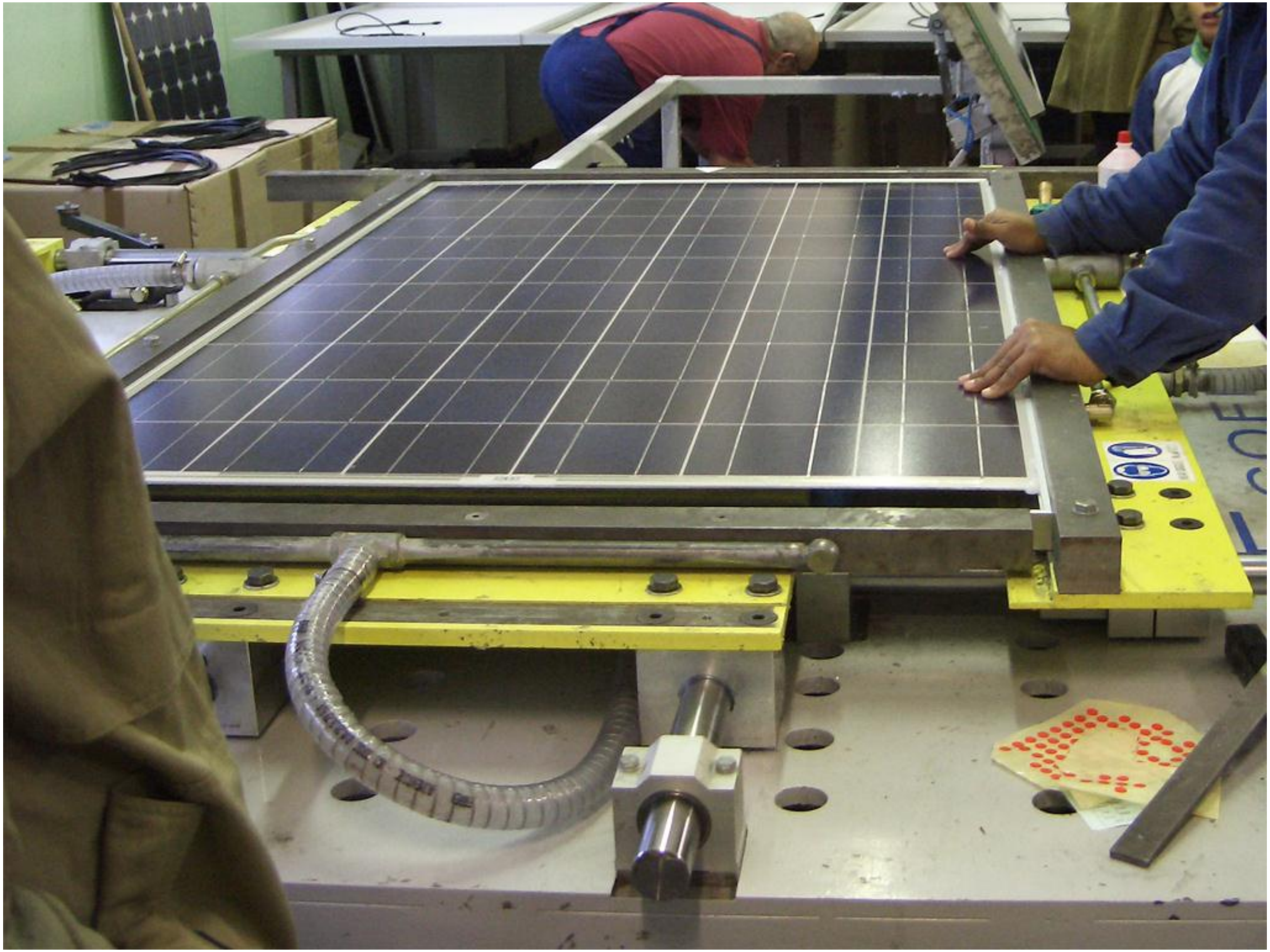
Encapsulant (EVA replacement)

Cells

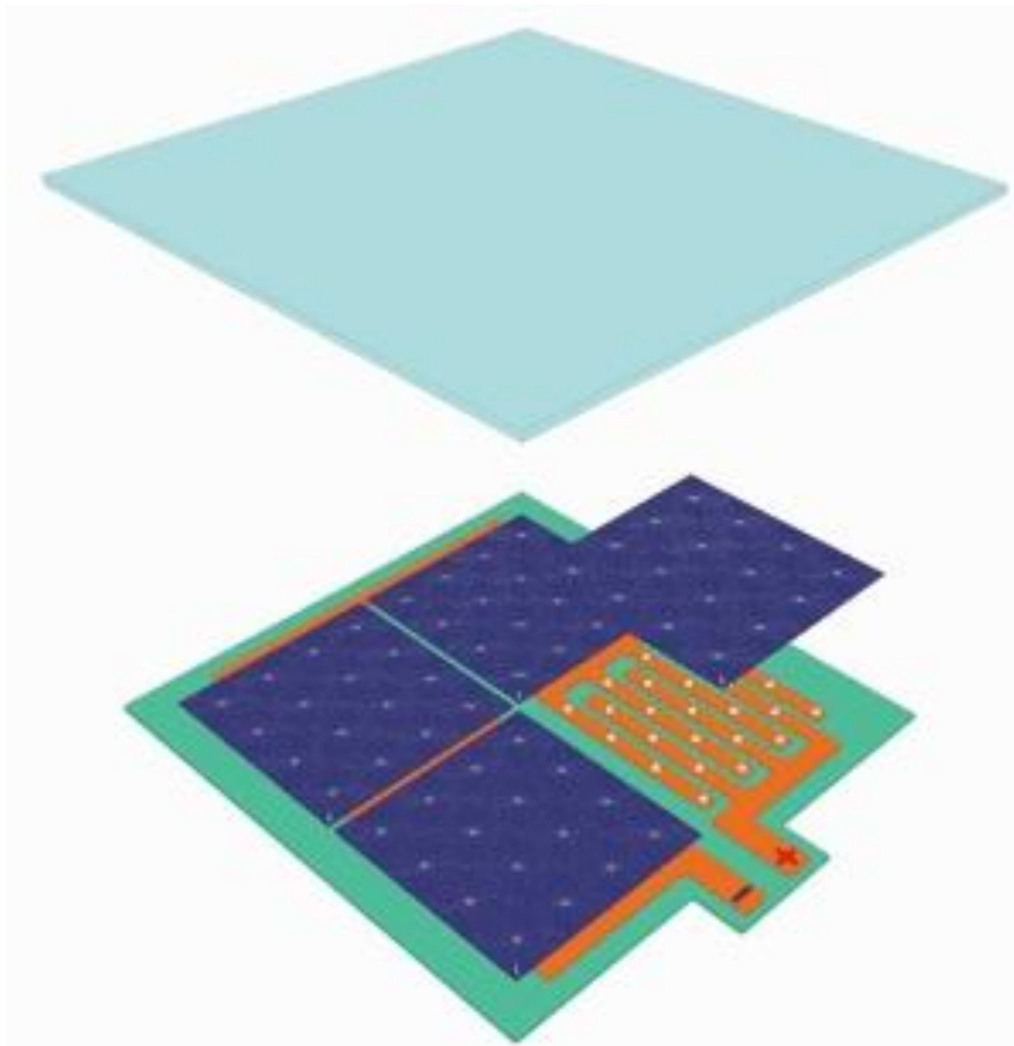
Encapsulant

Backskin (Tedlar replacement)

Frame (Al replacement)



Solar Module Technology Outlook: Back-Contacted Cells



Sample PV Module Spec Sheet

Spec sheet samples removed due to copyright restrictions.
See lecture 17 video for discussion.

- Sharp Electronics ND-187U1
- Evergreen Solar ES-A
- First Solar FS Series 3

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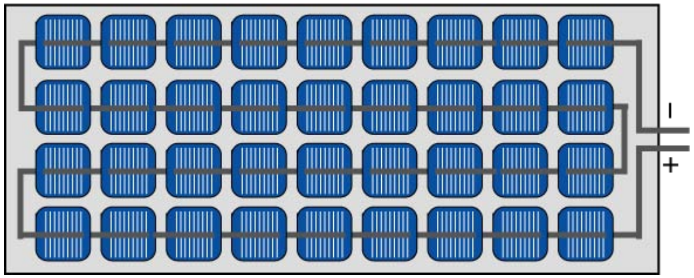
<u>Ideal</u> Equivalent Circuit for Solar Module

$$I_{total} = MI_L - MI_0\left[\exp\left(\frac{qV_{total}}{nkTN}\right) - 1\right]$$



Courtesy of PVCDROM. Used with permission.

M = cells in parallel
N = cells in series

Source: PVCDROM

In *practice*, current and voltage output reduced by mismatch losses.

Parallel Mismatch

Images removed due to copyright restrictions. See Lecture 17 video.

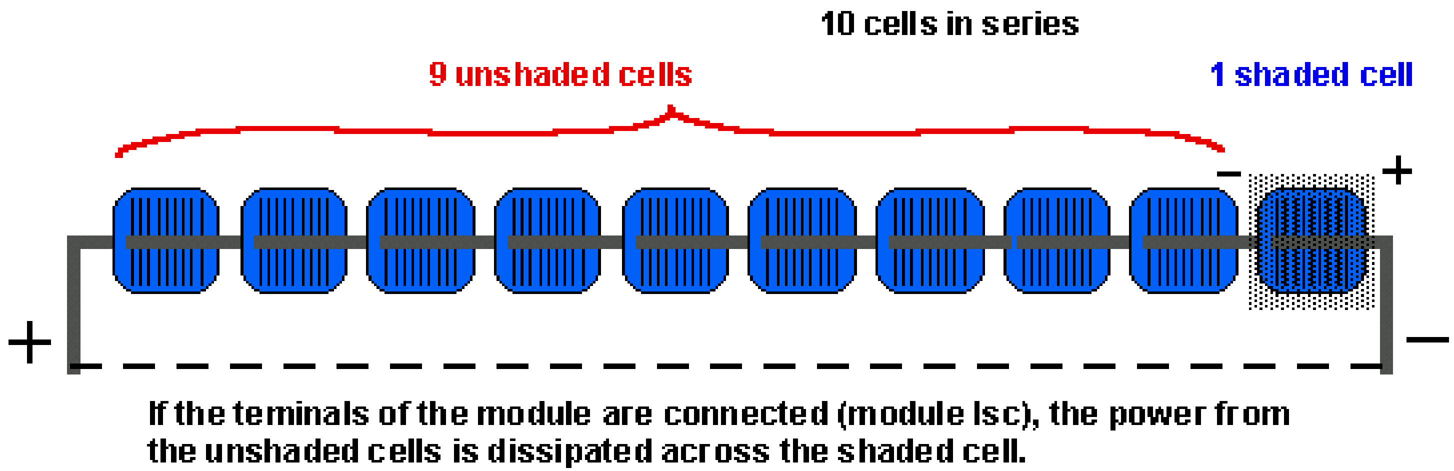
Figures 5.2 (schematic) and 5.3 (graph) from Wenham, S. R., et al. *Applied Photovoltaics.* 2nd edition. Routledge, 2007. [Preview with Google Books]

Series Mismatch

Images removed due to copyright restrictions. See Lecture 17 video.

