ESREF 2010

Tutorial on

"RELIABILITY ISSUE OF PHOTOVOLTAIC DEVICES AND SYSTEMS"

Part I - PV Devices

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Enea Portici Research Centre

October 2010 11th - 15th
Monte Cassino Abbey and Gaeta- Italy

ESREF 2010

Summary

PART I: : Reliability of Photovoltaic devices

- PV Technology
- PV Solar cells & Module manufacturing:
  - Wafer based Silicon Technology
  - Thin film (Thin Silicon, CIGS, CdTe)
  - PV Concentration
  - Organic and hybrid Solar cells
- Reliability and Qualification Tests
- Overview of Solar cells and PV Modules Failure Mechanisms

Summary

PART II: : Reliability of Photovoltaic Systems

- Photovoltaic Power Management Systems
- DC-AC Converter Architectures
- DC-DC Converter Topologies
- Reliability Theory
- Reliability Model
- DC-DC Converter Reliability Evaluation

Part I: references

- Handbook of Photovoltaic Science and Engineering Antonio Luque, Steven Hegedus John Wiley & son ltd ISBN-0-471-49196-9 (2002)
- An Introduction to Reliability and Maintainability Engineering, Ebeling, Charles, McGraw-Hill Companies, Inc., Boston, (1997)
- NREL-DOE Photovoltaic Module Reliability Workshop February 18-19, 2010 Denver, Colorado (USA) http://www1.eere.energy.gov/solar/pv_module_reliability_workshop_2010.html
- Photovoltaic-reliability R&D toward a solar-powered world, S.Kurtz, J. Granata and M.Quintana Proc. SPIE, Vol. 7412, 74120Z (2009); doi:10.1117/12.825649
- "History of accelerated and qualification testing of terrestrial photovoltaic modules: a literature review," Osterwald, C. R. and McMahon, T. J., Prog. Photovolt: Res. Appl. 17, 11-33 (2009)
- "Module 30 Year Life: What Does it Mean and is It Predictable/Achievable?," McMahon, G. Jorgensen, R. Hulstrom, NREL, Reliability Physics Symposium, 2008 (IRPS 2008); IEEE Inter., April 27, 2008-May 1, 2008 pp.: 172–177.
- G. TamizhMani et.. Al. Failure Analyisis of design qualification testing 2007 vs 2005 33nd PVSC Conference San Diego, 2008
- The results of performance measurements of field-aged crystalline silicon photovoltaic modules. Prog. Photov: Res and Appl. 2008; 17: 227–240

Part I: references

- Reliability of PV-modules Natural, accelerated and simulated degradation Projects PV-Zuverlässigkeit and Performance SP5 Michael Köhl Fraunhofer ISE,D SPIE Conference 7048-4

IEC Technical norms

- IEC 61215: Crystalline silicon terrestrial photovoltaic (PV) modules –design qualification and type approval
- IEC 61646 : 'Thin-film terrestrial photovoltaic (PV) modules – design qualification and type approval',
- IEC 62108: Concentrator photovoltaic (CPV) modules and assemblies – design qualification and type approval

Part I: references (…ctd)

This conference:

Oct,12-2010 16.20
Reliability of III-V Concentrator Solar Cells.- Carlos Algora (Solar Energy Institute, Polytechnic University of Madrid, Spain)

Oct,13-2010 15.00 G.A.2
Humidity Study of a-Si PV Cell.- C.M.Tan,[2], BK.E..Chen[2], K.P.Toh[1] ([1]Nanyang Technological University, [2]SIMTech)

Oct,13-2010 16.00 G.A.4
Novel accelerated testing method for III-V concentrator solar cells N.Núñez[1],[2],.- M.Vazquez[1],[2], J.González[1], C.Algora[1], P.Espinet[1] ([1]IES-Universidad Politécnica de Madrid, [2]EUITT-Universidad Politécnica de Madrid)

Oct,13-2010 17:00-18:30 G.P.5
Induced degradation on c-Si solar cells for concentration terrestrial applications L.Lancellotti[1], R.Fucci[1], A.Romano[1], A.Sarno[1], S.Daliento[2] ([1]ENEA, [2]University of Naples Federico II)

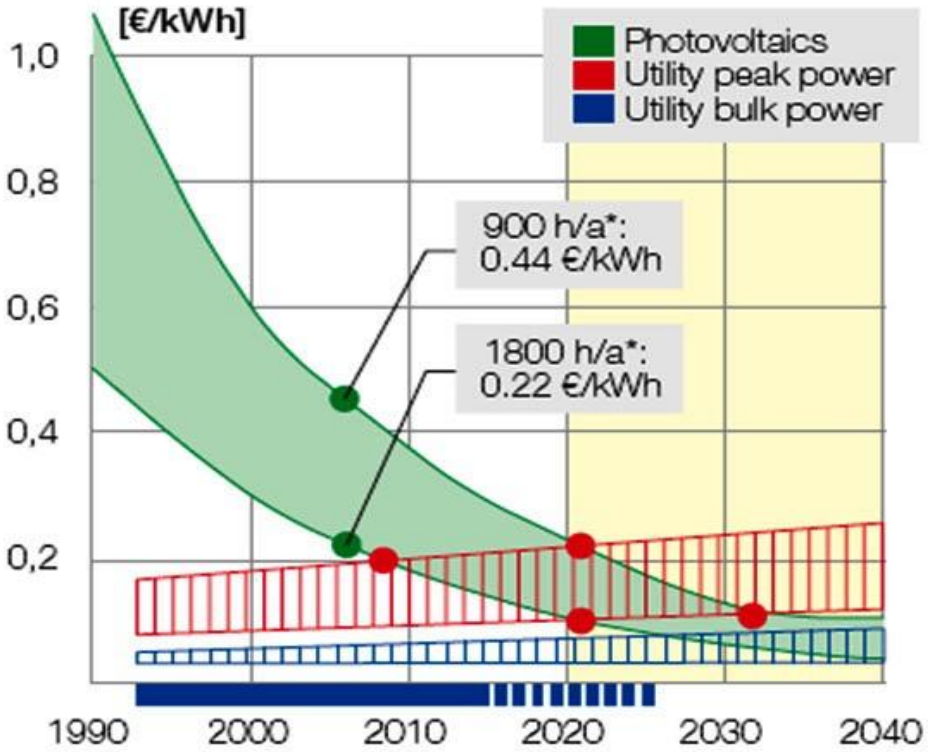
Oct,13-2010 17:00-18:30 G.P.5
G.p.6 Development and reliability of antireflective coatings specific for PV Concentration Applications F.Roca[1], E.Bobeico, G.Gradit[1], L.La Notte, A.Merola, F.Russo (ENEA)

PV Market & Perspective

Generation cost for PV

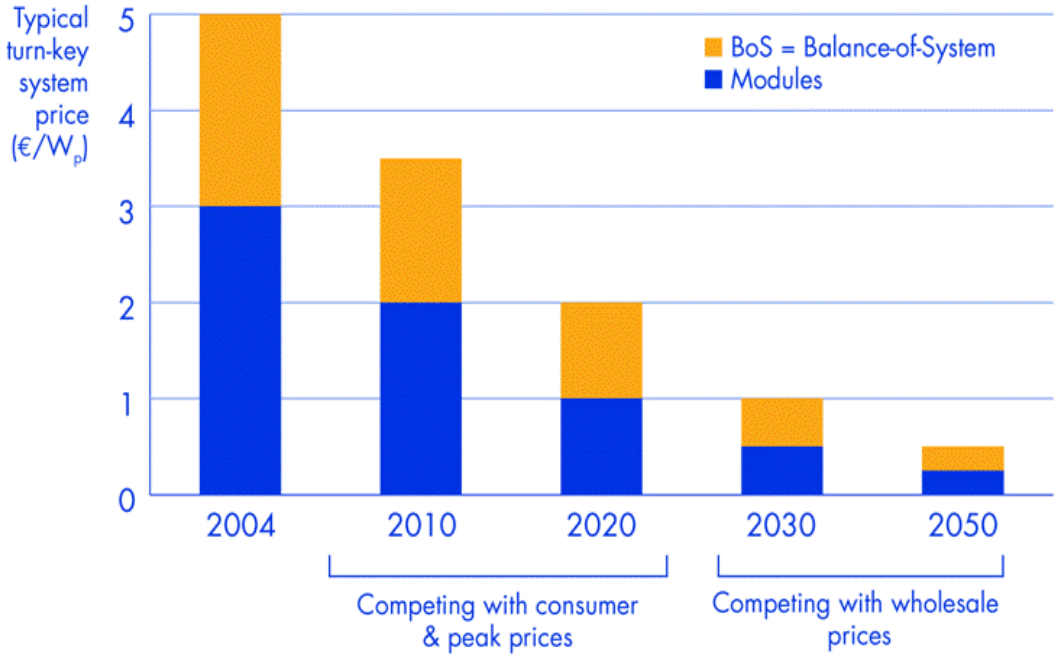
Generation cost for PV

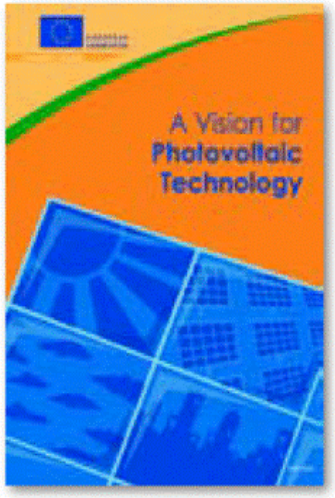
(EPIA:Toward an Effective Industrial Policy for PV (RWE Shott Solar)



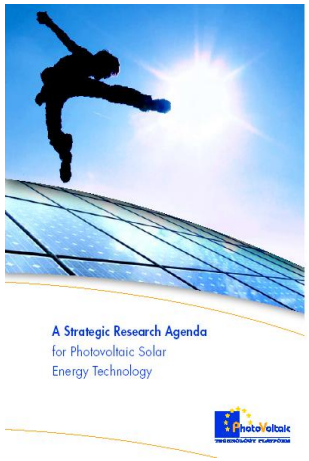
*h/a: Hours of sun per annum
900 h/a corresponds to northern countries of Europe
1800 h/a corresponds to southern countries of Europe

Evolution of the turn-key System prices





Key target



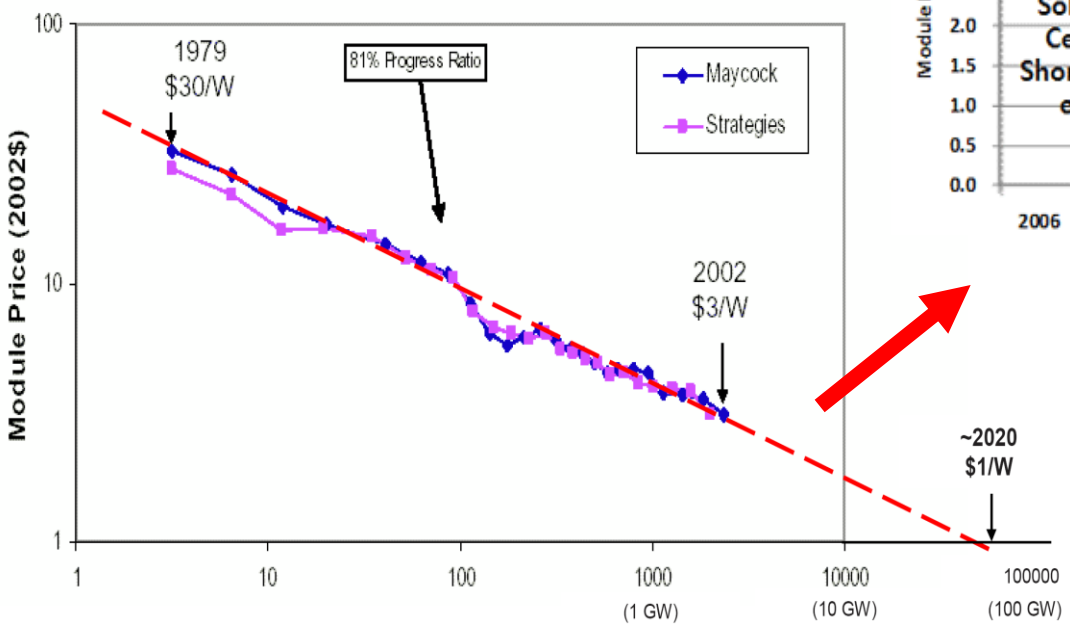
The table below summarises the key targets contained in the SRA.
The figures are rounded and indicative.

