2.626 Fundamentals of Photovoltaics
Fall 2008

Modules, Systems, and Reliability

Lecture 17 – 2.626

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Topics of Today's Lecture

- Module manufacturing: encapsulation materials, availability, trends.
- Systems: Grid-tied and stand-alone, tracking and non-tracking.
- System components, including balance of systems components.
- The energy storage challenge.
- Life cycle analysis.

Topics of Next Lectures

- Design criteria, tradeoffs, costs.
- Building integration, BIPV.
- System integration.
- Scaling, and integration into the power grid.
- Appropriate technology selection.
- Failure: failure modes in stationary and tracking systems, accelerated testing, field testing, service and warranty contracts.

Definitions

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http://www.infinitepower.org/pdf/FactSheet-11.pdf

Module manufacturing: encapsulation materials, availability, trends.

Solar Module Technology

- Modules require little maintenance
  - Water rinse 2-3 time/year
- No moving parts
- 25 year manufacturer warranty typical
- 12V and 24V modules traditional; in between voltages now popular.

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Picture courtesy of Astro Power

Sample PV Module Spec Sheet

Sample PV Module Spec Sheet

Sample PV Module Spec Sheet

Text removed due to copyright restrictions. Please see “Standard Test Conditions” and “Temperature Coefficients” in http://evergreensolar.com/upload/ES-A%20fa3%20Datasheets/ES-A_fa3_200_205_210_US_010409.pdf

Sample PV Module Spec Sheet

Images and text removed due to copyright restrictions. Please see specification sheets for any First Solar photovoltaic module.

Solar Module Technology Trends: Cheaper, Better Encapsulants

Transparent Front Surface (e.g., Glass)

Encapsulant (e.g., EVA)

Cells

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Encapsulant (e.g., EVA)

Backskin (e.g., Tedlar) or Back Surface (e.g., Glass)

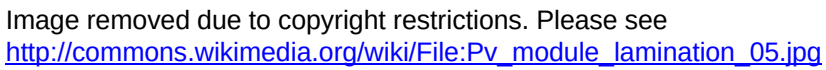


Image removed due to copyright restrictions. Please see
http://commons.wikimedia.org/wiki/File:Pv_module_lamination_05.jpg

Solar Module Technology Outlook: Back-Contacted Cells

Solar Module Technology Trends: BIPV Modules

Images removed due to copyright restrictions. Please see
http://www.renewableenergyworld.com/assets/images/story/2005/6/24/1332_SI_meridian_closeup.jpg
http://www.inhabitat.com/images/bipv1.jpg
http://www.inhabitat.com/images/bipv3.jpg

Systems: Tracking and non-tracking, concentrating and non-concentrating.

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

Two Sub-Groups:

1. Non-concentrating

Image from Wikimedia Commons, http://commons.wikimedia.org

2. Concentrating

Image removed due to copyright restrictions. Please see http://www.polarpowerinc.com/info/operation20/figures/figure2-36.gif

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

1. Non-concentrating, non-tracking

a. Roof-mounted

b. Ground-mounted

Images from Wikimedia Commons, http://commons.wikimedia.org

See also: 120 kW_p Domaine Carneiros, Napa, CA, and Jim Fournier's system, Nicasio, CA

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

2. Concentrating, non-tracking

a. External (mounted) reflectors

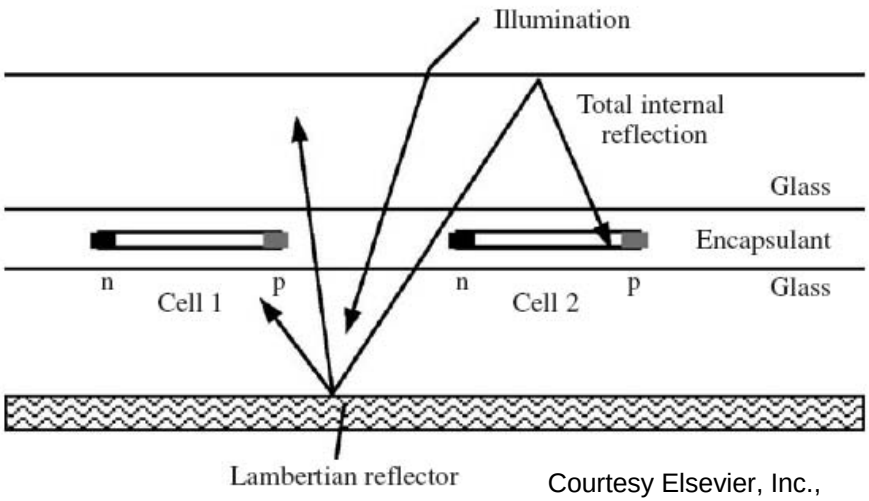
Image removed due to copyright restrictions. Please see
http://www.polarpowerinc.com/info/operation20/figures/figure2-36.gif

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

2. Concentrating, non-tracking

b. Internal reflectors



Sliver Cell (A.N.U.)