Figures 5.5 (schematic) and 5.6 (graph) from Wenham, S. R., et al. *Applied Photovoltaics.* 2nd edition. Routledge, 2007. [Preview with Google Books]

Shaded Cells



Courtesy of PVCDROM. Used with permission.

http://pveducation.org/pvcdrom/modules/hot-spot-heating

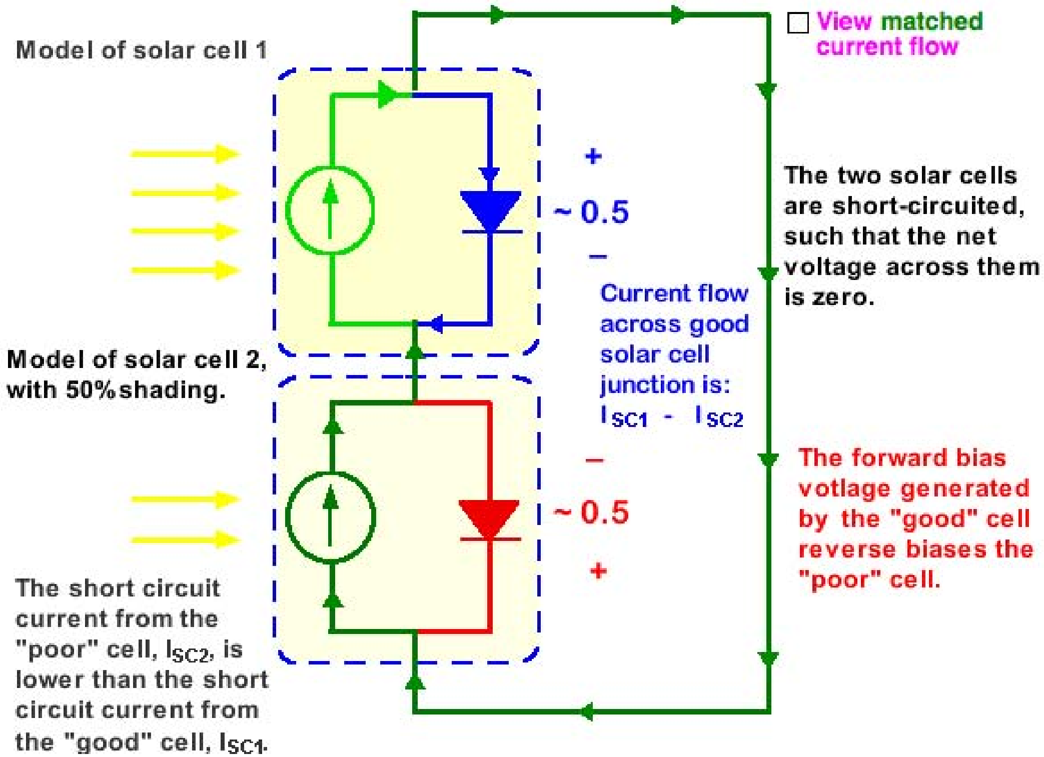
Images removed due to copyright restrictions. See Lecture 17 video.

Figures 5.8 (schematic) and 5.9 (graph) from Wenham, S. R., et al. *Applied Photovoltaics.* 2nd edition. Routledge, 2007.

Example from PVCDROM

SERIES CONNECTED SOLAR CELLS WITH MISMATCHED SHORT CIRCUIT CURRENTS

The short circuit current from the poor cell, I_{SC2}, is the maximum current that can flow in the external circuit. Therefore, extra current from the good cell, mathematically given by $I_{SC1} - I_{SC2}$, is forced to flow across the good solar cell junction, forward biasing it and generating a voltage.

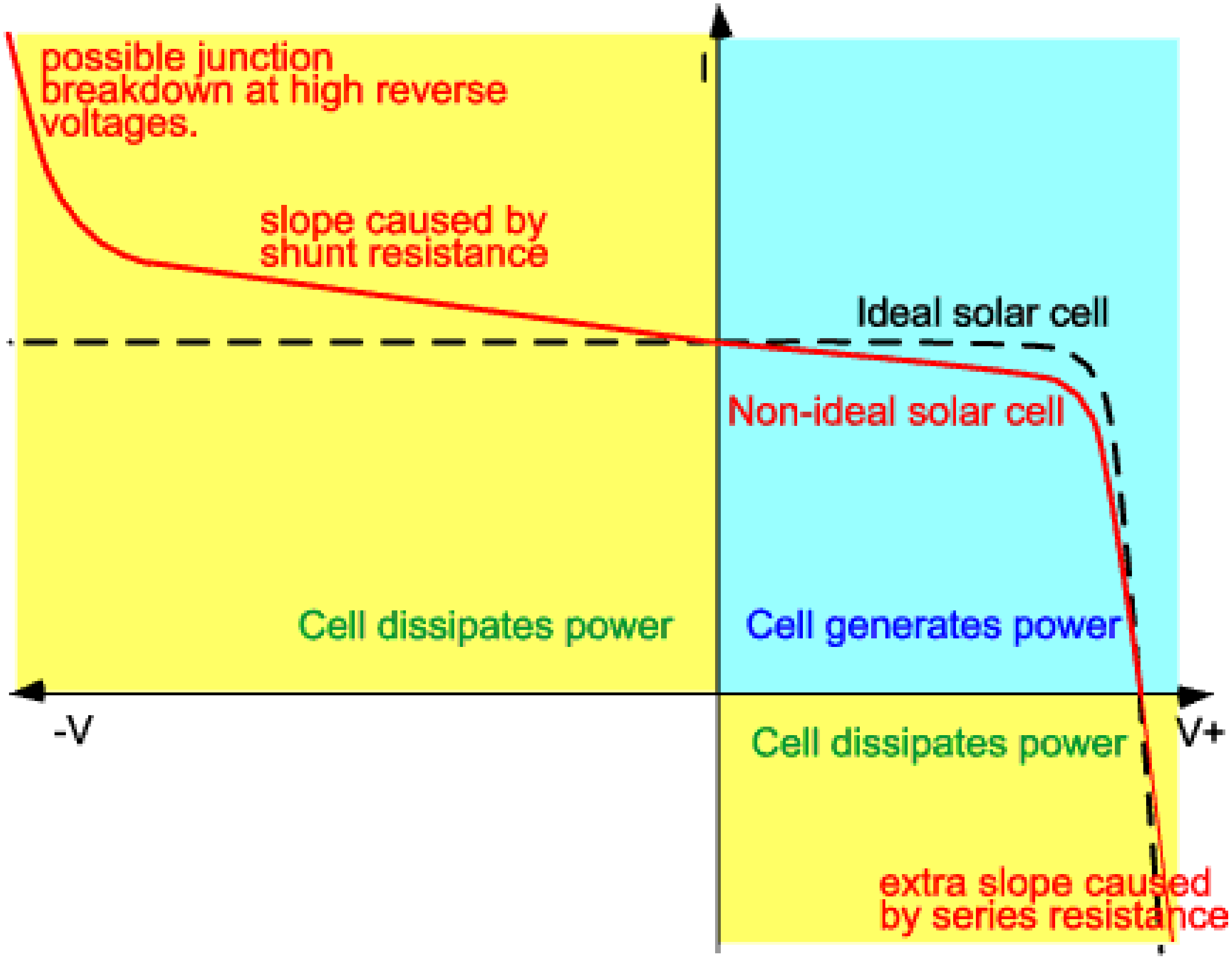


In the animation, cell 2 has a lower output voltage than cell 1.

Courtesy of PVCDROM. Used with permission.

http://pveducation.org/pvcdrom/modules/mismatch-for-cells-connected-in-series

Mismatch Losses and Breakdown



Courtesy of PVCDROM. Used with permission.

http://pveducation.org/pvcdrom/modules/mismatch-effects

Underperforming Cells & Hotspots

Image depicting Lock-In Thermography removed due to copyright restrictions.
See Lecture 17 video.

http://www.renewableenergyworld.com/rea/images/lock-in-thermography-enables-solar-cell-development/51184

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Bypass Diodes

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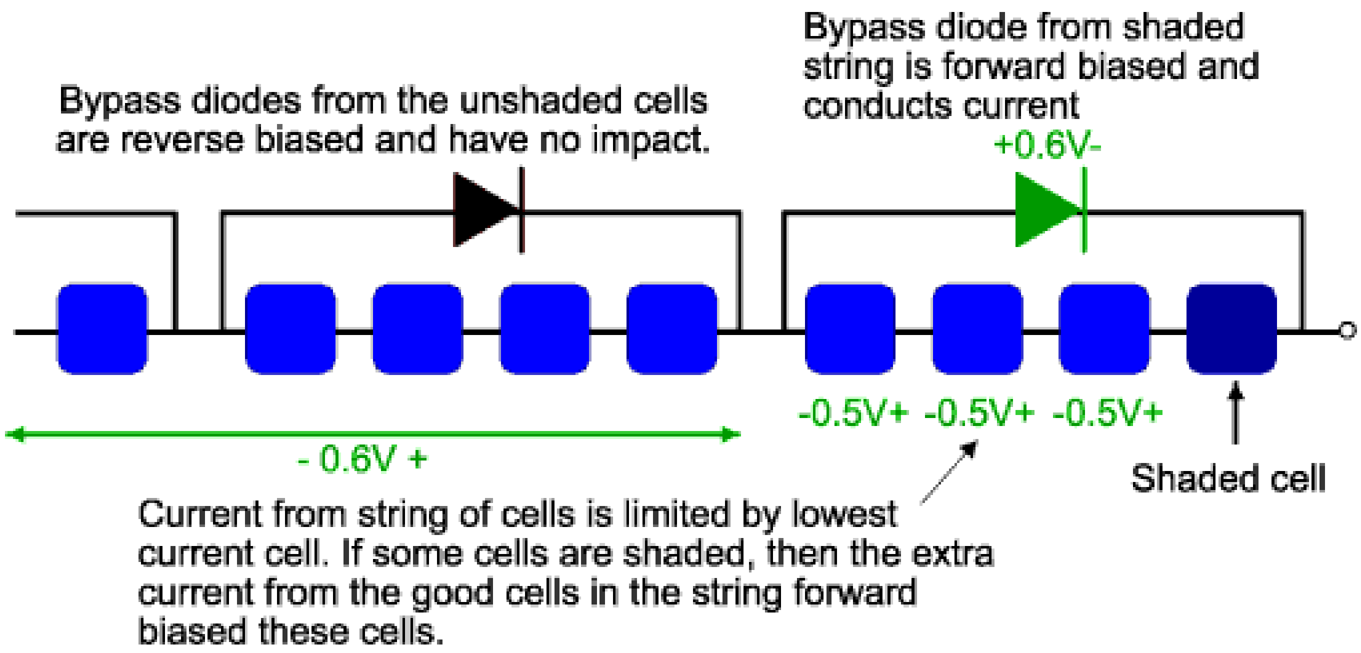
Figures 5.12 and 5.13 from Wenham, S. R., et al. *Applied Photovoltaics.* 2nd edition. Routledge, 2007.