	1980	Today	2015	2030	Long term potential
Typical turn-key system price (2006 €/W_p, excl. VAT)	>30	5	2.5	1	0.5
Typical electricity generation costs southern Europe (2006 €/kWh)	>2	0.30	0.15 (competitive with retail electricity)	0.06 (competitive with wholesale electricity)	0.03
Typical commercial flat-plate module efficiencies	up to 8%	up to 15%	up to 20%	up to 25%	up to 40%
Typical commercial concentrator module efficiencies	(~10%)	up to 25%	up to 30%	up to 40%	up to 60%
Typical system energy pay-back time southern Europe (years)	>10	2	1	0.5	0.25

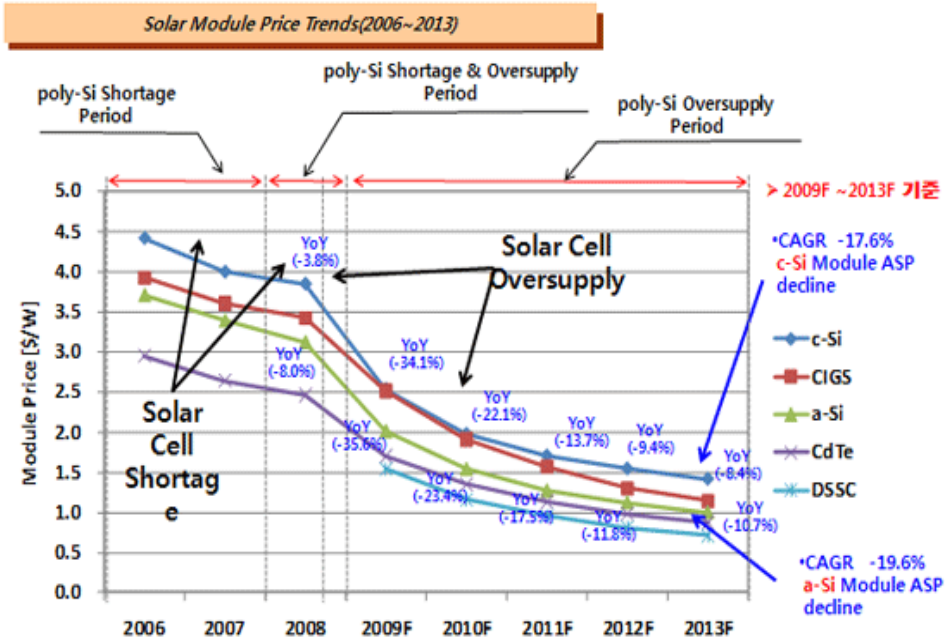
"Flat plate" refers to standard modules for use under natural sunlight, "concentrator" refers to systems that concentrate sunlight (and, by necessity, track the sun across the sky).

Module price trends :

Opportunities and Threats

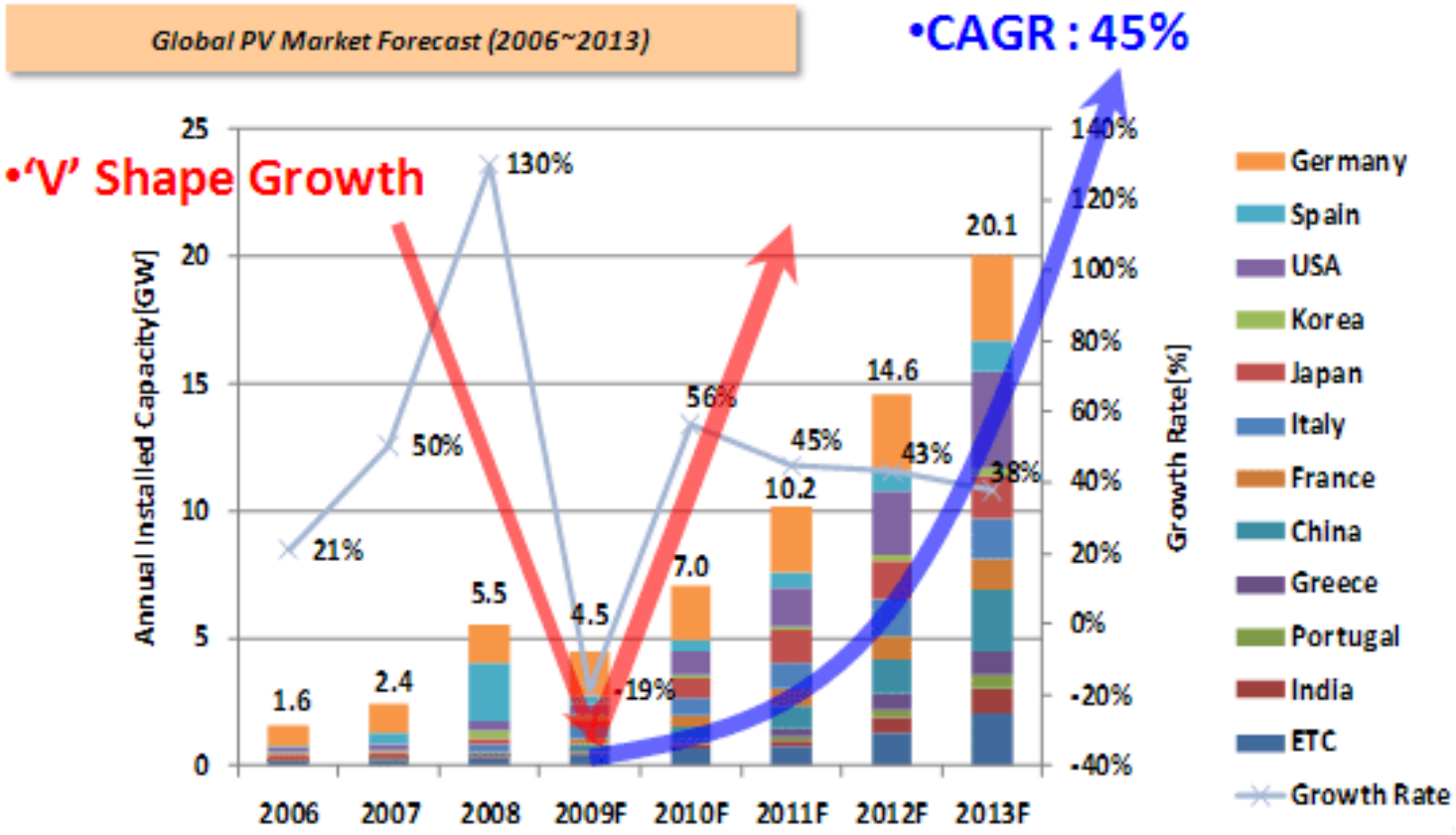


Source: Maycock, Strategies Unlimited



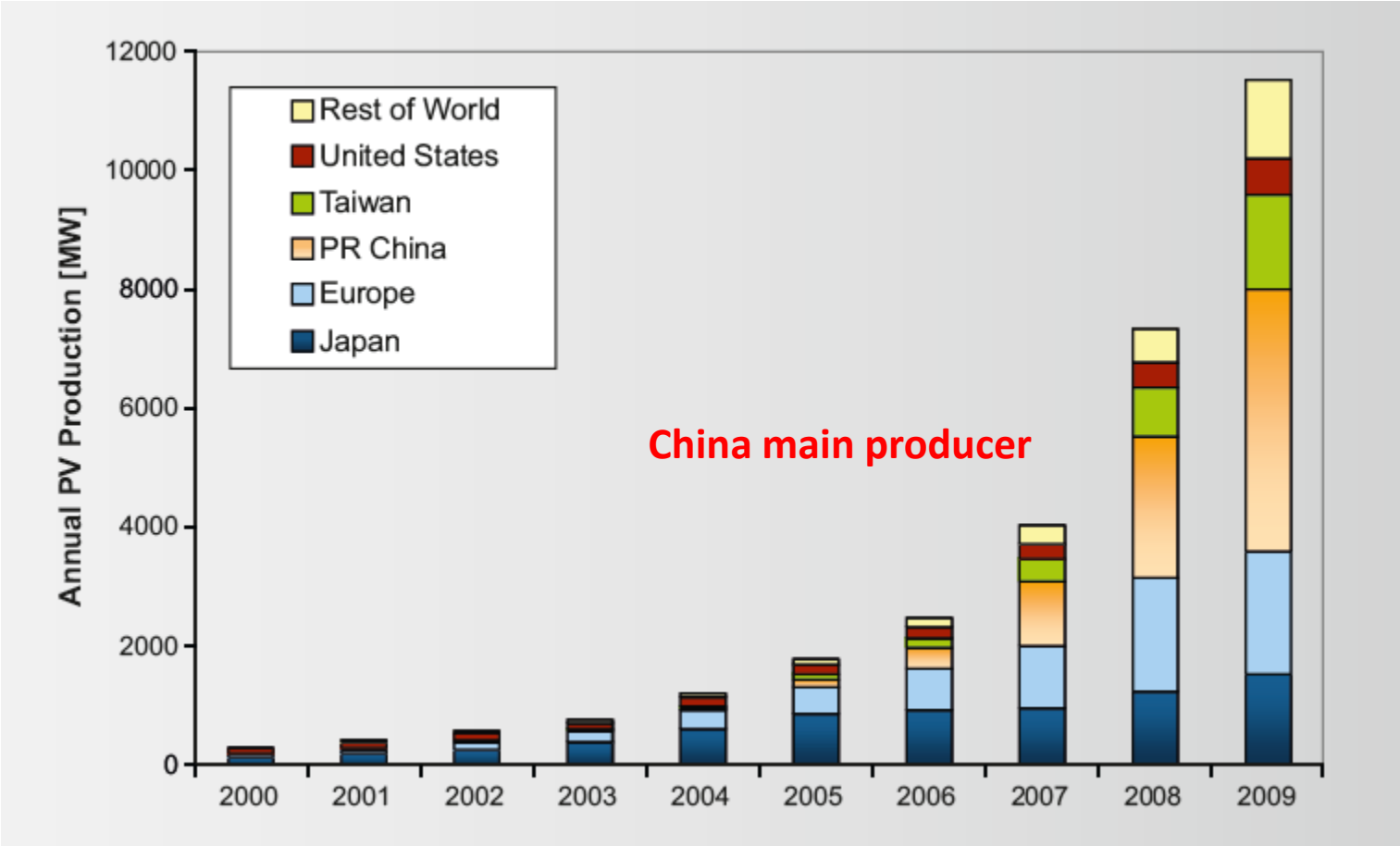
Source: DisplayBank

PV market forecast:



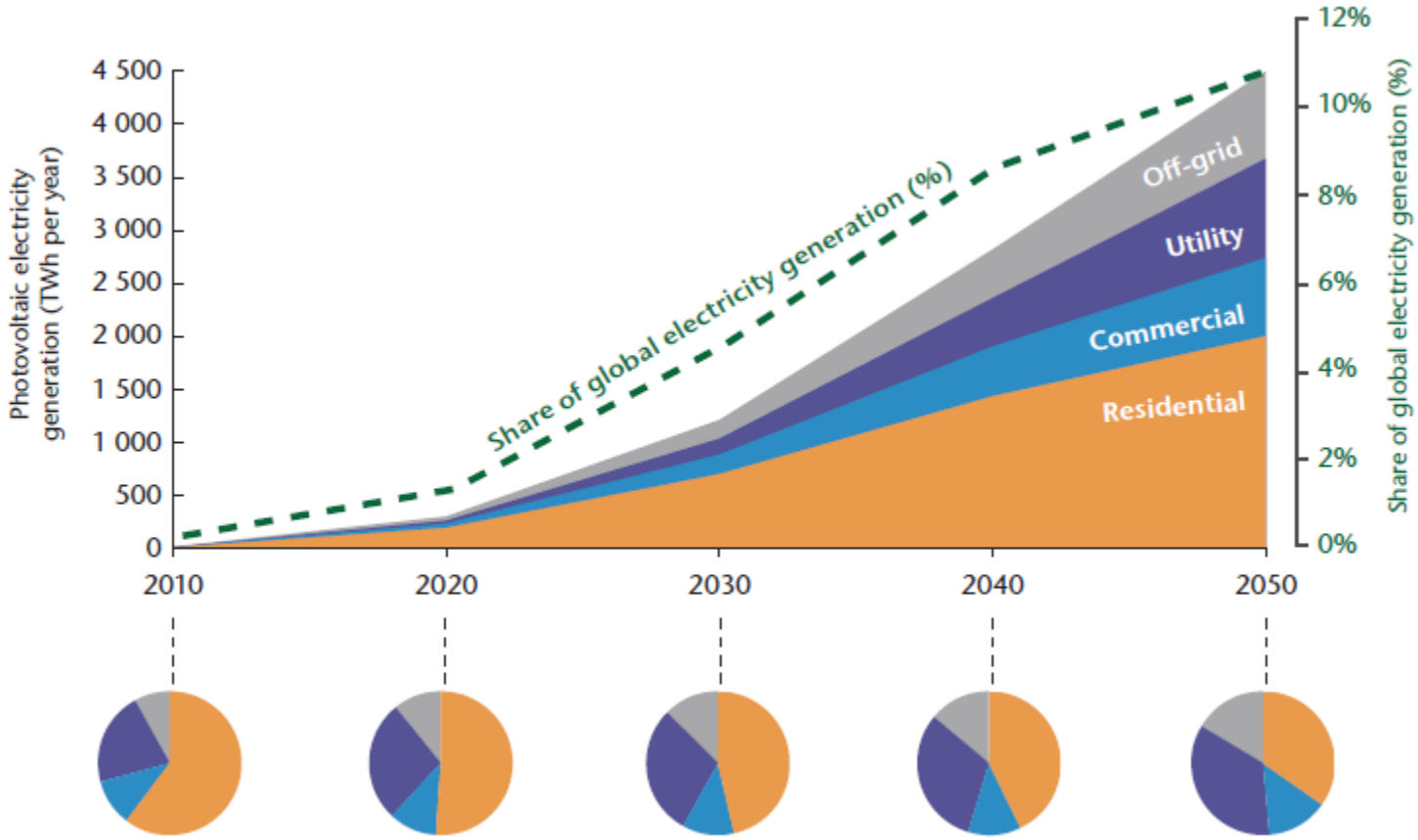
Source: DisplayBank

PV cells and Modules production:



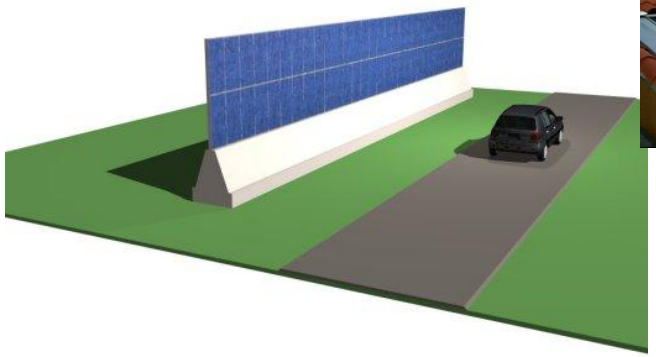
World PV Cell/Module Production from 1990 to 2009 (data source J.A.Waldau.- PV Status Report 2010.- Research, Research, Solar Cell Production and.- Market Implementation of Photovoltaics analysis .- : Data source: Navigant [Min 2010, a], PV News [Pvn 2010] and A.J._Waldau
http://re.jrc.ec.europa.eu/refsys/

PV market Share forecast (by application):



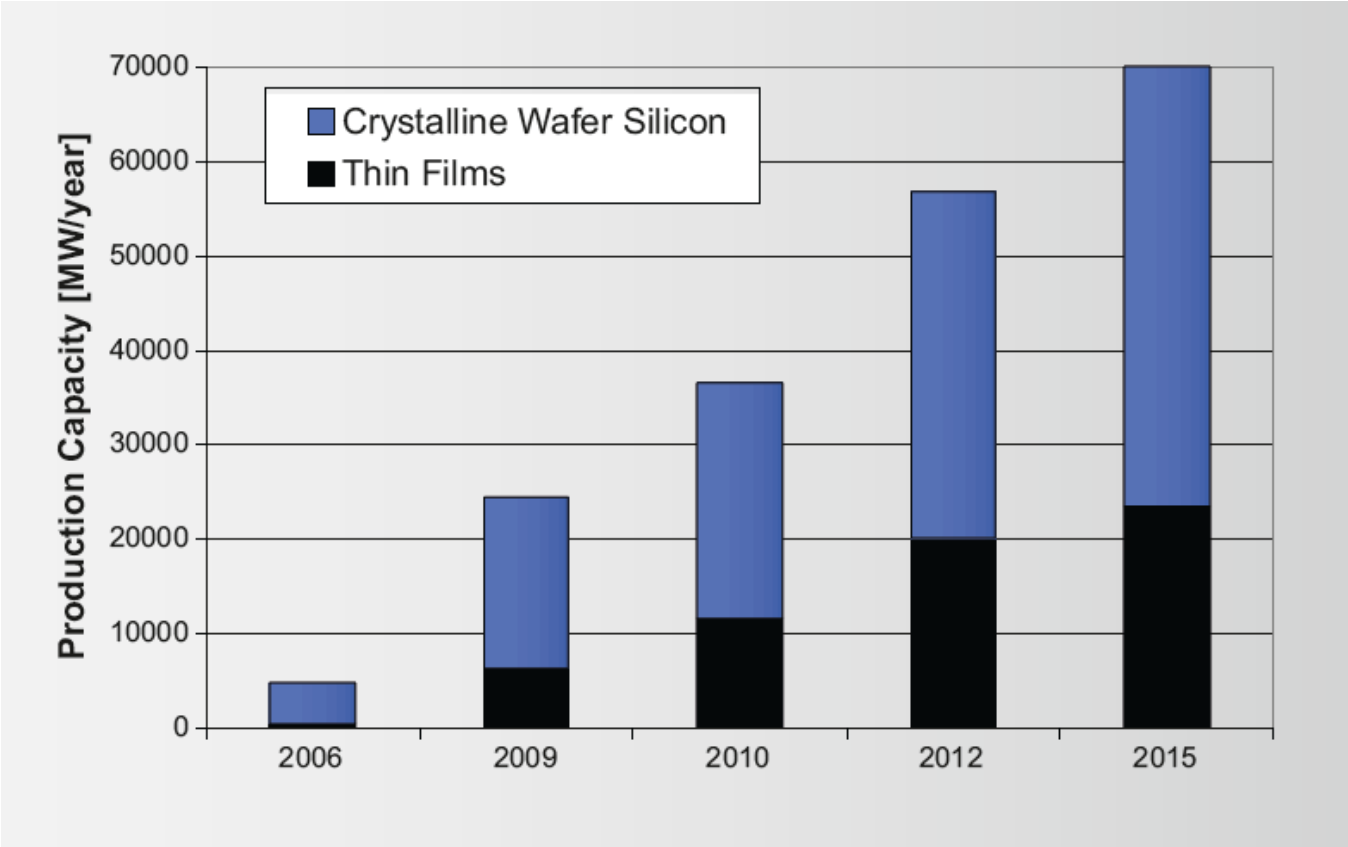
Source: IEA analysis based on survey reports of selected countries between 1992 and 2008, IEA PVPS, and IEA 2008 (ETP).

PV Installation:



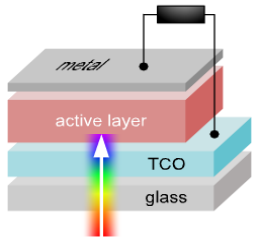
PV market forecast short term:

Annual PV Production capacities of Thin-Film and Crystalline Silicon based solar modules.