Courtesy Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

Image removed due to copyright restrictions. Please see http://www.technologyreview.com/files/15077/solaria_x220.jpg

Solyndra

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

2. Concentrating, non-tracking

c. Photon conditioning, internal reflectors

Image removed due to copyright restrictions.
Please see any diagram of a luminescent solar concentrator solar cell, such as http://www.covalentsolar.com/images/Applications_New_19.jpg.

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

The Basics of Tracking Systems:

One-Axis Tracking **Two-Axis Tracking**

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http://www.polarpowerinc.com/info/operation20/figures/figure2-28.gif

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

Two Sub-Groups:

1. Not Concentrating

Courtesy of DOE/NREL, Credit - Tom Stoffel.

2. Concentrating

Image removed due to copyright restrictions. Please see http://i.treehugger.com/images/2007/5/24/600_kw_suncubemark5gge.jpg

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

1. Not concentrating, tracking

a. Photovoltaics

Courtesy of DOE/NREL, Credit - Tom Stoffel.

Courtesy of DOE/NREL, Credit – Steve Wilcox.

http://recsolar.com/Library/images/Commercial%20Midsize/CA%20State%20Park%20-%20Tule%20Elk%20Reserve,%20Buttonwillow%20CA.jpg

Solar Energy Conversion Technology

Solar to Electricity		Solar to Heat Electricity		Solar to Heat		Solar to Fuels	
Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking	Non-Tracking	Tracking

2. Concentrating, tracking

a. (Fresnel) Lenses

Image removed due to copyright restrictions. Please see
http://i.treehugger.com/images/2007/5/24/600_kw_suncubemark5gge.jpg

SunCube Mark 5 Solar Appliance
Green and Gold Energy of Australia

Image removed due to copyright restrictions. Please see
http://www.statesadvancingsolar.org/wp/wp-content/uploads/AmonixCPV.jpg.

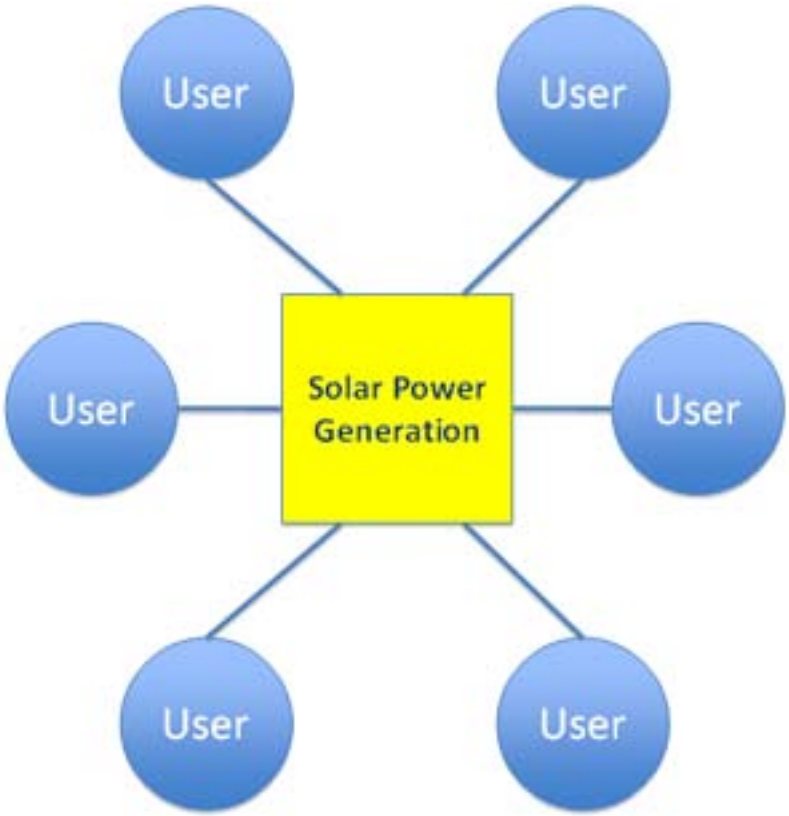
Systems: Grid-tied and stand-alone.