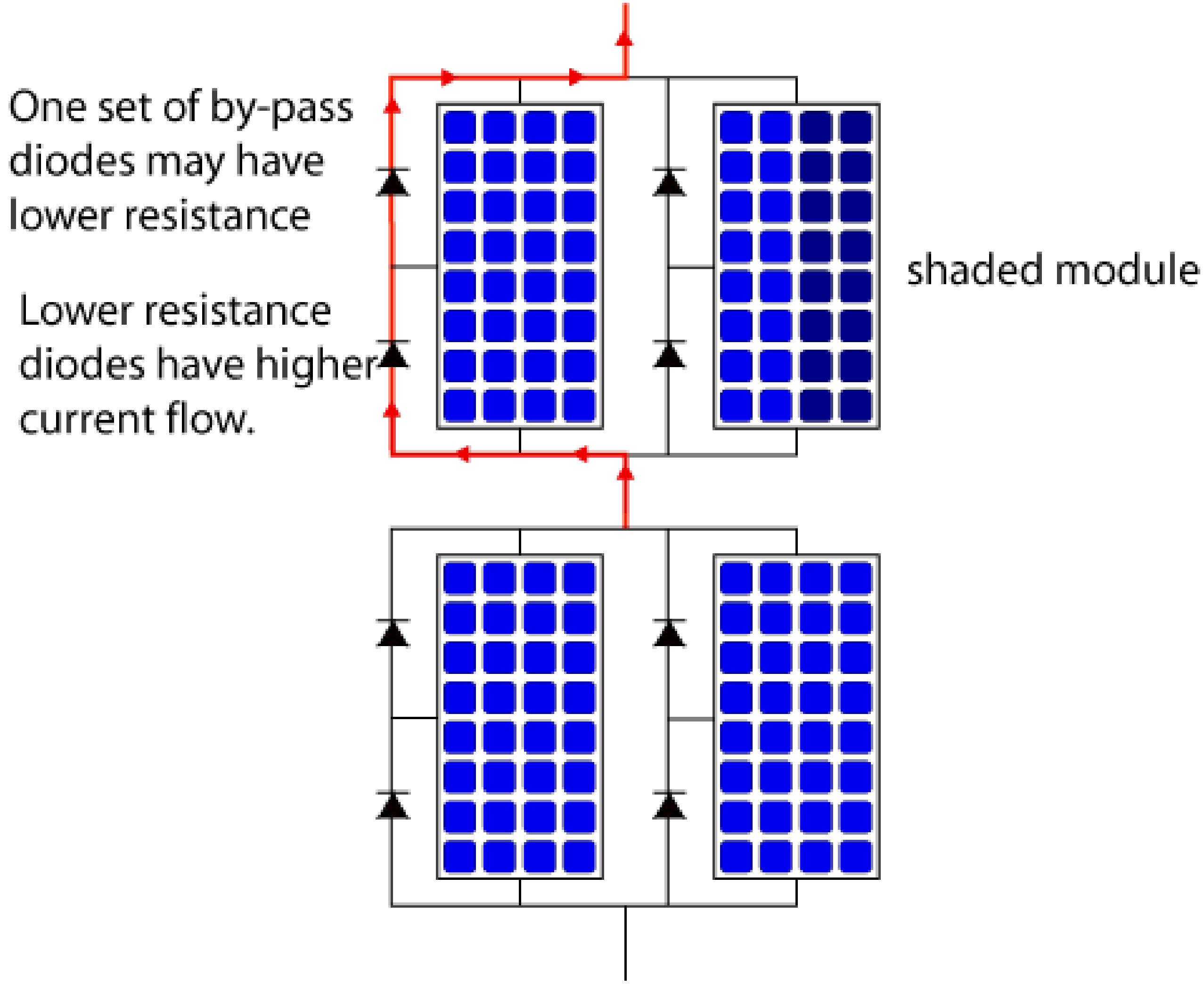
Bypass Diodes



Courtesy of PVCDROM. Used with permission.

http://pveducation.org/pvcdrom/modules/bypass-diodes

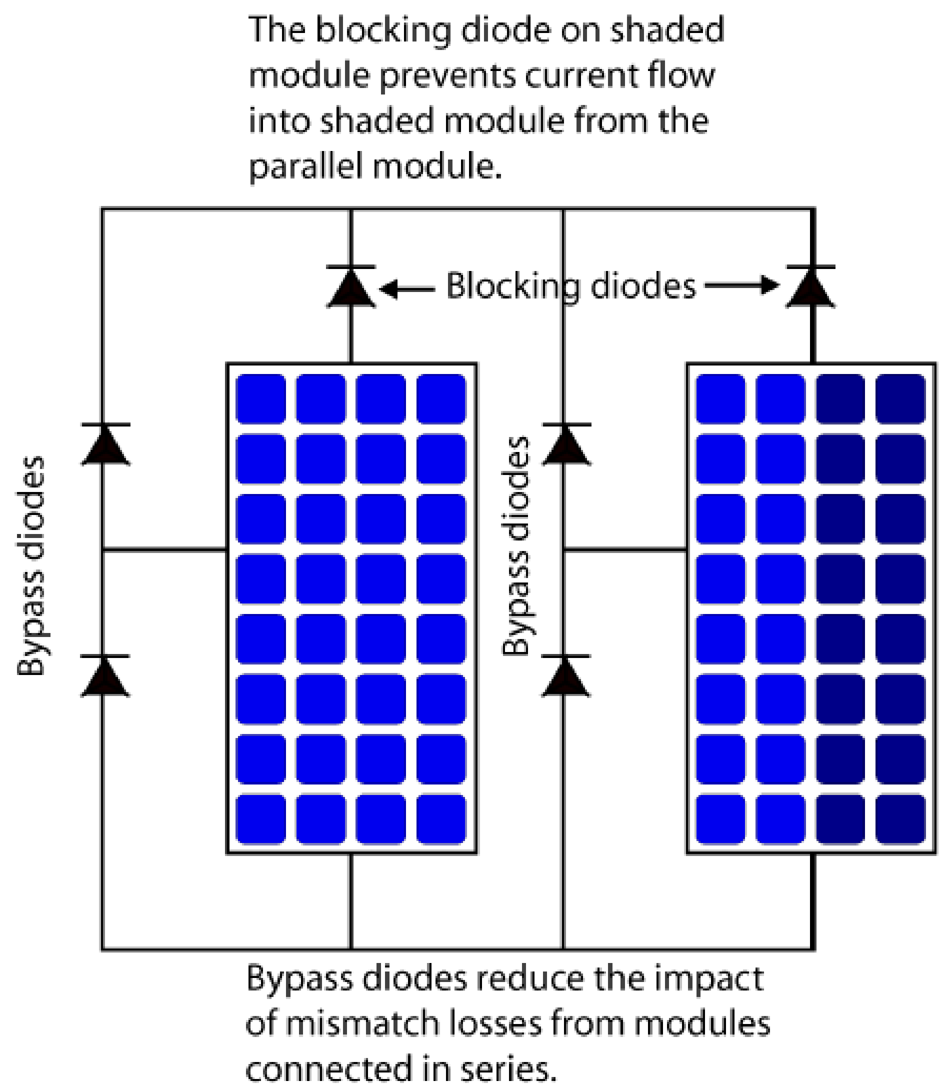
Bypass Diodes



Courtesy of PVCDROM. Used with permission.

http://pveducation.org/pvcdrom/modules/mismatch-effects-in-arrays

Blocking Diodes



Courtesy of PVCDROM. Used with permission.

http://pveducation.org/pvcdrom/modules/mismatch-effects-in-arrays

Power Optimizers and Microinverters

- Power optimizers are DC-to-DC electronics that optimize each module at the maximum power point.
- DC-to-AC microinverters transform DC electricity directly to AC at the module.
- Advantages of integrated power electronics include: Maximum power point tracking to increase system performance, ability to integrate several modules with different power outputs (*e.g.*, shading, angle on roof).
- Disadvantages of integrated power electronics include: Decreased mean time between failure, more difficult to replace distributed components when failure occurs, greater expense per peak watt.
- "Hot" topic in PV. Podcast debate: [illegible] central-inverters-is-there-a-clear-winner

Solar Module Technology Trends: BIPV Modules

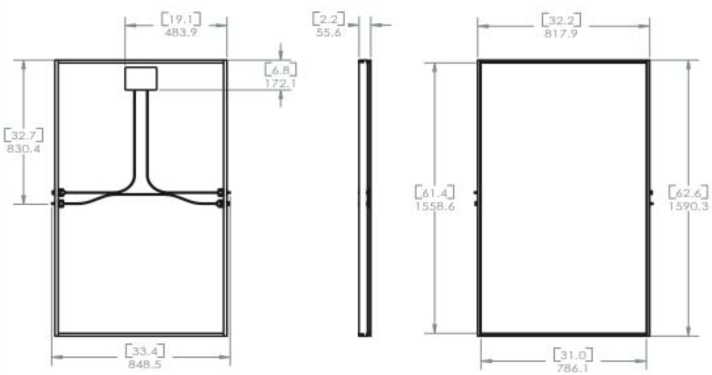
Photos removed due to copyright restrictions. See Lecture 17 video.

Four photos of Building-Integrated Photovoltaic (BIPV) modules.

Towards Facile Installation

Mechanical Specifications - Module

Length x Width	Thickness	Weight
62.6 x 32.2 inches	2.2 inches	40.7 lbs
159 x 82 cm	5.6 cm	18.5 kg



Mechanical Specifications - System

	ST175-1	Non-Andalay
Racking hardware	Integrated	External
Grounding wires	Integrated	External
Wiring connections	Factory-assembled	Installer-assembled
Module-module connections	Integrated (Threaded)	External (Friction Clips)
Space between modules	1/8"	Up to 3"
Roofing penetrations	25% Fewer	Standard

UCILIA WANG: DECEMBER 10, 2009

Do-It-Yourself Solar at Lowe's

Akeena Solar's Andalay systems are designed to make it possible for handy homeowners to do their own installations.

It's inevitable: More do-it-yourself solar panels will be available, this time in your nearest Lowe's.

Lowe's is now carrying solar panels from Los Gatos, Calif.-based **Akeena Solar** that feature built-in writing and racks and an installation technique that aims to simplify the steps and shorten the time it takes to put solar panels on a rooftop (see **video from Akeena**).

Lowe's is selling the Andalay **at $893 per panel**, available at 25 stores in California. Akeena said handy homeowners could install the panels themselves if they don't want to hire people to do it, but they might still need an electrician to connect the rooftop system to the home's circuit.

The announcement brings home what Akeena and some other solar companies see as the future of residential solar market. Instead of hiring contractors or roofers, homeowners could install solar panels themselves and save on labor costs (see **An Ikea for Solar?** and **Getting Solar Energy Cheap and Easy**).

A number of startups are developing this kind of do-it-yourself solar energy systems, including Armageddon Energy (see **video**). Meanwhile, companies such as Dow Chemical are working on solar cell-embedded roofing materials, which will require strong insulation to protect the cells from moisture and other weather elements (see **Dow to Roofers: Our Solar Shingles Are Coming**).

Other big-box retailers such as **Home Depot already sell solar panels** and related parts, though they sell them along with installation services and even financing.

http://www.greentechmedia.com/articles/read/do-it-yourself-solar-at-lowes/

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Why Module Testing?

Value

- Ensure customer gets what (s)he pays for.

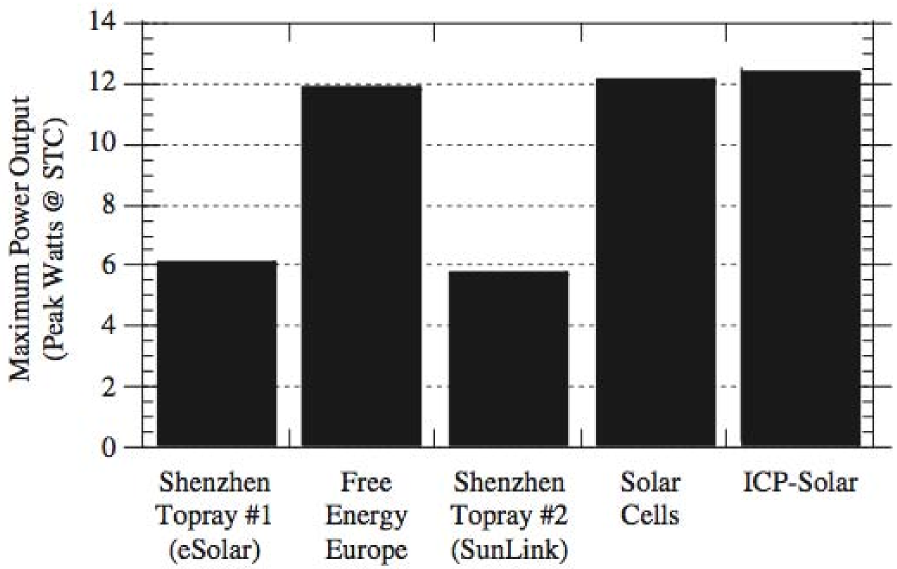
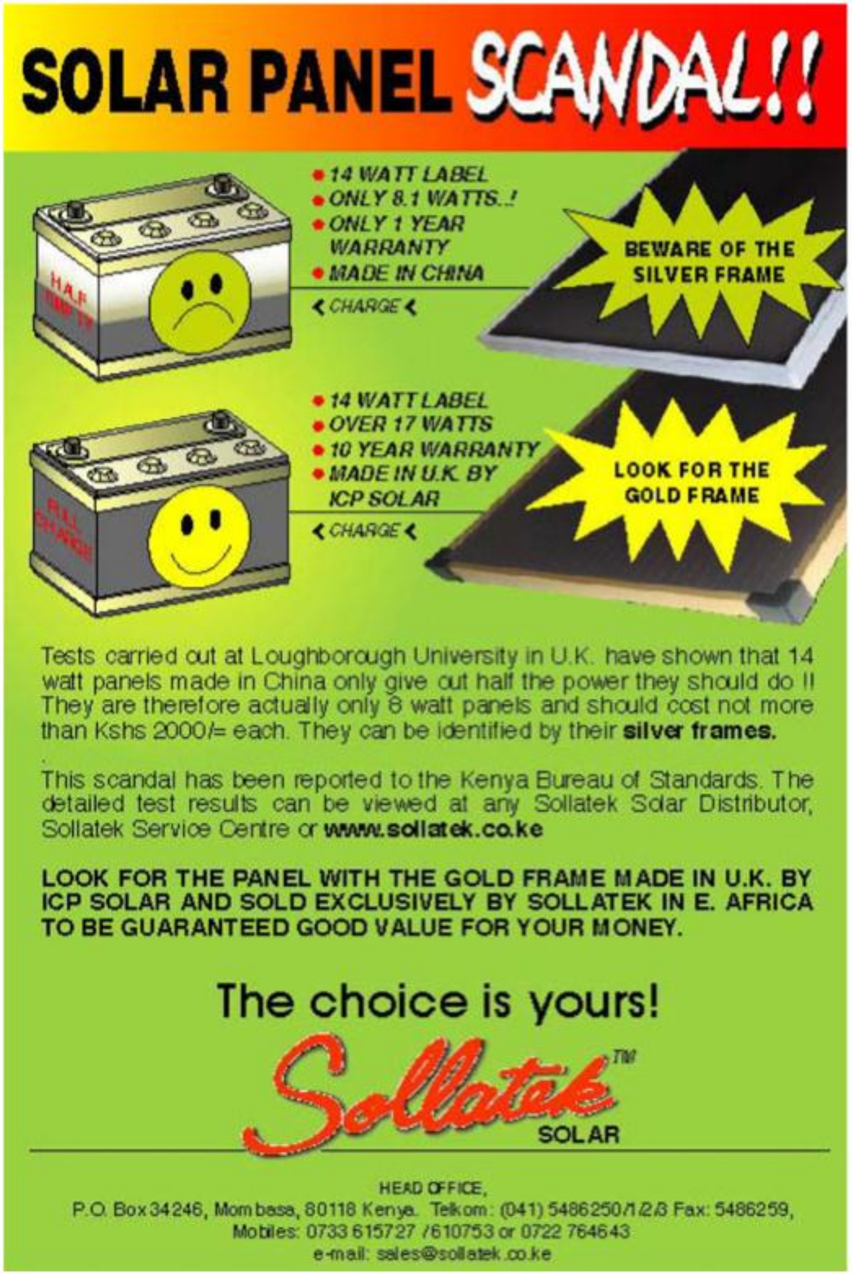