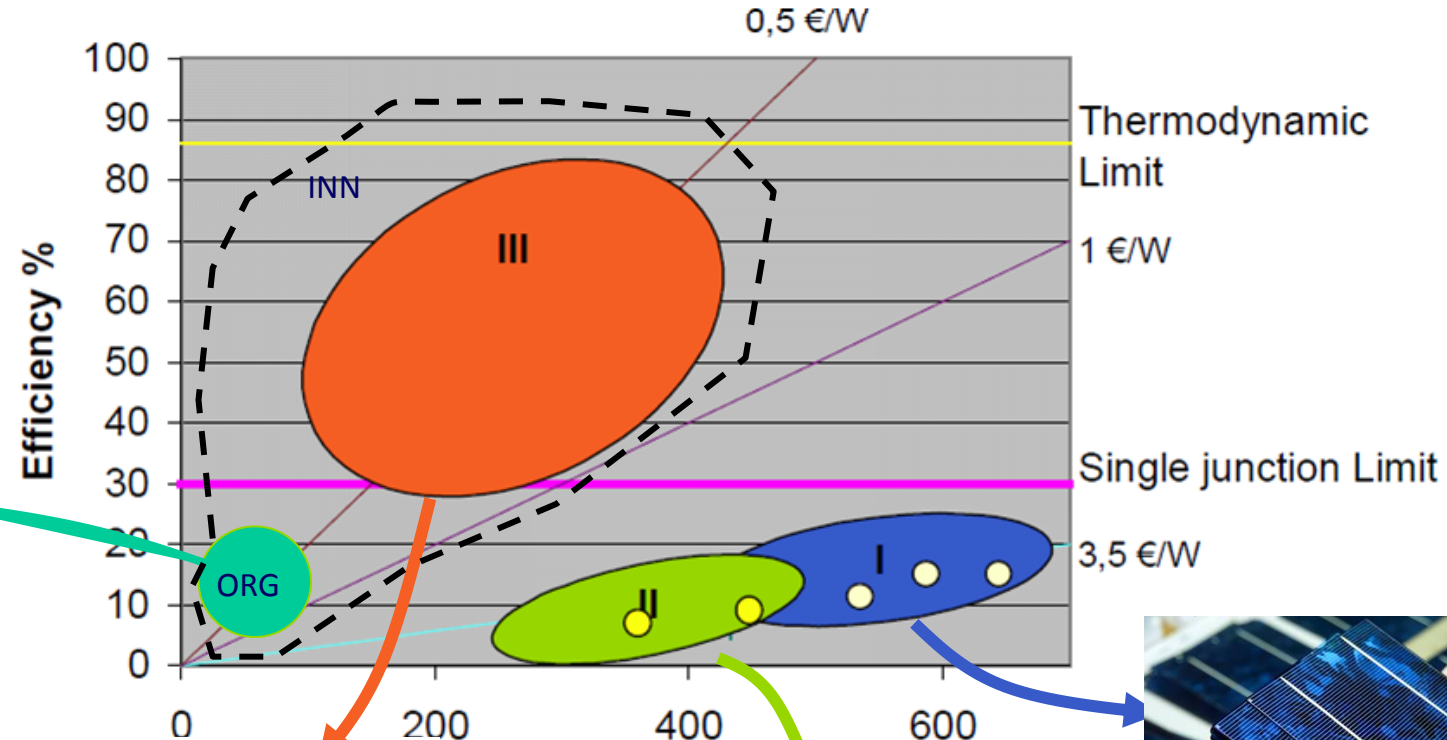


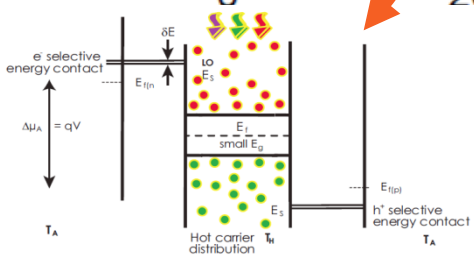
data source J.A.Waldau.- PV Status Report 2010.- Research, Research, Solar Cell Production and.- Market Implementation of Photovoltaics analysis .- : http://re.jrc.ec.europa.eu/refsys/

3rd PV Generation and Advanced concepts:

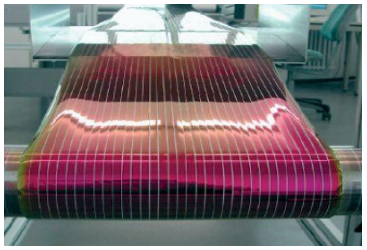


OSC & DSSC

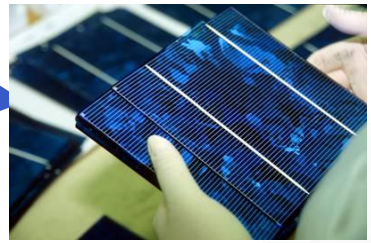




Advaced concepts for high efficiency

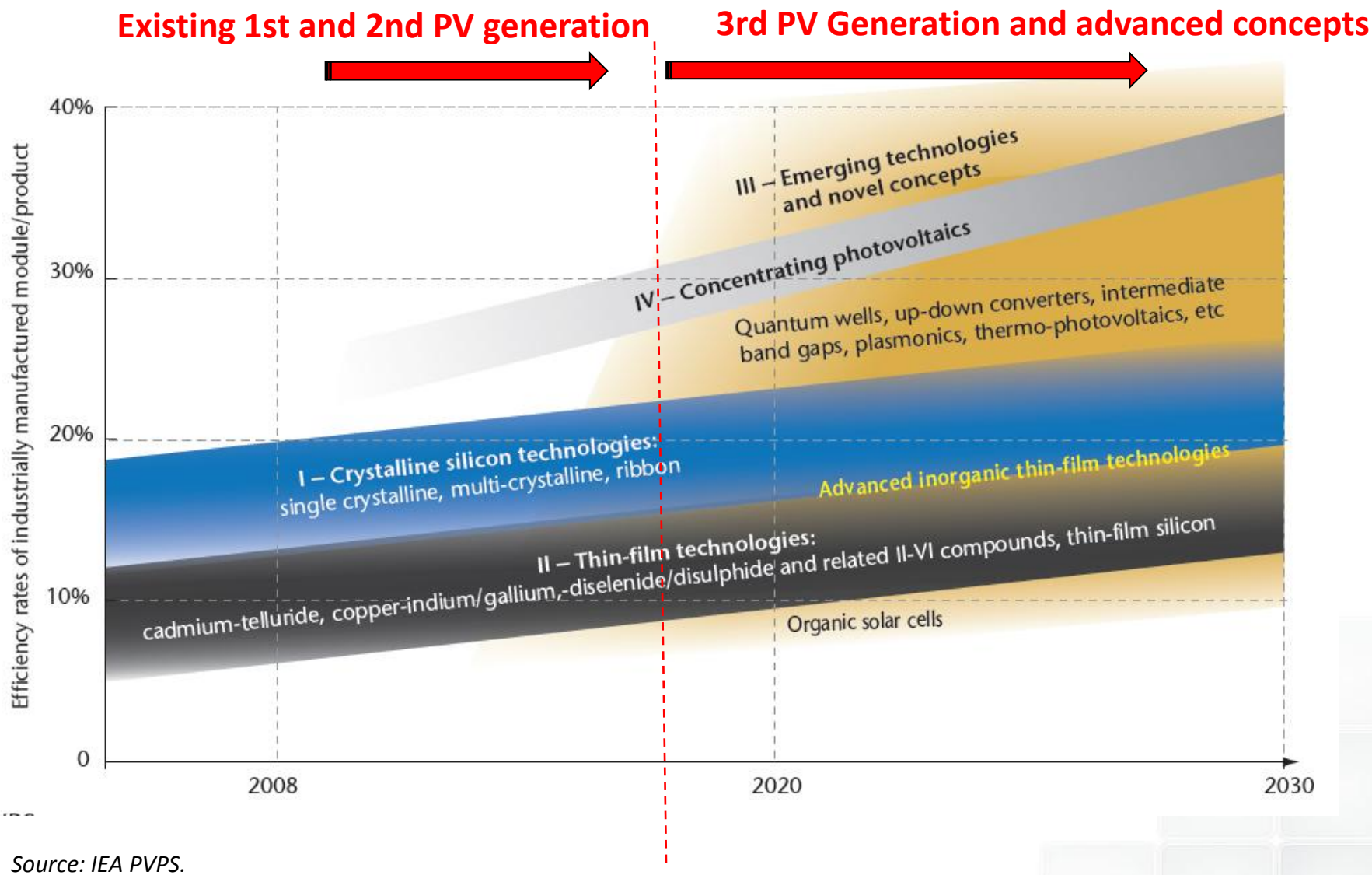


Thin Film



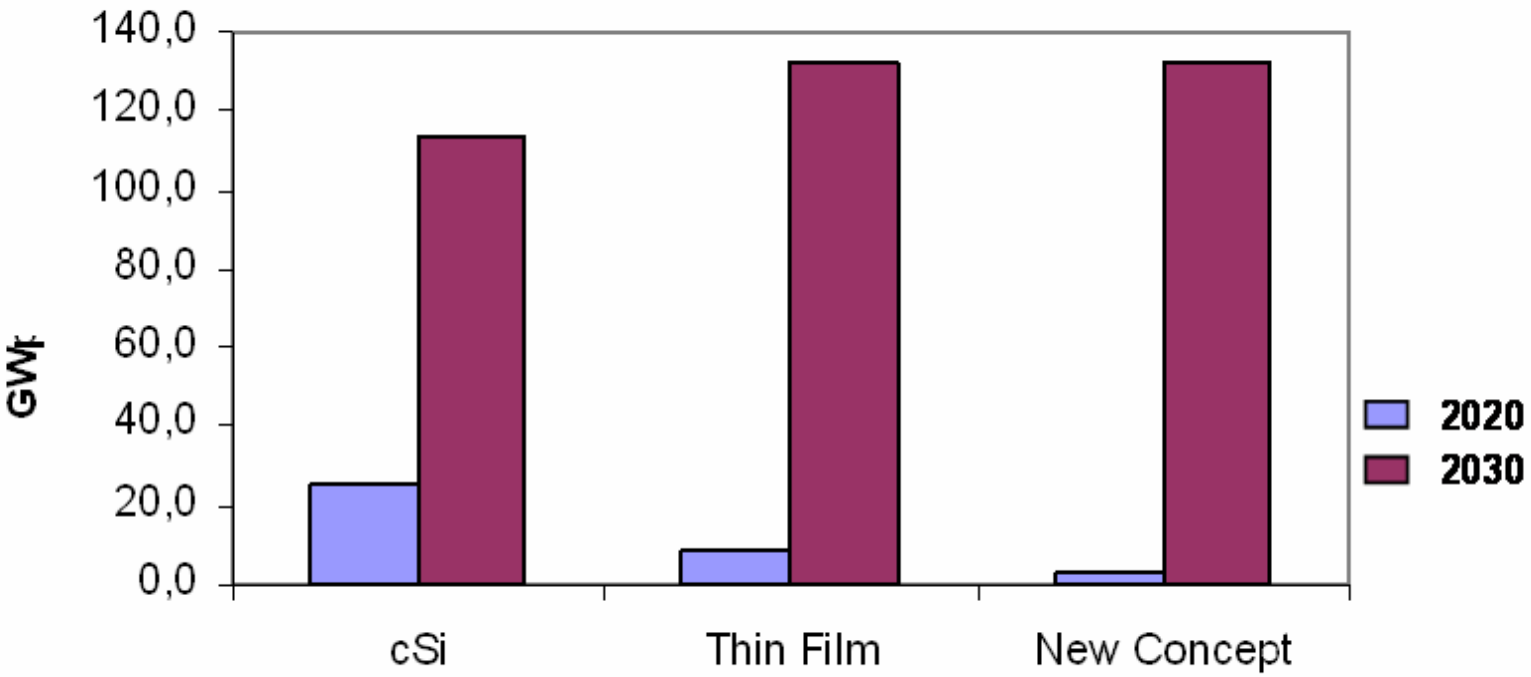
cSi

Photovoltaic technology prospects



Source: IEA PVPS.