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**

http://www.energysolar.org.uk/energy_solar_pics/11-mw-solar-power-plant.png
http://technology4life.files.wordpress.com/2008/01/jumilla_solar_farm.jpg
http://images.pennnet.com/articles/rew/cap/cap_0705rew_photo03_02.jpg

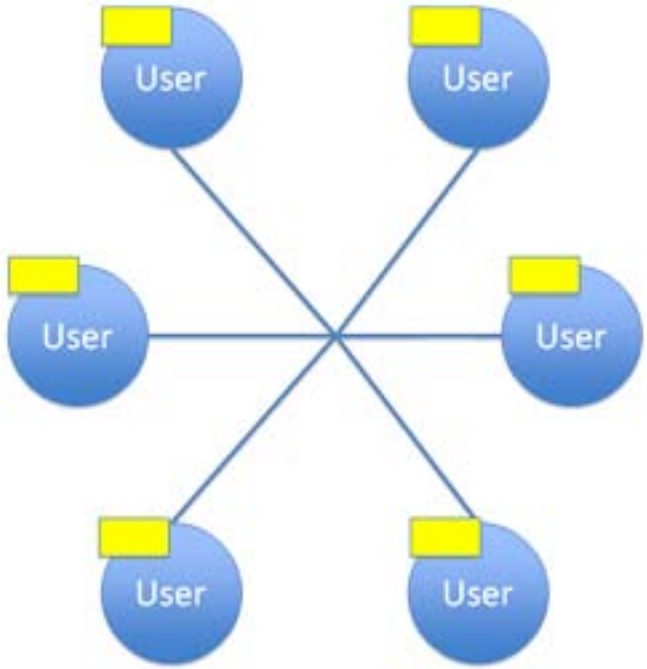
11 MW_p plant in Portugal

20 MW_p plant in Spain.

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**

http://www.iea-pvps.org/cases/images/nld_0109.jpg
http://www.wired.com/news/images/full/moscone_f.jpg
http://earth2tech.files.wordpress.com/2008/05/cudrefin_switzerlandashx.jpeg

675 kW_p system, Moscone Center, SF.

Amersfoort, Netherlands

House in Rochester, NY

Systems

Energy Production Centralized | **Energy Production Distributed**

Image removed due to copyright restrictions. Please see
http://www.smud.org/en/news/PublishingImages/IMG_0010.jpg

Zero energy homes, Rancho Cordova, CA
http://www.smud.org/news/multimedia.html

System components, including balance of systems components.

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

Image removed due to copyright restrictions. Please see http://imgs.sfgate.com/g/pictures/2006/01/25/ga_green_loren_ss.jpg

Picture credit: Borrego Solar

Grid-Tied PV Systems

Solar Panels

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http://www.cobaltpower.com/images/house_conceptual.jpg

Inverter

Existing Circuit Breaker Panel

Utility meter

Picture courtesy of Astro Power

Inverters

- Typically use higher voltage string inverters
  - Battery backup is exception
- Sizes range from 700-6000W
- Efficiencies range from 92-95%
- All have MPPT
- 5 Year manufacturer warranty
- Usually governed by array considerations

http://www.solarhome.org/images/sharpsunvista.gif
http://www.fronius.com/internet/img_usa/SE/products_Fronius_IG_2000_3000_2500LV_rdax_100.jpg
http://www.solarsolar.com/SMA2500.jpg
http://www.altersystems.com/catalog/images/inverters/Outback/Outback_Vented_20VFX.jpg

Slide content courtesy of Borrego Solar

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!

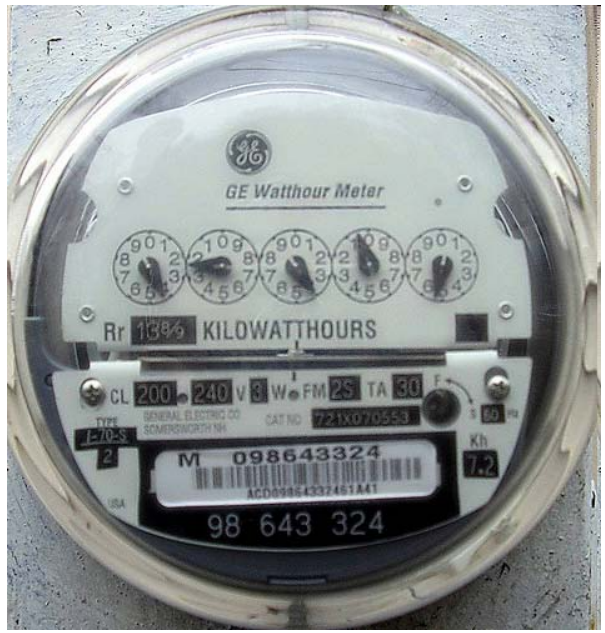

Image courtesy flickr user Mark Sardella.