Fig. 5. Average stabilized maximum power output for five brands of 14 W rated amorphous silicon solar modules sold in Kenya. (Maximum Power at Standard Test Conditions, STC, of 1000 W/m^2 and 25 °C.)



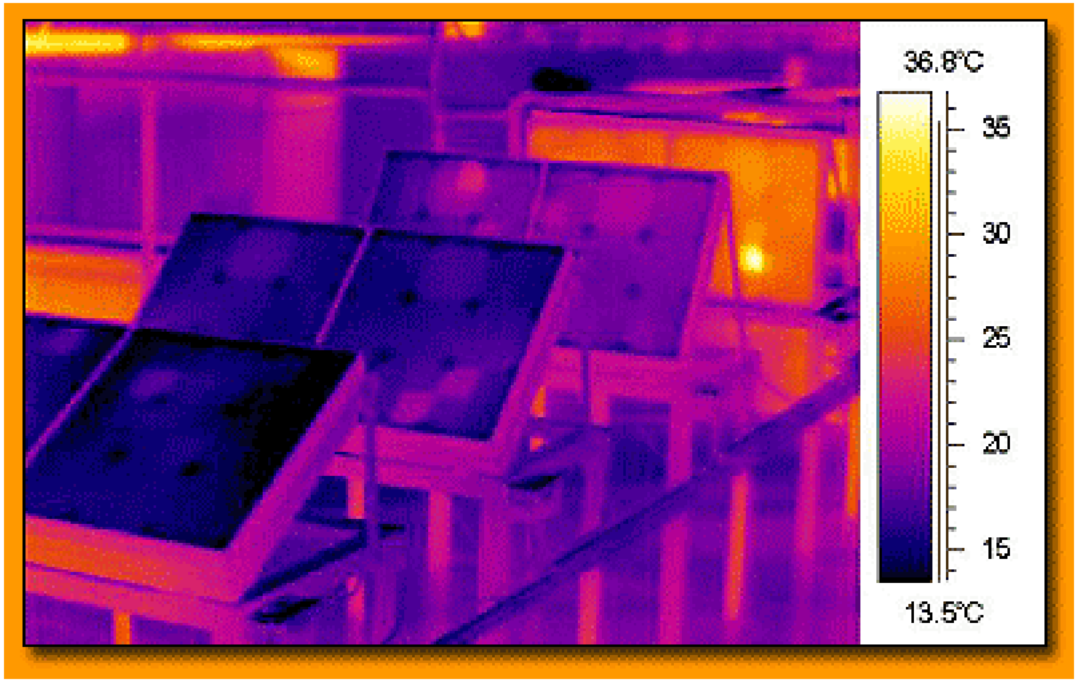
A. Jacobson and D. Kammen, "Engineering, institutions, and the public interest: Evaluating product quality in the Kenyan solar photovoltaics industry," *Energy Policy* **35**, 2960 (2007).

Buonassisi (MIT) 2011

Why Module Testing?

Safety

- Poorly made modules can have electrical arcs in their junction boxes or hotspots on the module itself, which can cause fires.



Hotspot on solar module imaged by thermography: http://www.chemeng.ntua.gr/solarlab/Research_Photovoltaic.html

How Module Testing?

Standard IEC Tests for crystalline silicon and thin film modules:
http://www.iecee.org/ctl/equipment/pdf/pv/EL_IEC61646_Ed1_final.pdf
http://www.iecee.org/ctl/equipment/pdf/pv/EL_IEC61730-2_approved.pdf
http://www.iecee.org/ctl/equipment/pdf/pv/EL_IEC61215_Ed1_final.pdf

Photos of PV module testing removed due to copyright restrictions.
See Lecture 17 video.

Reliability & Safety

Reliability and Safety

Tested by leading international institutes and certified for reliability and safety.

- Certified to IEC 61646
- Certified to IEC 61730
- CE Mark
- Safety Class II @ 1000 V
- UL 1703 and ULC 1703 Listed (Class C Fire Rating)
- Eligible CSI PV Module
- FSEC Certification

http://www.firstsolar.com/

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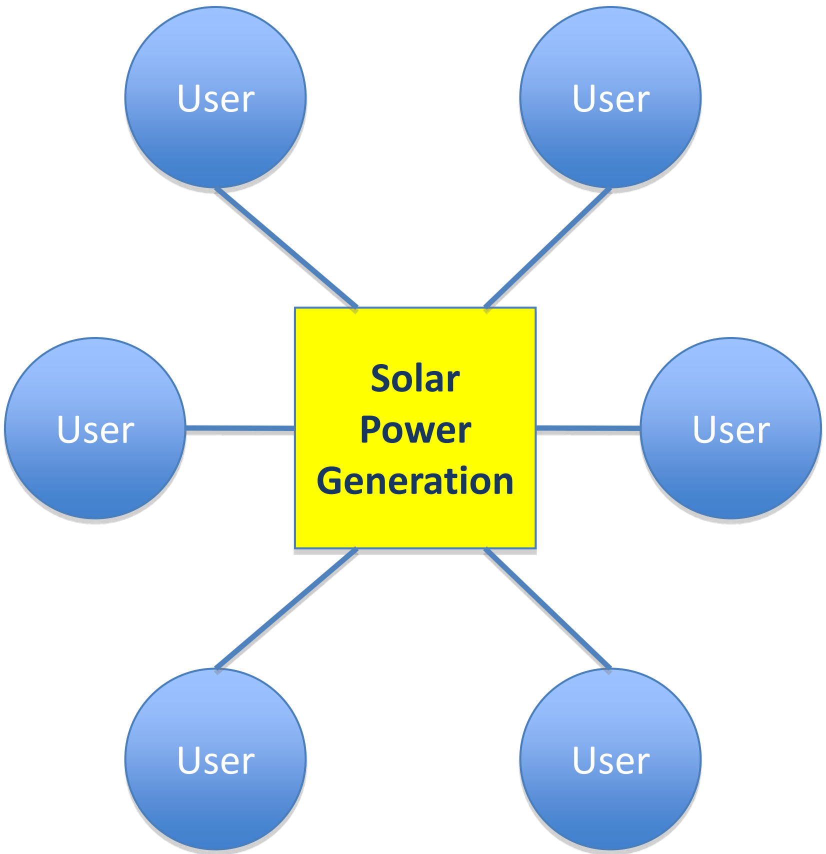
Systems: Grid-tied and stand-alone.

System Design
(Infrastructure Beyond Conversion Devices)

Systems	
Energy Production Centralized	**Energy Production Distributed**

Systems

Energy Production Centralized | **Energy Production Distributed**



Today's typical centralized installation typically exceeds 500 kW_p.

Systems

Energy Production Centralized | **Energy Production Distributed**

Please see the Lecture 17 video for these three examples.

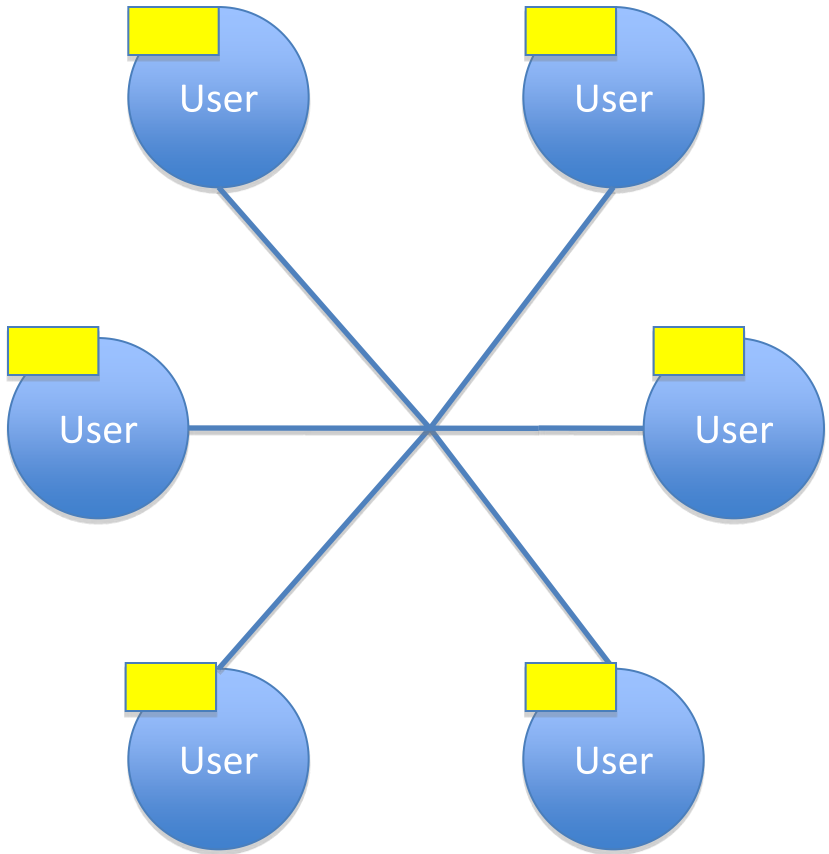
20 MW_p plant in Spain.

11 MW_p plant in Portugal

Bavaria, Germany

Systems

Energy Production Centralized	**Energy Production Distributed**



Today's typical distributed installation is typically less than 10 kW_p, but can 675 kW_p or larger.

Systems

Energy Production Centralized | **Energy Production Distributed**

Please see the Lecture 17 video for these three examples.

675 kW_p system, Moscone Center, SF.