PV market forecast mid- long-term:



PV market sumary:

- Short Mid- term

- Continuation to expand solar grade silicon production capacities in line with solar cell manufacturing capacities;
- Accelerated reduction of material consumption per silicon solar cell and Wp, e.g. higher efficiencies, thinner wafers, less wafering losses, etc.;
- Accelerated ramp-up of thin-film solar cell manufacturing;

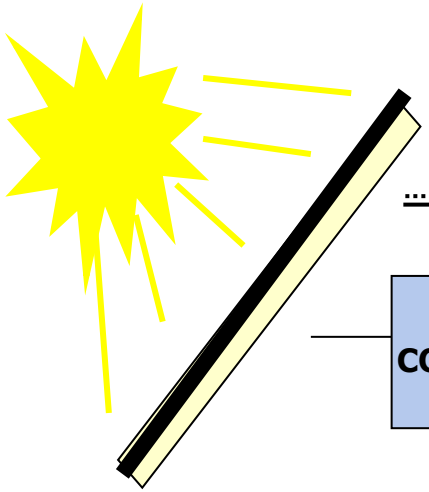
- Mid- long term

- Accelerated CPV and very high efficiency SC introduction into the market, as well as capacity growth rates above the normal trend
- Advanced concepts for low cost-high reliability

PV Solar Cells and modules
Technology & reliability

PV Systems

Off Grid PV system



PV Module

DC

POWER CONDITIONING UNIT

Storage

INVERTER

~ AC

Load

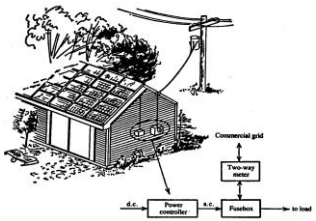
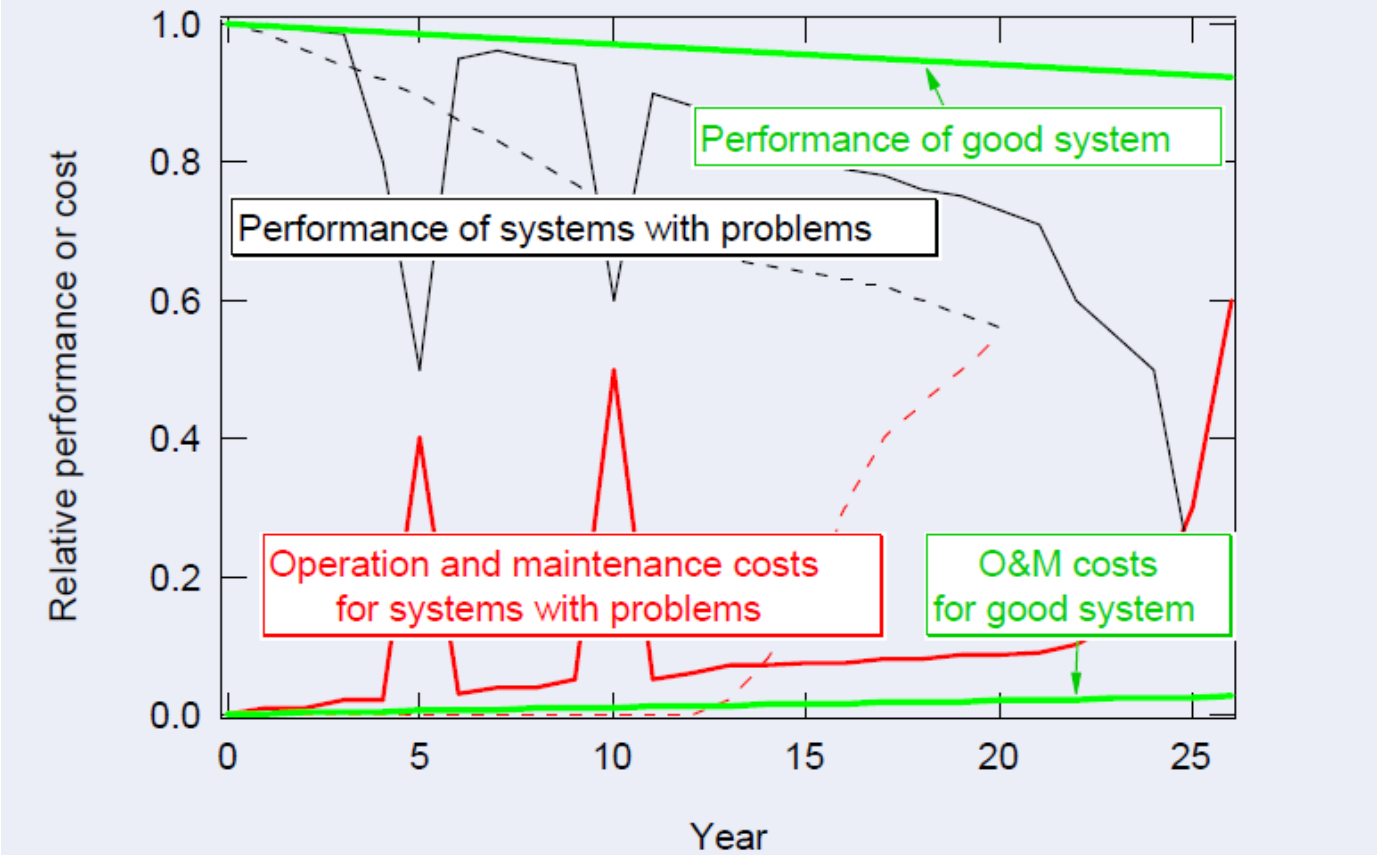


Fig. 3.11. *Model diagram of private house solar cell system.*

PV Modules

Importance of Reliability



Sarah Kurtz, NREL Workshop on Accelerated Stress Testing & Reliability
"Renewable Reliability" October 7-9, 2009 Jersey City, NJ, USA

Check Reliability

Prototype

Observe failure
↓
Identify mechanism
↓
Develop test
↓
Mitigate problem
↓
Identify next failure

Mature product

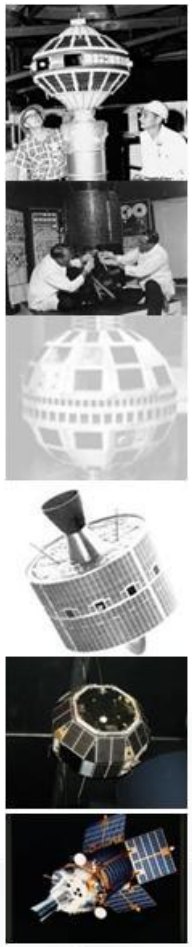
Failure analysis
↓
Identify mechanism
↓
Develop (ALT) test
↓
Measure acceleration
↓
Predict performance

PV Modules: Typical tests

- Corrosion of materials, especially metals
- Water-vapor intrusion
- Delamination of encapsulant materials, especially polymers
- Physical damage from wind, hail, and installation
- Thermal excursions, including coefficient of thermal expansion mismatches
- Ultraviolet (UV) radiation
- Deterioration of or damage to external components such as junction boxes

JPL-CALTECH Jet Propulsion Laboratory

Test	Block I	Block II	Block III	Block IV	Block V
Year	1975	1976	1977	1978	1981
Thermal Cycle (°C)	100 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	200 cycles -40 to +90
Humidity or humidity/freeze (RH is relative humidity)	70 C, 90%RH, 68 hr	5 cycles 40 C, 90%RH to 23 C	5 cycles 40 C, 90%RH to 23 C	5 cycles 54 C, 90%RH to 23 C	10 cycles 85 C, 85%RH to -40 C
Hot spots	-	-	-	-	3 cells, 100 hrs
Mechanical load	-	100 cycles ± 2400 Pa	100 cycles ± 2400 Pa	10000 cyc. ± 2400 P	10000 cyc. ± 2400 Pa
Hail	-	-	-	9 impacts 3/4" - 45 mph	10 impacts 1" - 52 mph
High pot	-	< 15 µA 1500 V	< 50 µA 1500 V	< 50 µA 1500 V	< 50 µA 2*Vs+1000



In the late 1970s, JPL conducted a series of Block Buys of PV modules . For each Buy, they required that the module design pass a set of tests. The modules were deployed and the resulting failures analyzed to revise the set of tests. A Block VI Buy was planned, but not implemented

Reliability of cSi PV Modules

*(Whipple 1993) *Pre-Block V : 45% module failure rate*
Post-Block V: <0.1% module failure rate

Joint Research Center of the European Commission, Ispra, Italy also developed qualification tests. Their early testing (CEC 201) included hail, UV, wind, temperature cycling, "smog," humidity cycling, and thermal degradation including shocks from cold-water spray. The CEC 201 test later evolved into CEC 501 and 502

IEC technical committee 82: Solar photovoltaic energy systems.

Commission Electrotechnique Internationale
International Electrotechnical Commission
МеждународнаяЭлектротехническаяКомиссия

http://www.iec.ch/

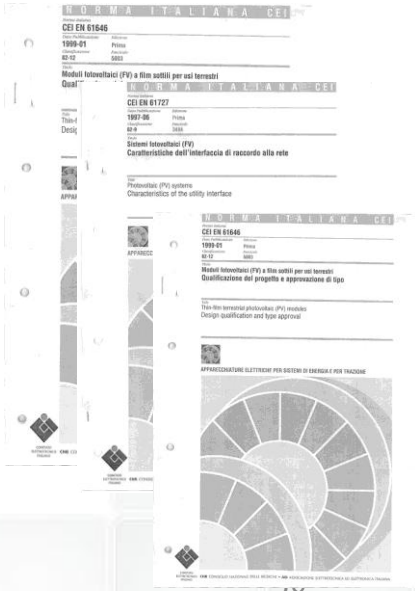
European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für elektrotechnische Normung

http://www.cenelec.eu/

National Committees

Comitato Elettrotecnico Italiano

http://www.ceiuni.it/



- * Photovoltaic-reliability R&D toward a solar-powered world, S.Kurtz, J. Granata and M.Quintana Proc. SPIE, Vol. 7412, 74120Z (2009); doi:10.1117/12.825649

JPL Block V – vs- IEC 61215

Test	Block I	Block II	Block III	Block IV	Block V	IEC 61215
Year	1975	1976	1977	1978	1981	2009
Thermal Cycle (°C)	100 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	50 cycles -40 to +90	200 cycles -40 to +90	200 cycles -40 to +85 w current flow
Humidity or humidity/freeze (RH is relative humidity)	70 C, 90%RH, 68 hr	5 cycles 40 C, 90%RH to 23 C	5 cycles 40 C, 90%RH to 23 C	5 cycles 54 C, 90%RH to 23 C	10 cycles 85 C, 85%RH to -40 C	10 cycles 85 C, 85%RH to -40 C; 1000 hr 85 C, 85%RH
Hot spots	-	-	-	-	3 cells, 100 hrs	5 hr, worst case
Mechanical load	-	100 cycles ± 2400 Pa	100 cycles ± 2400 Pa	10000 cyc. ± 2400 P	10000 cyc. ± 2400 Pa	3 cyc. 2400 Pa
Hail	-	-	-	9 impacts 3/4" - 45 mph	10 impacts 1" - 52 mph	11 impacts 25 mm - 23 m/s
High pot	-	< 15 μA 1500 V	< 50 μA 1500 V	< 50 μA 1500 V	< 50 μA 2*Vs+1000	1 min at 2*Vs+1000, then measure @ 500 V: R X A > 40 MΩ⊕m^2

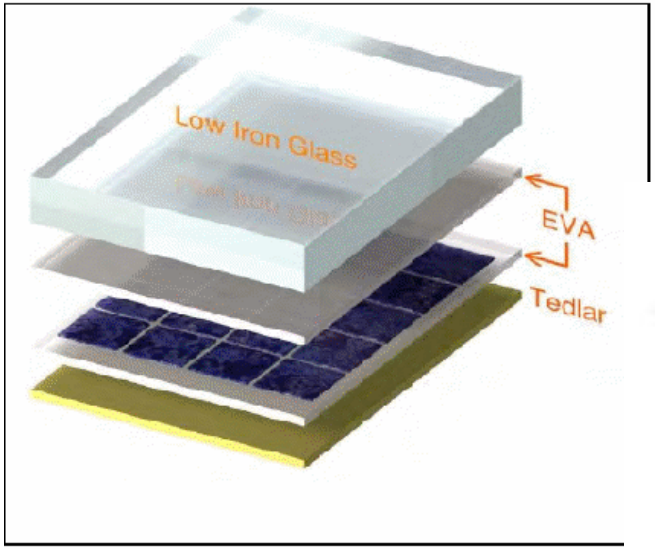
Crystalline Si PV modules

cSi PV Module (front)