Off-Grid PV Systems

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What about energy storage?

Energy storage, current embodiments

1. **Chemical:** Batteries (Pb, NiMH, Li), redox flow, fuels…
2. **Electromagnetic:** Capacitors, supercapacitors, SMES…
3. **Mechanical:** Fly-wheels, pneumatic, elastic, graviational…
4. **Thermal:** Storage tanks…

Systems			
Energy Production Centralized		**Energy Production Distributed**	
Storage Distributed	Storage Centralized	Storage Distributed	Storage Centralized

Images removed due to copyright restrictions. Please see
http://www.newenergyshop.com/pic.Energy.Storage/Energy.Storage.SolarStorageSystem.jpg
http://www.dep.state.pa.us/dep/DEPUTATE/minres/districts/homepage/Moshannon/Windmill/Windmill4.gif

Fuel cells (x2)

Batteries (lead acid)

Systems

Energy Production Centralized		Energy Production Distributed	
Storage Distributed	Storage Centralized	Storage Distributed	Storage Centralized

Courtesy flickr user S. J. Alexander.

Image removed due to copyright restrictions. Please see http://i.usatoday.net/money/_photos/2007/07/05/batteryx-large.jpg

“Utility-scale” energy storage

http://www.usatoday.com/money/industries/energy/2007-07-04-sodium-battery_N.htm?csp=34

The Grid*

**non-dispatchable storage solution!*

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!*

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http://www.ecn.nl/fileadmin/ecn/units/zon/images/LCA_Newsletter_april_2006/lca-figuur1.png

http://www.ecn.nl/en/news/item/article/155/1/

LCA Boundary Conditions

Image removed due to copyright restrictions. Please see Fig. 1 in Fthenakis, Vasilis M., Hyung Chul Kim, and Erik Alsema. “Emissions from Photovoltaic Life Cycles.” *Environmental Science and Technology* 42 (2008): 2168-2174.

http://www.nytimes.com/2008/02/26/science/26obsola.html
http://pubs.acs.org/cgi-bin/abstract.cgi/esthag/asap/abs/es071763q.html

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:

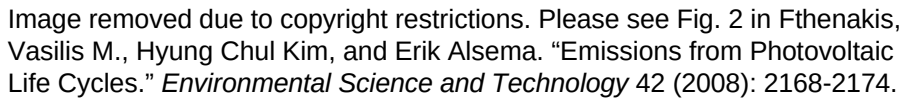
The outputs of comparative LCA studies are extremely sensitive to key inputs and to the boundary conditions. Hence, variations of a few percent – even a few tens of percent – are not generally considered significant. These studies are helpful when comparing orders of magnitude.

LCA Outputs: Life Cycle CO_2 Emissions

Images removed due to copyright restrictions. Please see
http://www.ecn.nl/fileadmin/ecn/units/zon/images/LCA_Newsletter_april_2006/lca-figuur3.png
http://www.ecn.nl/fileadmin/ecn/units/zon/images/LCA_Newsletter_april_2006/lca-figuur5.png

http://www.ecn.nl/en/news/item/article/155/1/

LCA Outputs: Life Cycle CO_2 Emissions



http://pubs.acs.org/cgi-bin/abstract.cgi/esthag/asap/abs/es071763q.html

LCA Outputs: Sensitivity to Energy Inputs

Image removed due to copyright restrictions. Please see Fig. 6 in Fthenakis, Vasilis M., Hyung Chul Kim, and Erik Alsema. “Emissions from Photovoltaic Life Cycles.” *Environmental Science and Technology* 42 (2008): 2168-2174.