Amersfoort, Netherlands

House in Rochester, NY

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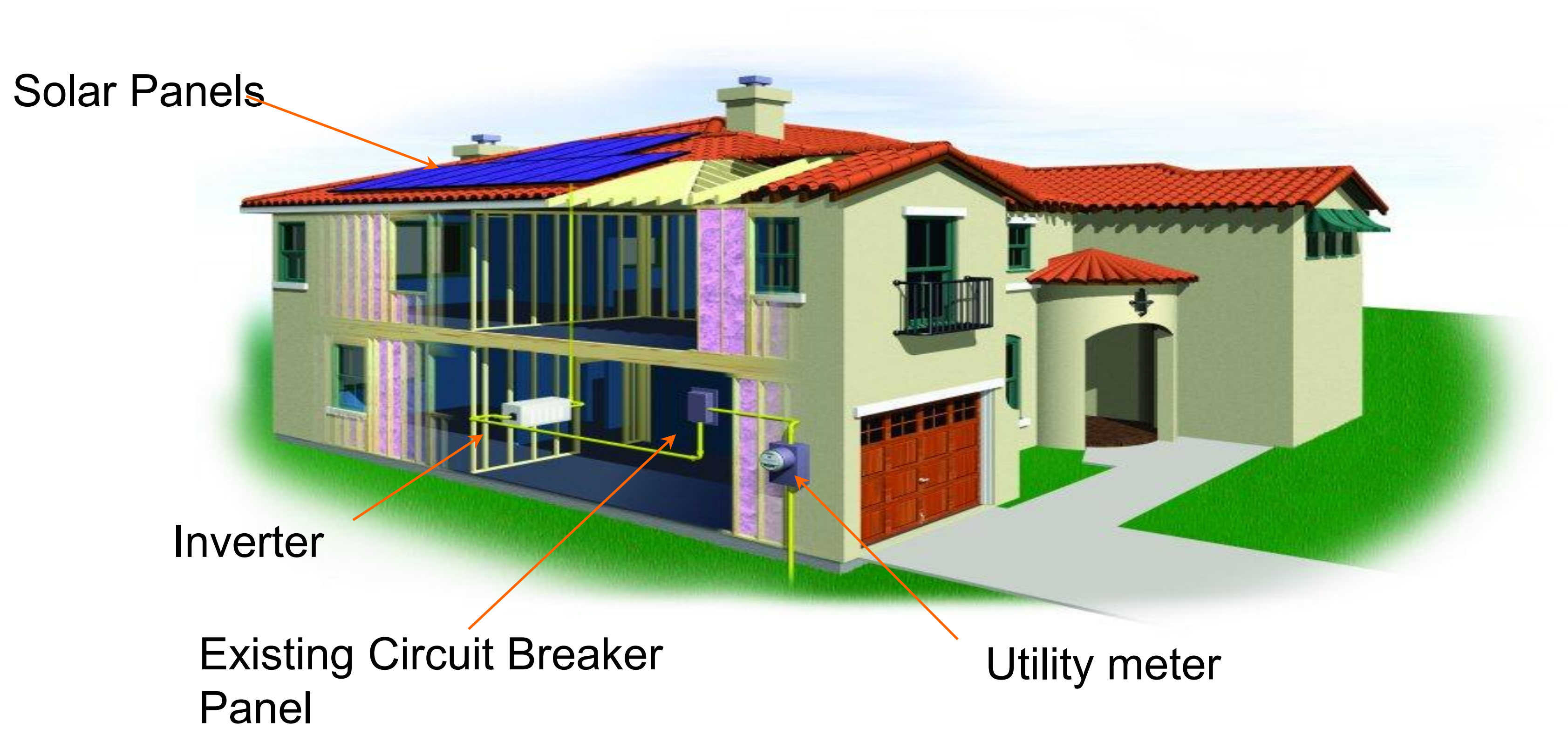
Grid-Tied PV Systems

- PV array connected to utility grid via an inverter
- Excess power sent to grid (e.g., meter spins backwards)
- Relies on utility grid as “energy storage device” (no batteries required)
- Mounted on roof or ground
- Any business or residence can use grid tied solar

Picture credit: Borrego Solar

Grid-Tied PV Systems



Inverters

- Typically use higher voltage string inverters
  - Battery backup is exception
- Sizes range from 700-6000W
- Modern efficiencies range from 94-99%
- All have maximum power point tracking (MPPT)
- 5 Year manufacturer warranty
- Usually governed by array considerations

Mounting Methods

- Roof Mount or Stand Off
  - Least expensive
  - Usually require penetrations
- Ground Mount
  - More expensive
  - Usually only option for large arrays
- Pole Mount
  - Can be more expensive
  - Adjustable height, and flexible orientation

Slide content courtesy of Borrego Solar

Grid-Tied PV Systems

- Under "net metering" (i.e., same price for all electrons): When panels produce excess power meter spins backwards. Only pay utility for distance meter spins forwards. Only pay once a year.

- Under "feed-in tariff" or "time-of-use" (i.e., price for electrons varies depending on time of day, value of source): Separate meters, for energy consumed and produced.

Meter Spins Backwards!

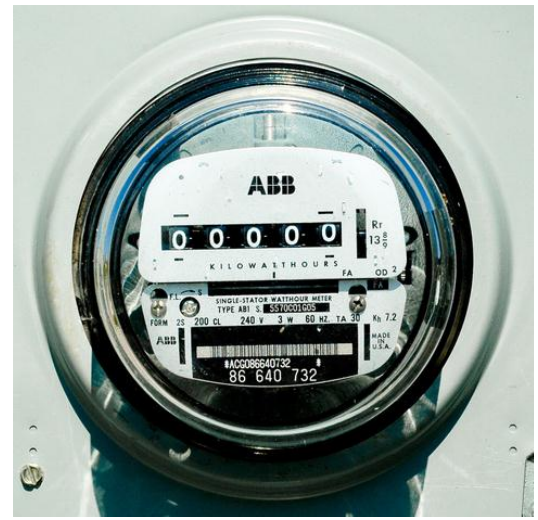


Photo courtesy of coldtaxi on Flickr.

Prof. Buonassisi's Electricity Bill

Account Nickname: Electricity

Account Number

Current Balance: -$163.57

"Go Paperless" and enjoy hassle free, paperless billing.

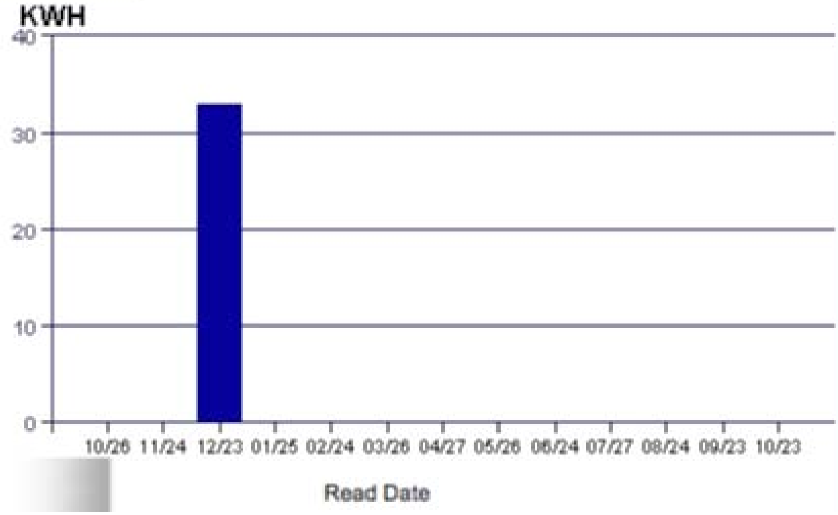
Billing Period: Nov 1, 2010

Download

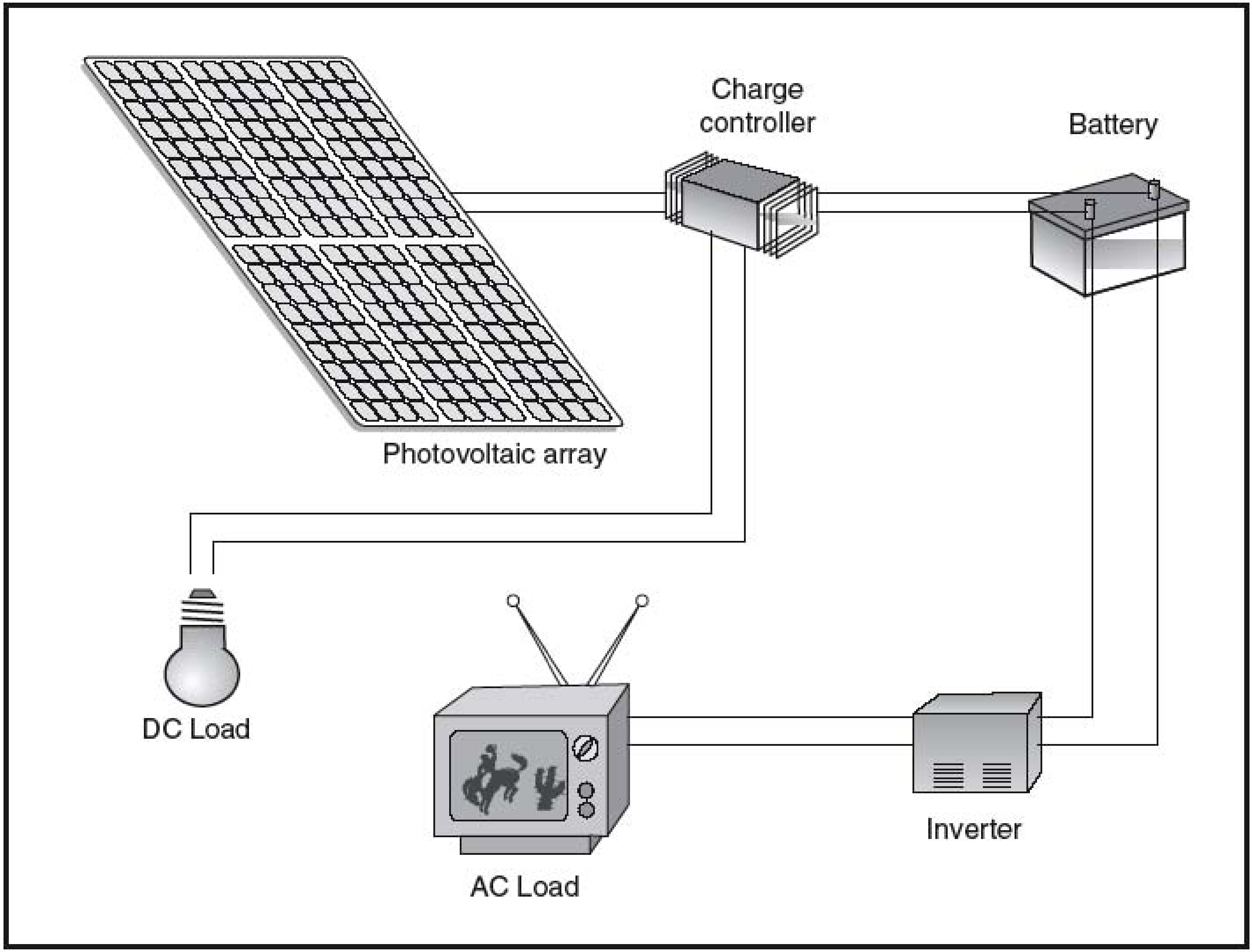
NSTAR Bill Summary

Account Number	**1153 371 0080**
Billing Date	**Nov 1, 2010**
Next Read Date	Nov 26, 2010
Previous Bill	-157.02
Other Credits	-13.42
Total Cost Electricity	6.87
Credit Balance	**- $163.57**

Usage Summary



Off-Grid PV Systems



Components of a typical off-grid PV system *Solar electricity can be used for many purposes, either directly, or by storing in batteries for use when the sun is not shining.*

Life is Good as an Installer…

Module prices ~$1/W_p$…

…but installations ~$5.20/W_p$!

NEWS | SOLAR
Tweet 29 | Share 3 | 59

ERIC WESOFF OCTOBER 14, 2011

Solar Module Pricing: $1.03 per Watt for c-Si

How low can it go?

Admittedly, Chinaland Solar Energy might not be the most bankable solar firm out there, but since they were kind enough to approach me via email, I figured, let's get a price quote.