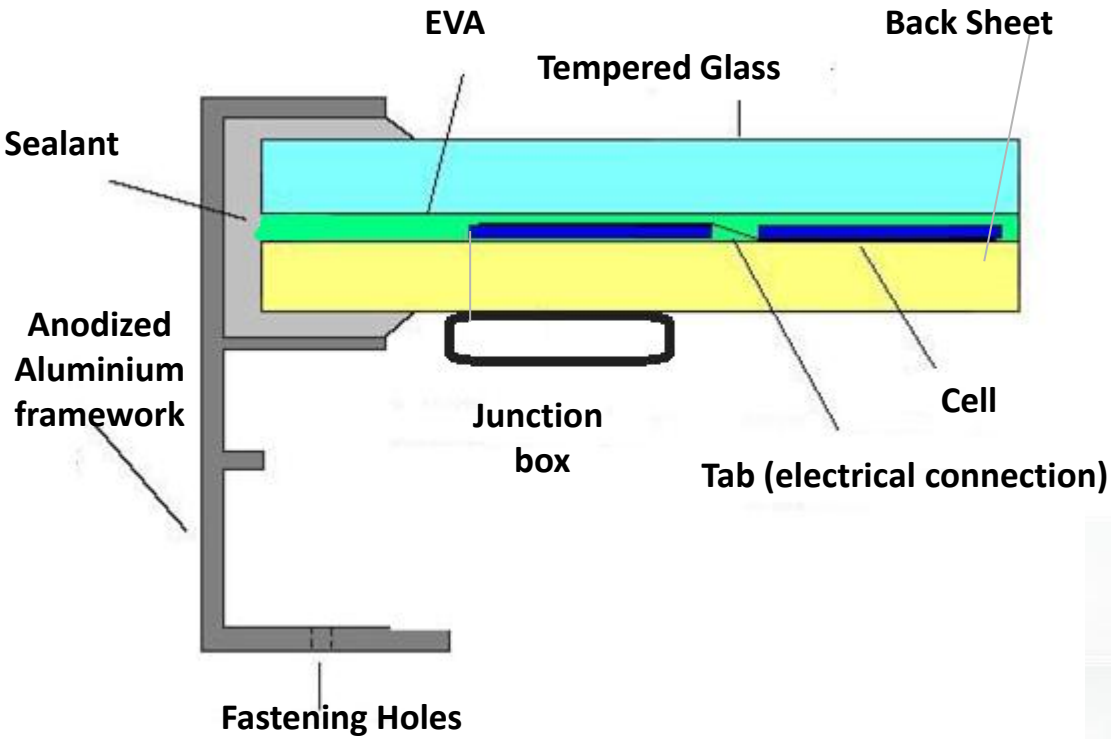
Multi Si PV Module (front)

Multi Si PV Module (back)

xSi module cross section



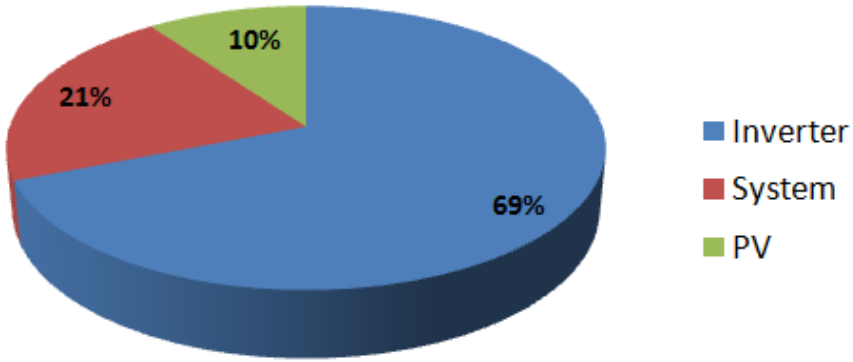
Common encapsulation materials
EVA Ethylene vinyl acetate - vinyl acetate
PET - polyethylene terephthalate
PVF - poly vinyl fluoride

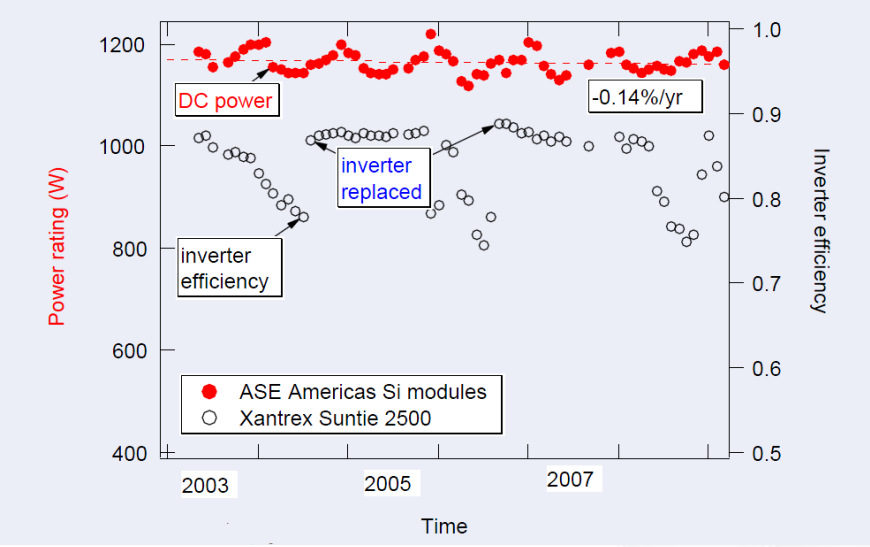


Very high reliability for cSi PV Modules (1st Generation PV)

Quality assurance (reduction of impurities in Si processing give light-induced degradation, quality of metallization, etc can assure fo cSi PV modules long-term, quantitative predictions

Typical degradation rates are 0-1%/yr (difficult to measure); field failure rates are often < 0.1%/



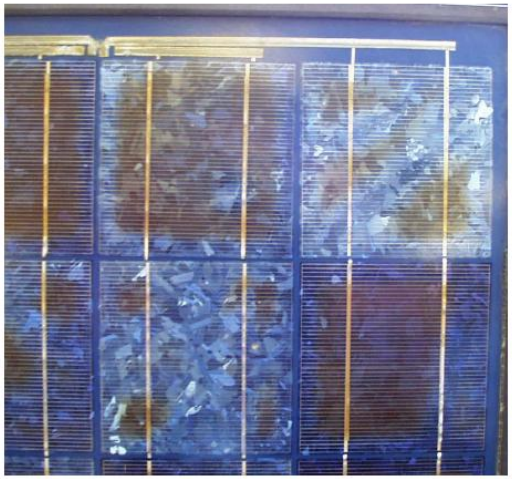


Currently, most reports imply that c-Si module failures dominated by improper installation, lightning strikes, critters, etc.

Typical damages

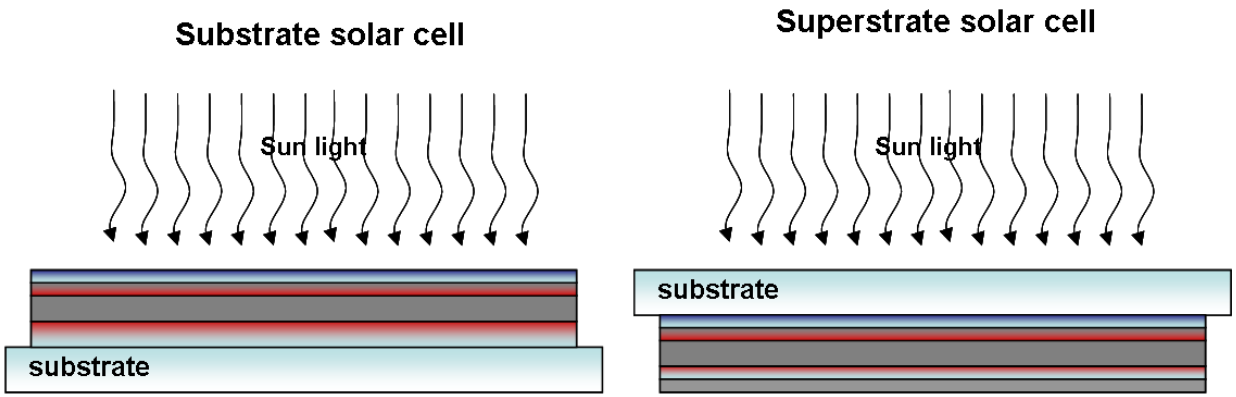
Ag gridline corrosion visible

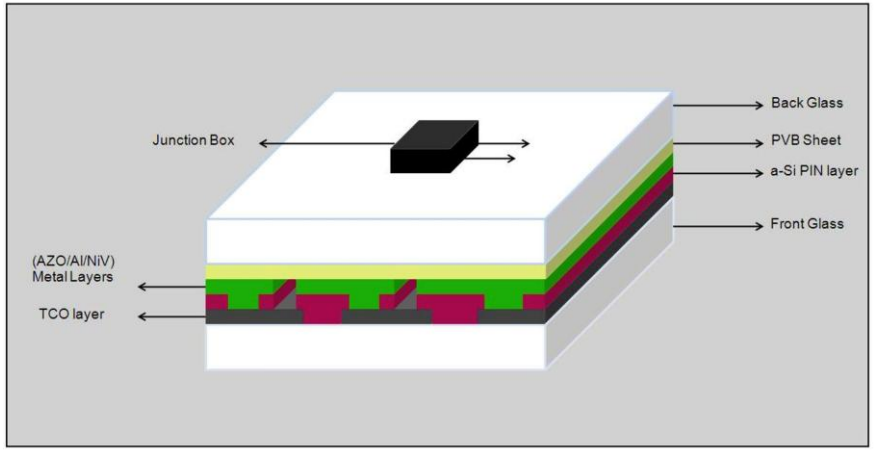
Connector damage

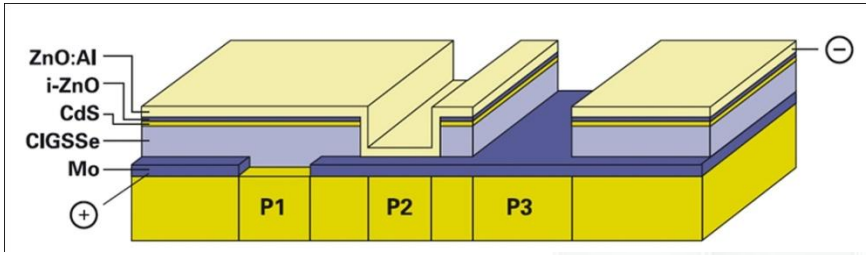


EVA Yellowing

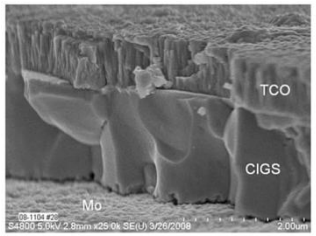
Thin Film Solar cells (2nd Generation PV)