http://pubs.acs.org/cgi-bin/abstract.cgi/esthag/asap/abs/es071763q.html

LCA Outputs: Energy Payback

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http://www.ecn.nl/fileadmin/ecn/units/zon/images/LCA_Newsletter_april_2006/lca-figuur2.png
http://www.ecn.nl/fileadmin/ecn/units/zon/images/LCA_Newsletter_april_2006/lca-figuur4.png

http://www.ecn.nl/en/news/item/article/155/1/

LCA Outputs: Energy Payback

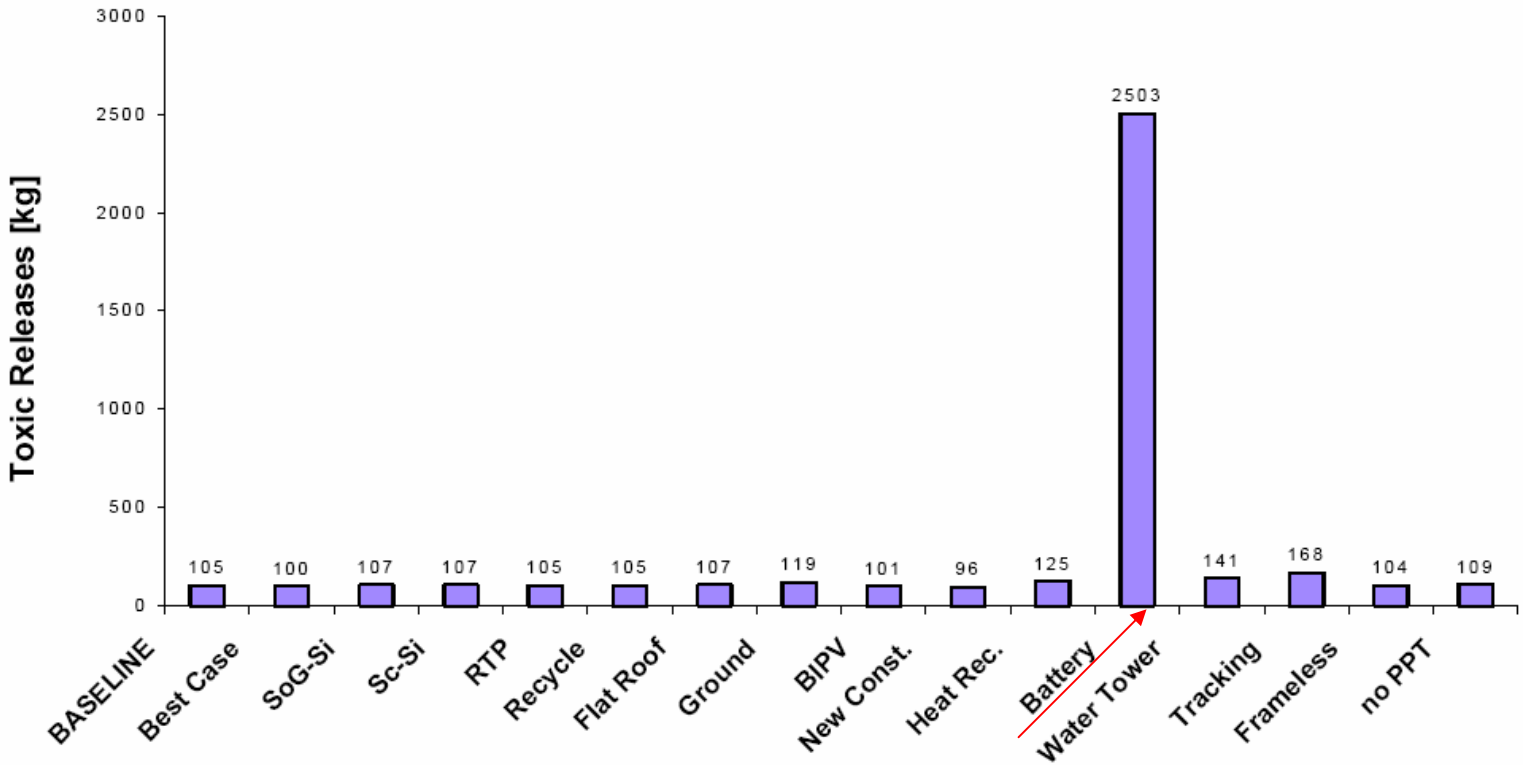
Great study, but old data (2000).

Tables removed due to copyright restrictions. Please see Tables 3 and 4 in Frisson, L., et al. “Recent Improvements in Industrial PV Module Recycling.” Glasgow, UK: *Proceedings of the 16th European Photovoltaic Solar Energy Conference*, 2000.

L. Frisson *et al.* 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!

Image removed due to copyright restrictions. Please see Fig. 3 in Fthenakis, Vasilis M., Hyung Chul Kim, and Erik Alsema. "Emissions from Photovoltaic Life Cycles." *Environmental Science and Technology* 42 (2008): 2168-2174.

http://pubs.acs.org/cgi-bin/abstract.cgi/esthag/asap/abs/es071763q.html

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.