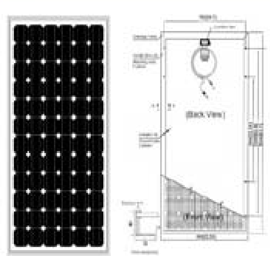
I requested a quote for 100 units of a 200-watt solar panel and received this response within 30 minutes.

Chinaland Solar Energy Co., Ltd.

Address: Feidong New City Economic Development Zone, Hefei, 231600, Anhui Province, PR China

TEL: 0086 551 7758558-8029 Mobile: 0086 13275799897 FAX: 0086 551 7758555

E-mail chn2012@chnland.com website www.chnland.com

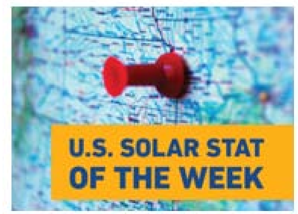
Image	Model	Specification	
Polycrystalline solar panel Remark: The Specification is just for reference, the exact one subjects to flash report tested for each shipment.			
	CHN200-72P	Cell type	Monocrystalline
		Max Output Power	200W
		Max Power Voltage	37V
		Max Power Current	5.41A
		Open Voltage	45V
		Short Circuit Current	5.8A
		Dimension of module	1580*808*40 mm
		20ft/40ft container	372pcs/784pcs
		Cell type	156*156mm 72pcs
		Conversion efficiency	18.31%
		Certificate	CE, TUV, IEC, MCS, ISO
		Life time	25 years
		1*20'FCL/1*40FCL	372pcs/784pcs
Payment terms	30% DEPOSIT 70% AFTER SENDING SCANNED ORIGINAL BL		
Price	FOB USD1.03/W		
Delivery time	5 days after receiving 30% deposit		

RESEARCH & ANALYSIS | USSMI
Tweet 46 | Share 11 | 130

CAROLYN CAMPBELL OCTOBER 17, 2011

US Has an Average Solar System Price of $5.20/W

Decrease of just 3 percent in Q2 2011



Average weighted photovoltaic installation price decreased just 3 percent in the second quarter of 2011 to $5.20 per watt, according to GTM Research and the Solar Energy Industries Association's latest quarterly **U.S. Solar Market Insight report**.

Residential system prices were virtually flat quarter over quarter, increasing slightly from $6.39 per watt in the first quarter to $6.42 per watt in the second quarter of 2011. Residential systems are typically slow to adjust… **Read More ›**

Source: www.greentechmedia.com

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3. Describe how microinverters and microelectronics can improve module performance output.
4. List the necessary tests a PV module must pass to ensure reliable multi-decade service life in the field, as well as the shortcomings of these tests.
5. Describe the differences between various types of PV systems: Grid-tied and stand-alone, tracking and non-tracking.
6. List major balance of system components.
7. Describe current consensus of life cycle analysis studies, and recycling of modules.

Life Cycle Analysis (LCA) of PV Technologies

Key Factors:

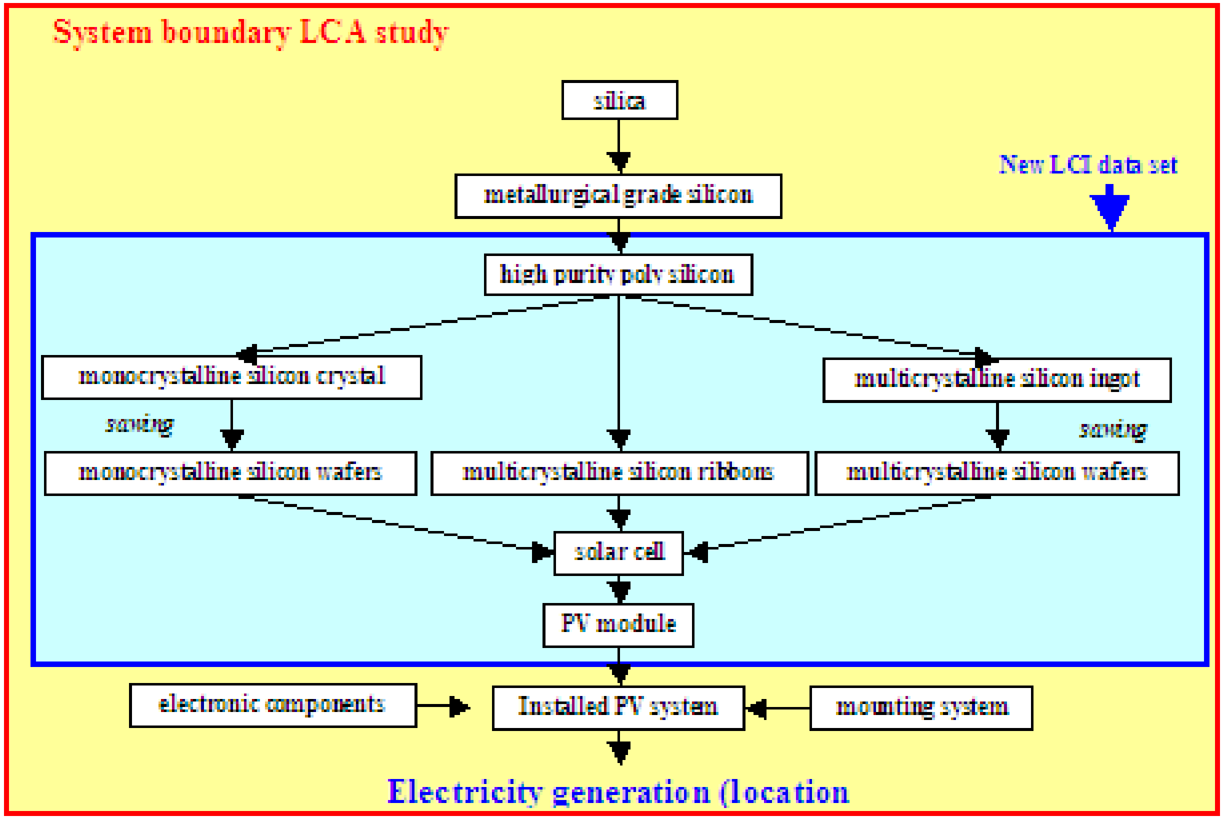
- Boundary Conditions
- Inputs
- Outputs

Notable Groups:

- Vasilis M. Fthenakis (Brookhaven National Laboratory)
- Energy Center of the Netherlands

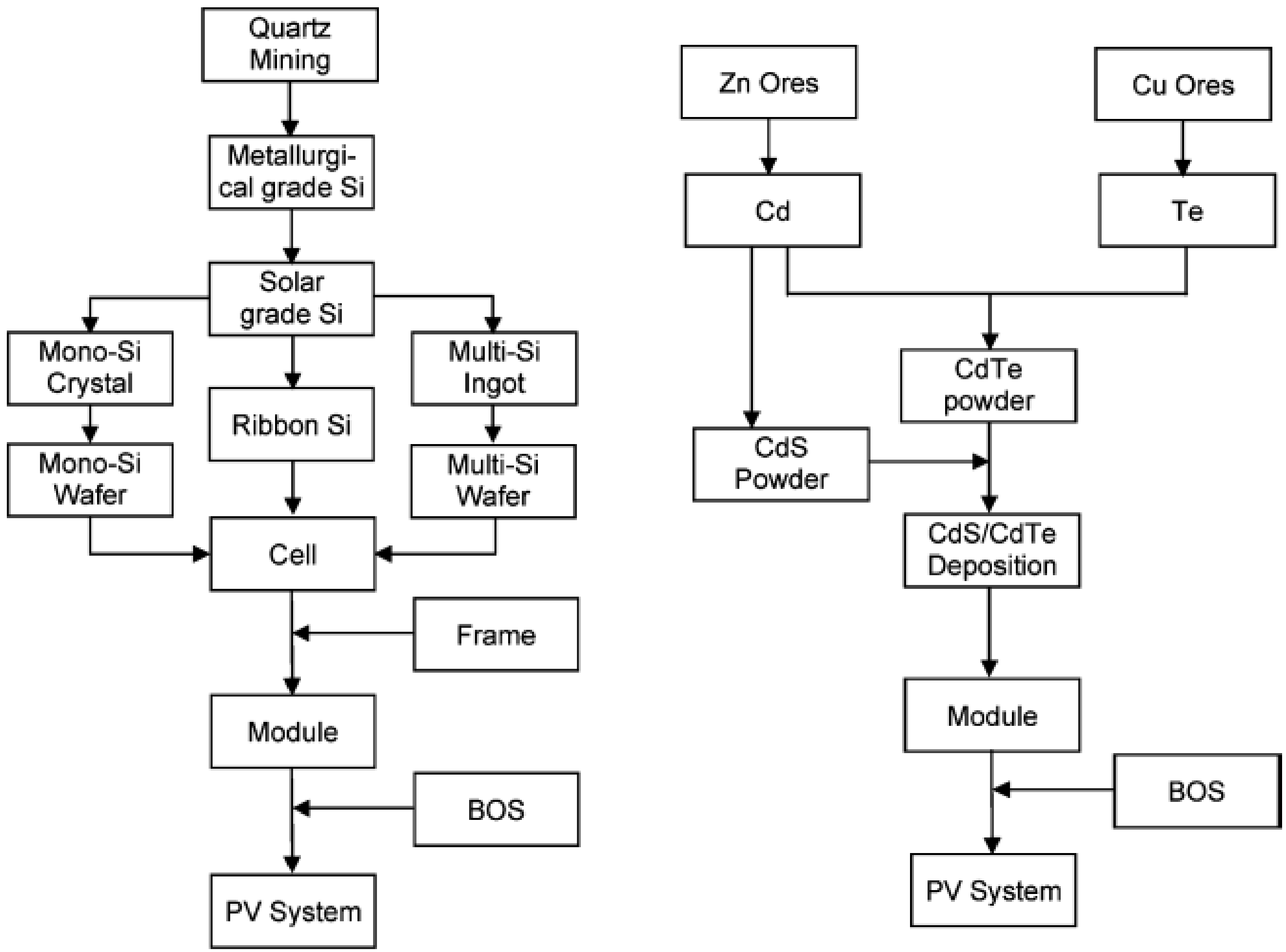
LCA Boundary Conditions

Boundary conditions define the scope. *Limited boundary conditions may compromise validity of the study!*



"State-of-the-art photovoltaic systems have Energy Pay Back Times as low as 1.7 years." *ECN News*, 15 May 2006.

LCA Boundary Conditions



(a) Silicon PVs (b) CdTe PVs (frameless)

Fthenakis, V. M., et al. "Emissions from Photovoltaic Life Cycles." *Environ. Sci. Technol*. 42, no. 6 (2008): 2168-2174.

See also "Photovoltaic Cells Are Still Very Green, Comparative Test Shows." *The New York Times*, Feb. 26, 2008.

LCA Inputs

Some Key Inputs (Assumptions!) into LCA Models:

- Module lifetime
- Wafer thickness
- Cell / module efficiency
- Manufacturing yield
- Energy mix

Nota bene:

The outputs of comparative LCA studies are extremely sensitive to these key inputs.