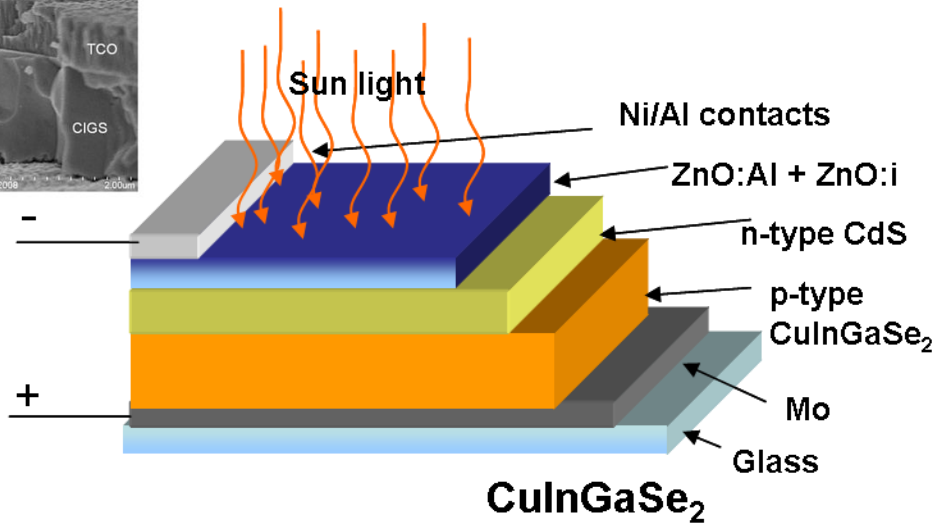


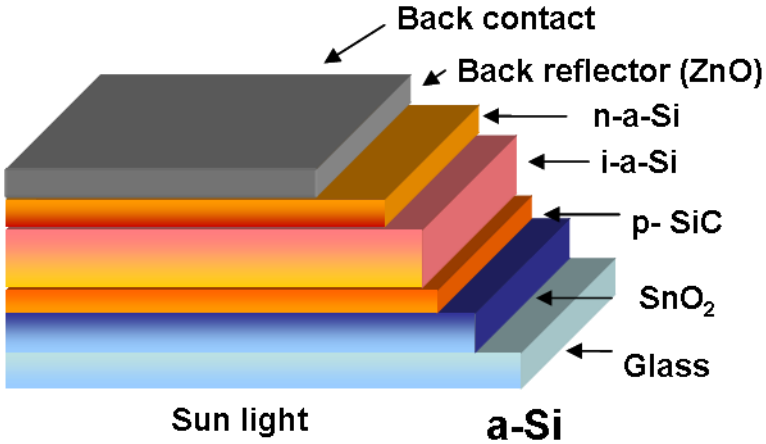


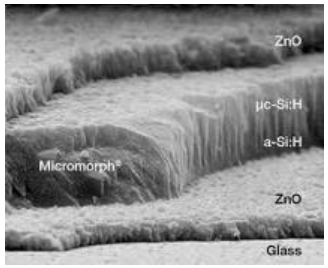


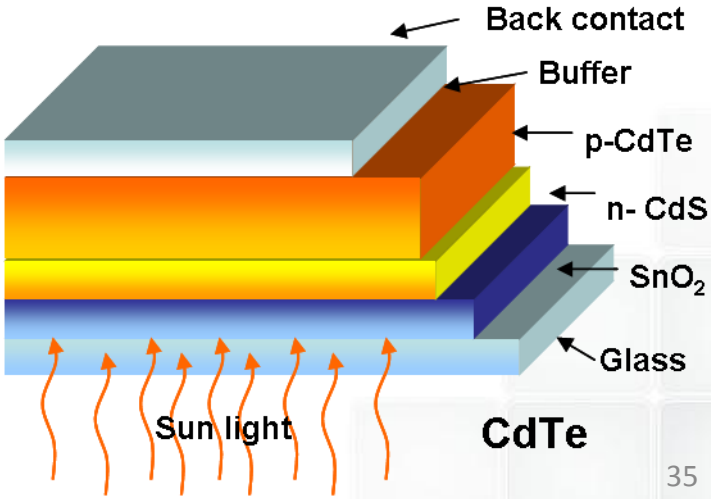
Thin Film Solar cells (ThinSi, CIGS, CdTe)



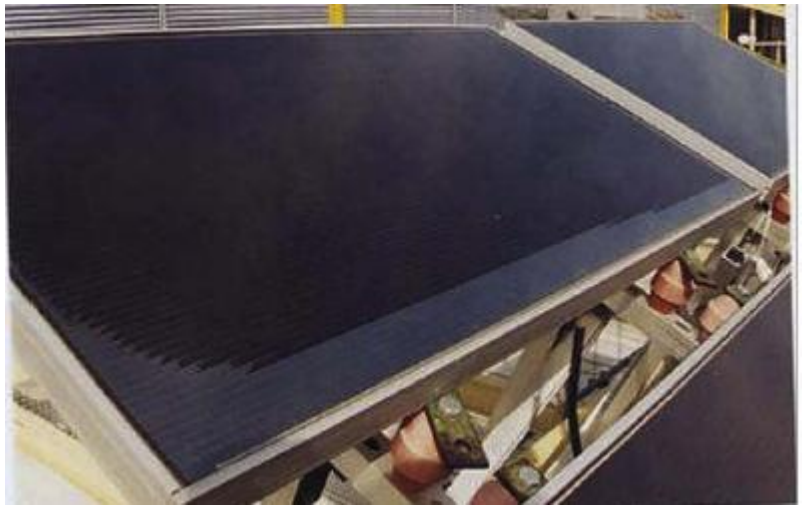


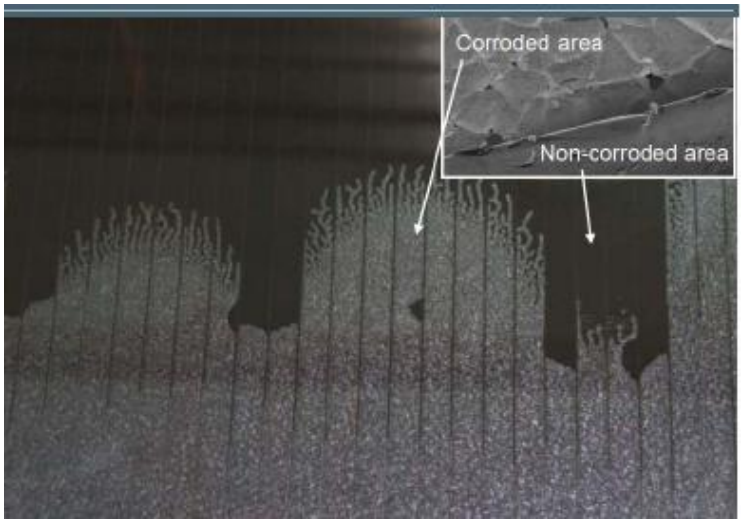






Effect of Damp Heat with System Bias





a-si

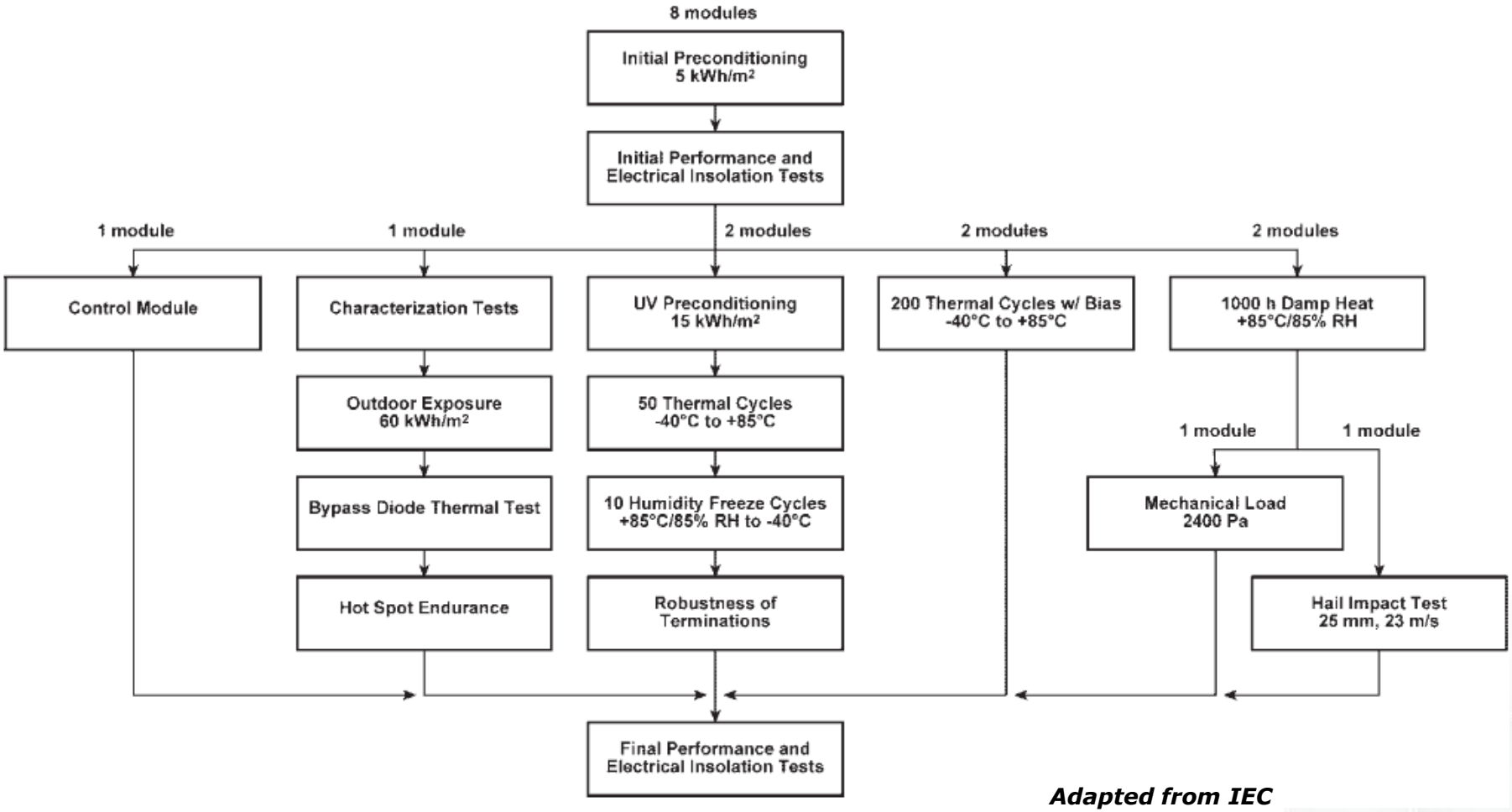
- 600 V
- 12 Months in the field
- Electrochemical corrosion from Sodium ion with water at the TCO/glass interface cause delamination of the TCO

Key drivers are

- Negative celle polarity vs ground
- Moinsture ingression
- Temperature
- Low Na content in glass