LCA Outputs

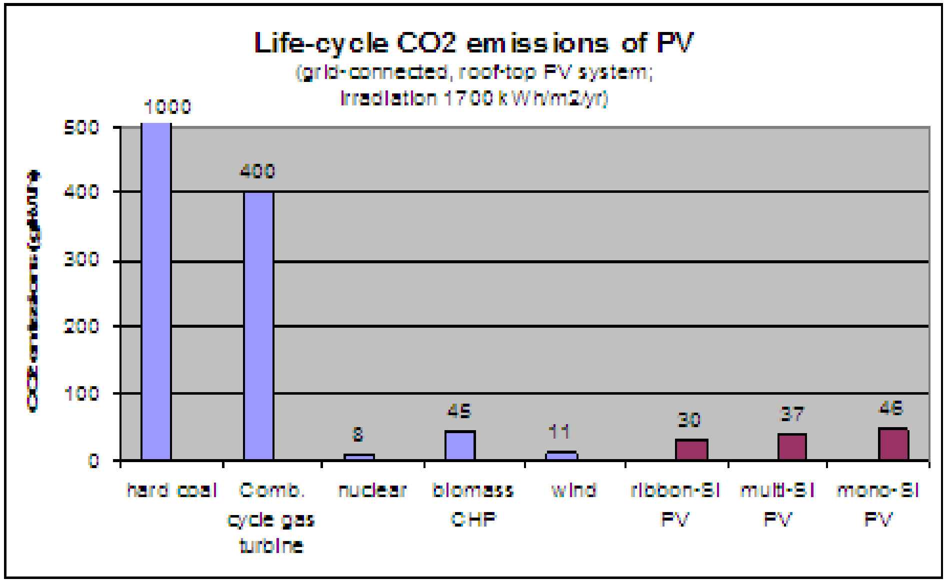
Some Key LCA Outputs:

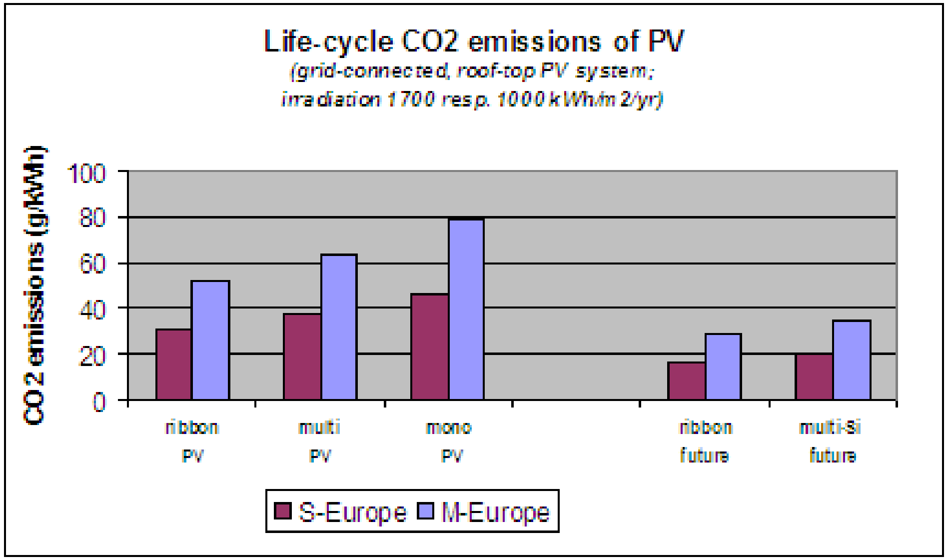
- Energy payback time
- CO_2 emissions per unit energy produced
- Toxic releases

Nota bene:

The outputs of comparative LCA studies are extremely sensitive to key inputs and to the boundary conditions. Hence, variations of a few percent – even a few tens of percent – are not generally considered significant. These studies are helpful when comparing orders of magnitude.

LCA Outputs: Life Cycle CO_2 Emissions





"State-of-the-art photovoltaic systems have Energy Pay Back Times as low as 1.7 years." *ECN News*, 15 May 2006.

LCA Outputs: Life Cycle CO_2 Emissions

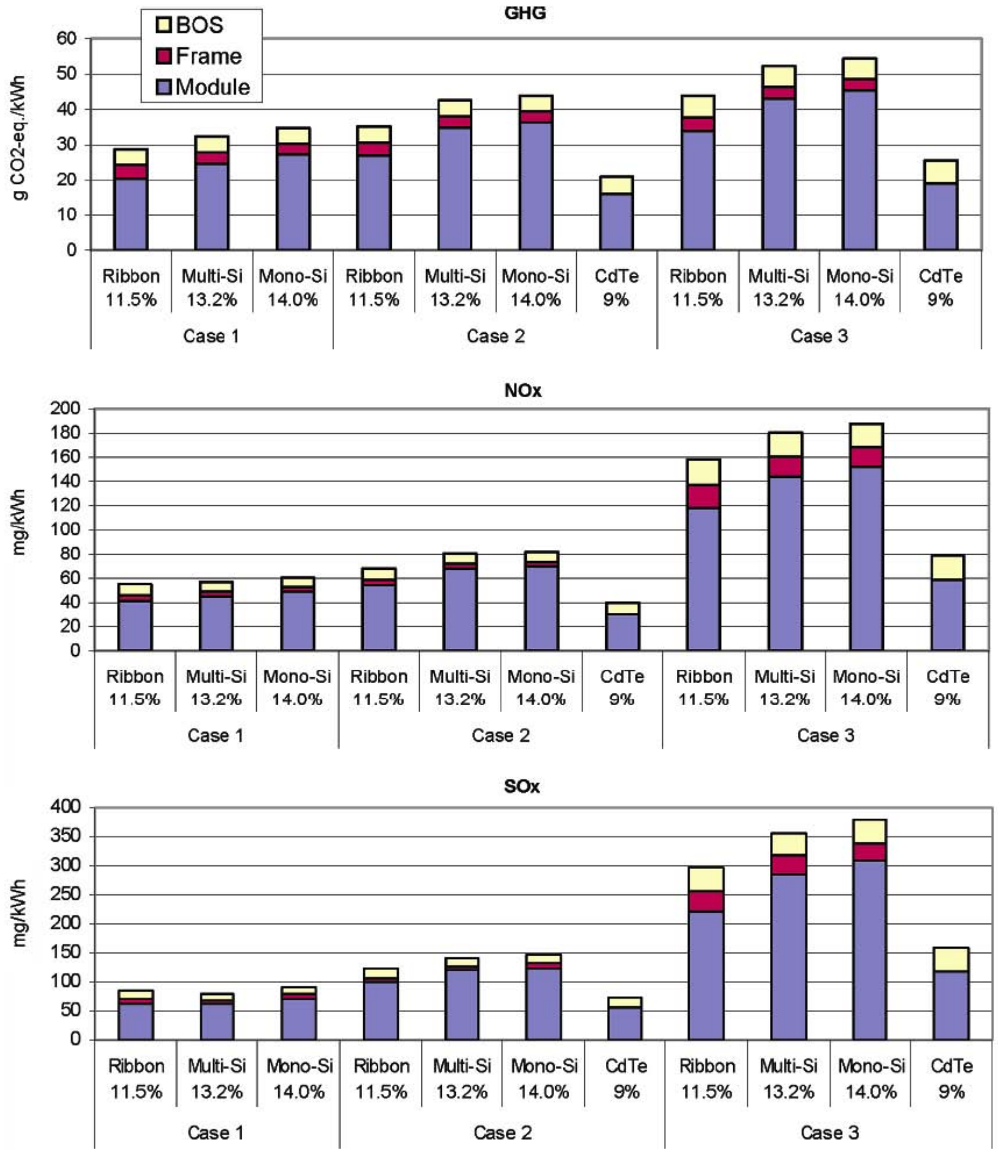


FIGURE 2. Life-cycle emissions from silicon and CdTe PV modules. BOS is the Balance of System (i.e., module supports, cabling, and power conditioning). Conditions: ground-mounted systems, Southern European insolation, 1700 kWh/m²/yr, performance ratio of 0.8, and lifetime of 30 years. Case 1: current electricity mixture in Si production—CrystalClear project and Ecoinvent database. Case 2: Union of the Co-ordination of Transmission of Electricity (UCTE) grid mixture and Ecoinvent database. Case 3: U.S. grid mixture and Franklin database.

Fthenakis, V. M., et al. "Emissions from Photovoltaic Life Cycles." *Environ. Sci. Technol.* 42, no. 6 (2008): 2168-2174.

LCA Outputs: Sensitivity to Energy Inputs

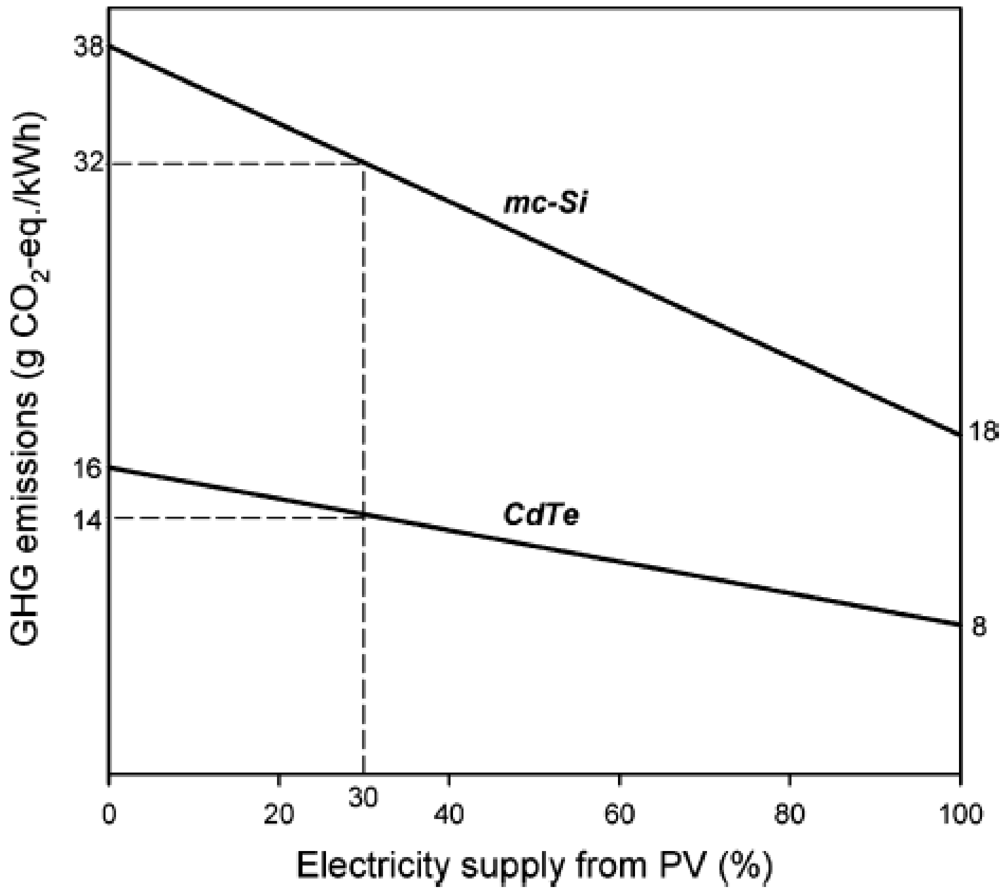
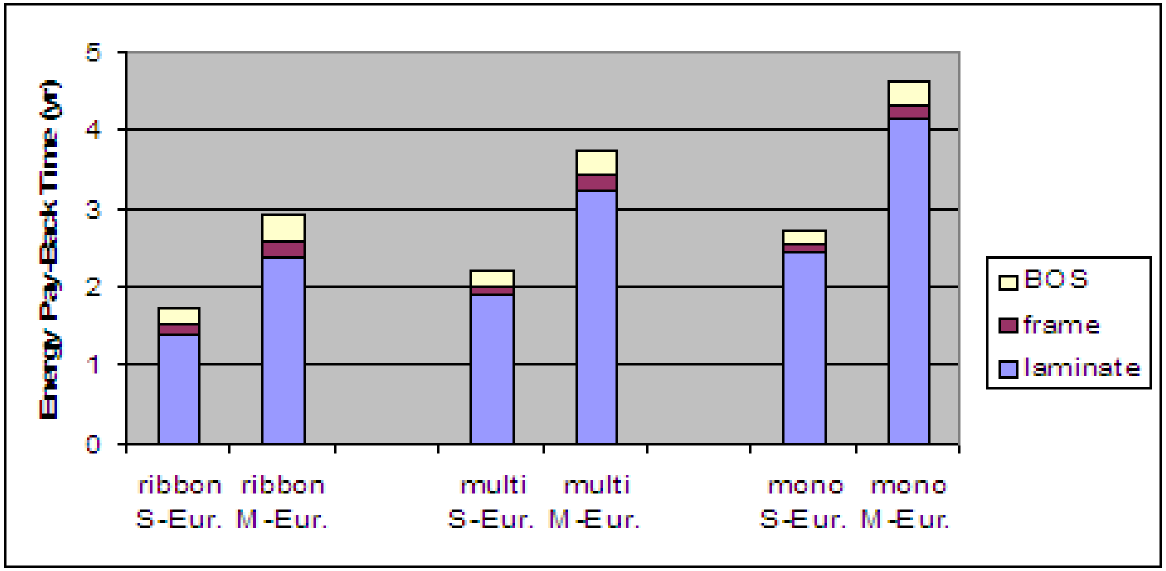
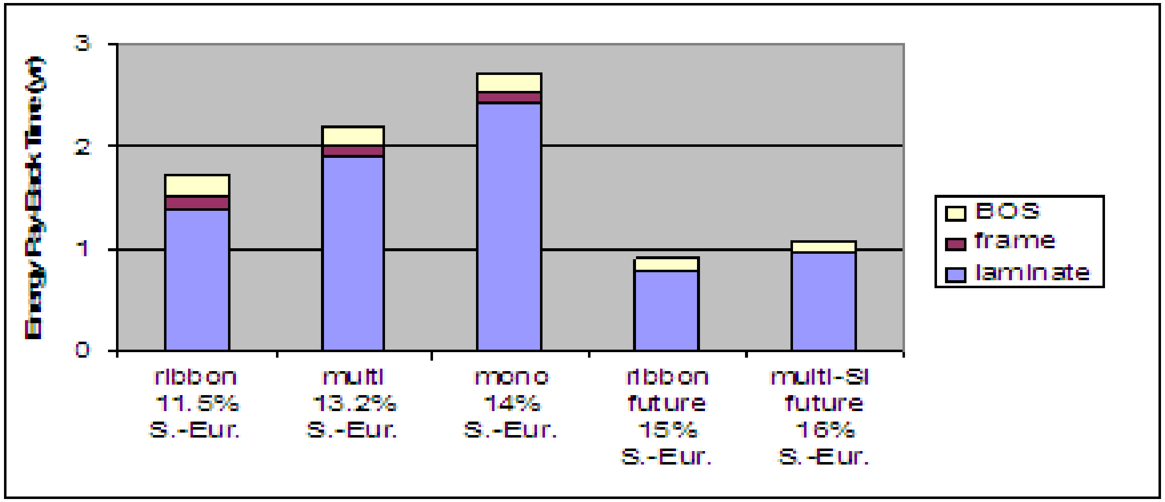


FIGURE 6. Greenhouse gas emissions profile for PV modules when using a PV breeder that supplies electricity for PV production. Insolation of 1700 kWh/m²/yr, performance ratio of 0.8, and lifetime of 30 yrs are assumed. BOS is not included. In 2005, the total (100%) electricity corresponded to 250 kWh/m² for mc-Si and 59 kWh/m² for CdTe PV.

Fthenakis, V. M., et al. "Emissions from Photovoltaic Life Cycles." *Environ. Sci. Technol.* 42, no. 6 (2008): 2168-2174.

LCA Outputs: Energy Payback





"State-of-the-art photovoltaic systems have Energy Pay Back Times as low as 1.7 years." *ECN News*, 15 May 2006.

LCA Outputs: Energy Payback

	Consumed energy of PV module	
	Standard	Recycled
Silicon production	7,55 kWh/wafer	-
Solar cell production	0,65 kWh/wafer	0,65 kWh/wafer
Module production	1,12 kWh/wafer	1,12 kWh/wafer
Recycling at end of life	-	0,4 kWh/wafer
Total	9,32 kWh/wafer 0,129 kWh/kWh_{Gen}	2,17 kWh/wafer 0,030 kWh/kWh_{Gen}

Table 3: Energy content of a module using virgin wafers and a module using recycled wafers

Great study, but old data (2000).

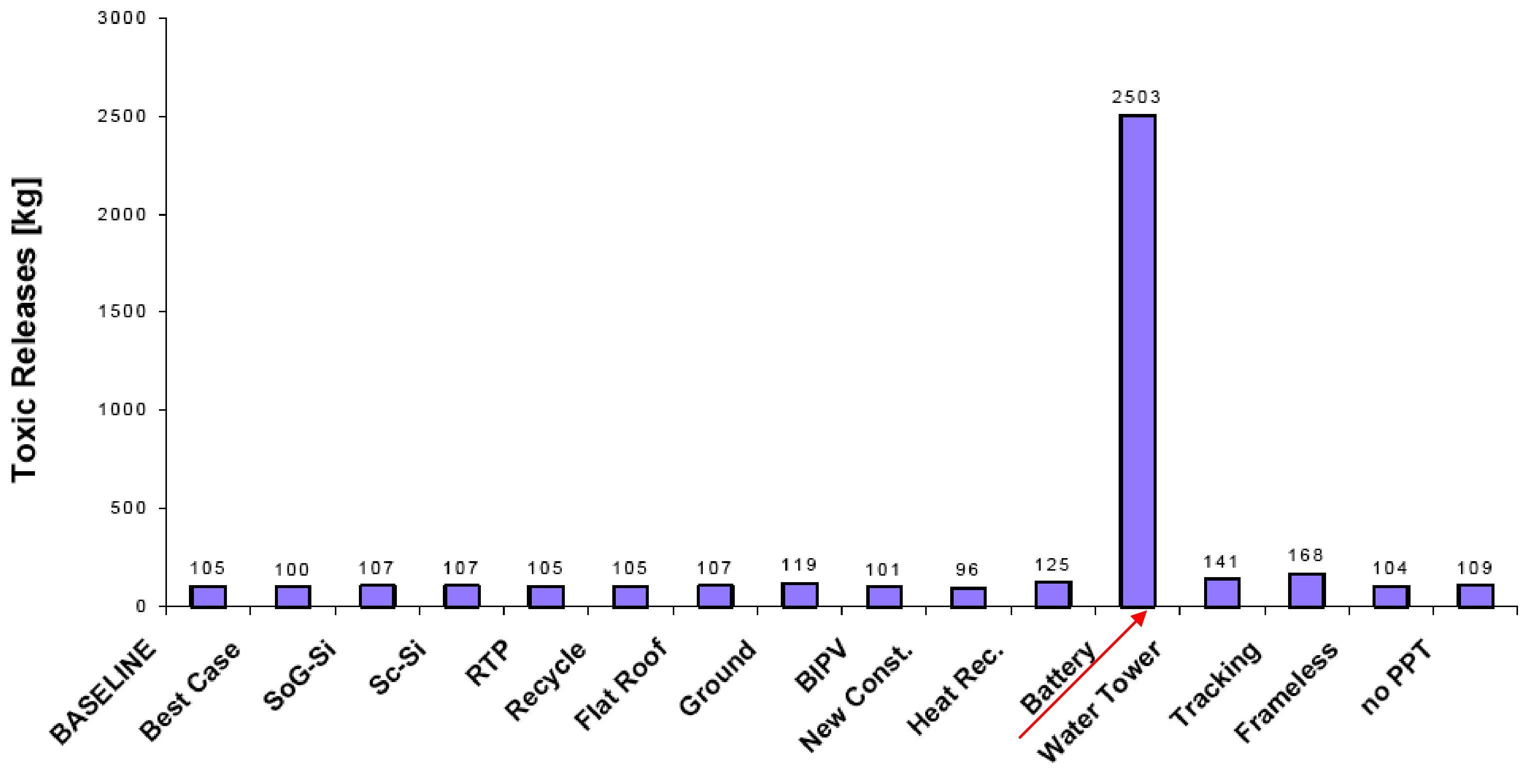
	Standard	Recycled
Energy input	9,32 kWh/wafer or 4,26 kWh/Wp	2,17 kWh/wafer 0,99 kWh/Wp
Energy pay back time		
Sunny regions	2,58 years	0,6 years
Continental regions	4,92 years	1.14 years

Table 4: Energy pay back time for a module using virgin wafers and a module using recycled wafers

L. Frisson *et al.* "Recent Improvements in Industrial PV Module Recycling." *16th European PV Solar Energy Conference*, Glasgow, UK (2000)

LCA Outputs: Toxic Releases

Batteries: Add financial cost, environmental impact.



Technology Choices for the PV Industry: A Comparative Life Cycle Environmental Impact Perspective.

T. Williams, S. Boyd, T. Buonassisi, Proc. 21st EU-PVSEC (Barcelona, Spain, 2005)

LCA Outputs: Toxic Releases

Cadmium: Topic of controversy!

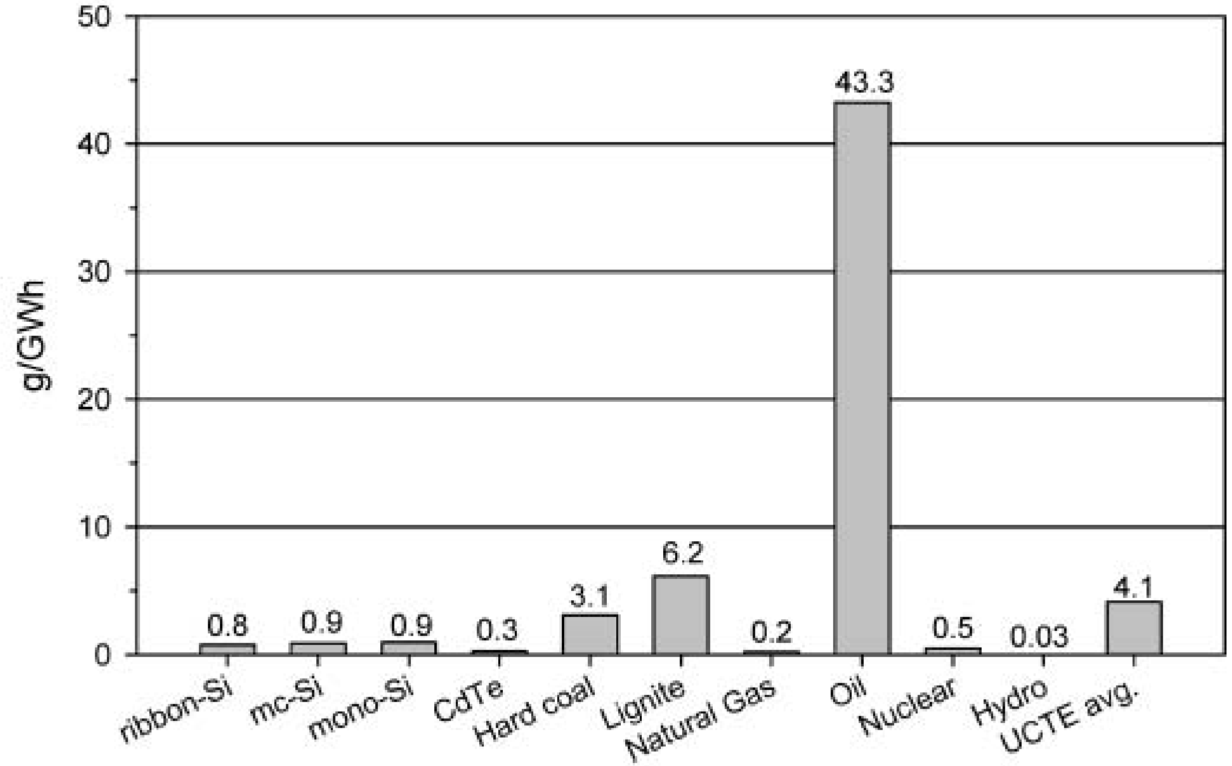


FIGURE 3. Life-cycle atmospheric Cd emissions for PV systems from electricity and fuel consumption, normalized for a Southern Europe average insolation of 1700 kWh/m²/yr, performance ratio of 0.8, and lifetime of 30 yrs. Ground-mounted BOS (*18*) is assumed for all PV systems; comparisons with other electricity generation options.

Fthenakis, V. M., et al. "Emissions from Photovoltaic Life Cycles." *Environ. Sci. Technol.* 42, no. 6 (2008): 2168-2174.

LCA Bottom Line

LCAs indicate that current PV technology:

- Emits 90-96% less CO_2/kWh than coal.
- Has a 1-5 year energy payback.
- Has little differences between PV technologies.

PV Module Recycling

- Required by law in some places for certain types of modules (*e.g.*, First Solar modules in Germany).
- Industry-wide groups promote best practices.
- Necessary to develop for when the industry reaches steady-state (while growth rate is positive, the volume of new panels swamps out those being recycled).

Visual presentation by First Solar at the 2009 EU-PVSEC