Testing sequences

Typical testing sequence for PV modules



Adapted from IEC 61215/IEC61646

1st and 2nd Generation PV Reliability

- IEC 61215: Crystalline silicon terrestrial photovoltaic (PV) modules –design qualification and type approval
- IEC 61646 : 'Thin-film terrestrial photovoltaic (PV) modules – design qualification and type approval',

A module design shall be judged to have passed the qualification tests, and therefore to be IEC type approved, if each sample meets the following criteria:

- The degradation of the maximum power output at standard test conditions (STC) does not exceed 5% after each test nor 8 % after each test sequence;
- The requirements of tests 10.3 (and 10.20) are met;
- No major visible damage (breakage or cracks in cells or glass, detachment of the embedding mass, etc.);
- No sample has exhibited any open circuit or ground fault during the tests;
- For IEC 61646 only: the measured maximum output power after final light-soaking shall not be less than 90% of the minimum value specified by the manufacturer

Metastability

Overview of IEC61215/IEC 61646

Overview of IEC 61215 / IEC 61646 tests

Code	Qualification Test	Test Conditions
10.1	Visual Inspection	according defined inspection list
10.2	Performance at STC	cell temperature = 25 °C irradiance = 1000 W/m² spectral irradiance distribution according to IEC 60904-3
10.3	Insulation Test	1000 VDC + twice the open circuit voltage of the system at STC for 1 min, leakage current < 50 μA, isolation resistance >50 M□ at 500 VDC
10.4	Measurement of Temperature Coefficients	Determination of the temperature coefficients of short circuit current and open circuit voltage in a 40°C interval
10.5	Measurement of NOCT	total solar irradiance = 800 W/m² spectral irradiance distribution according to IEC 60904-3 wind speed = 1 m/s
10.6	Performance at NOCT	cell temperature = NOCT irradiance = 800 W/m² spectral irradiance distribution according to IEC 60904-3

Overview of IEC61215/IEC 61646

10.7	Performance at low Irradiance	cell temperature = 25°C irradiance = 200 W/m² spectral irradiance distribution according to IEC 60904-3
10.8	Outdoor Exposure Test	60 kWh/m² solar irradiation
10.9	Hot-Spot Endurance Test	5 one hour exposures to 1000 W/m² irradiance in worst-case hot-spot condition
10.10	UV-Exposure according IEC 61345	7,5 kWh/m² UV-radiation (280 - 320 nm and ≥15 kWh/m² UV-radiation (280 - 400 nm) at 60°C module temperature
10.11	Thermal Cycling	50 and 200 cycles -40°C to +85°C
10.12	Humidity Freeze Test	10 cycles -40°C to +85°C, 85% RH
10.13	Damp Heat	1000 h at +85°C, 85% RH
10.14	Robustness of Terminations	As in IEC 60068-2-21
10.15	Twist Test	Deformation angle 1.2° over the module diagonal
10.16	Mechanical Load Test	Two cycles of 2400 Pa uniform load, applied for 1 h to front and back surfaces in turn

Overview of IEC61215/IEC 61646

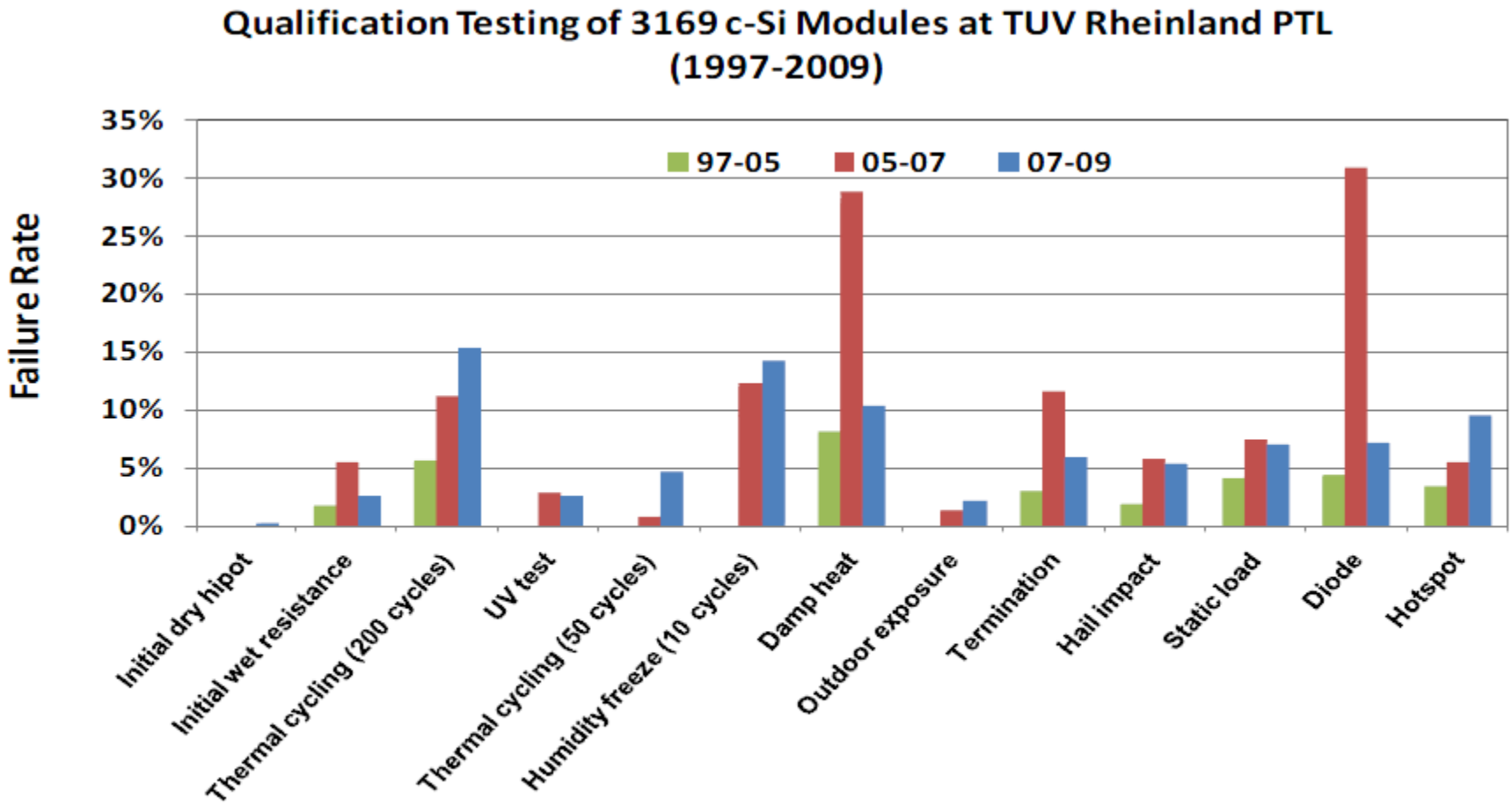
10.17	Hail Test	25 mm diameter ice ball at 23 m/s, directed at 11 impact locations
10.18*	Light soaking	Light exposure of 800 W/m^2 to 1000 W/m^2, until Pmax is stable within 2 %
10.19*	Annealing	Heat soak at 85 °C until Pmax is stable within 2 %
10.20*	Wet leakage current test	Water spray of terminals and edge immersion with 500 V d.c. applied to determine leakage current

* Tests only relevant for IEC 61646 qualification

Qualification Testing

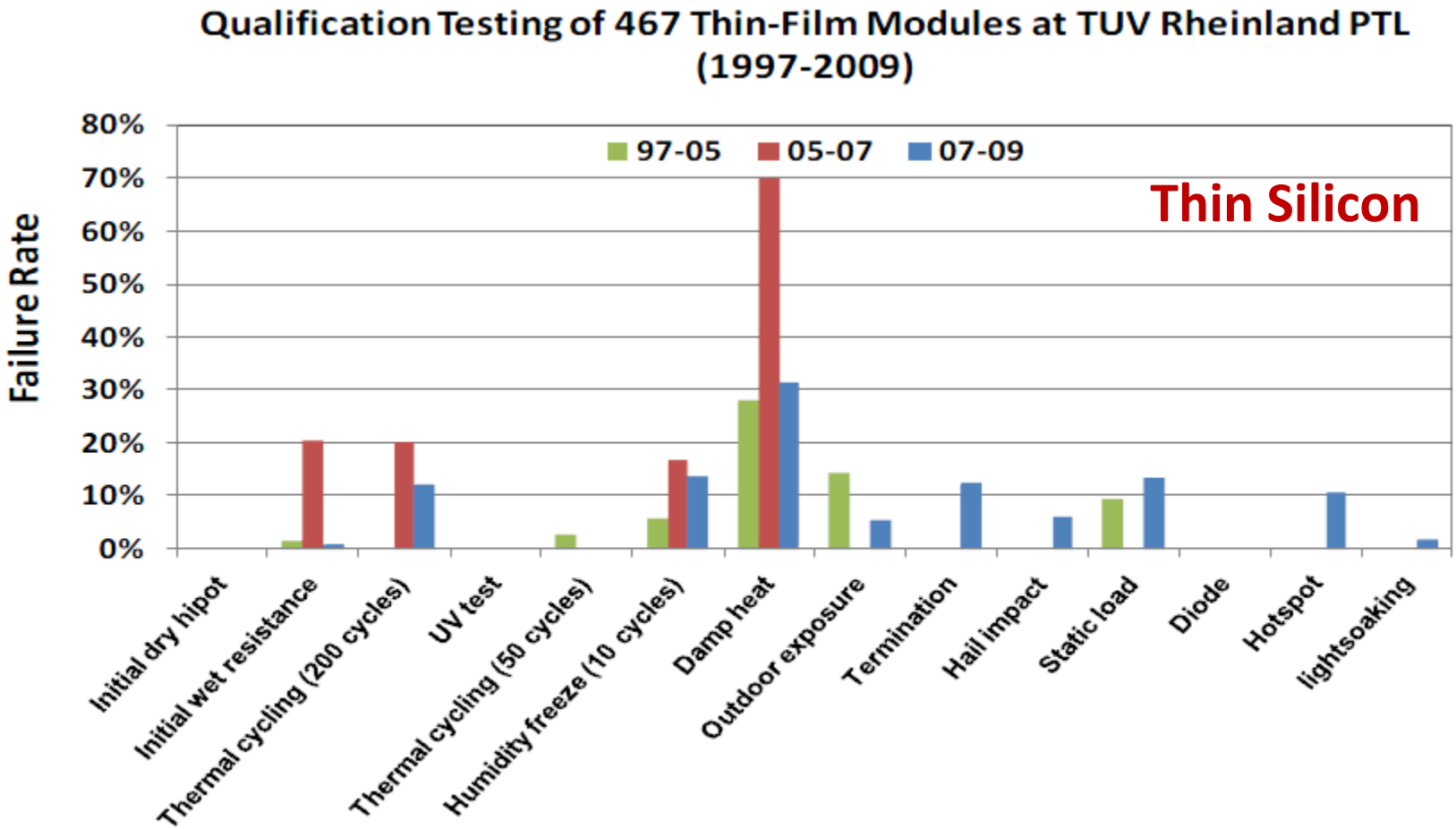
Past success does not guarantee future success

cSi



TamizhMani et.. Al. Experience with Qualification and Safety Testing ofPhotovoltaic NREL Reliability Workshop February 18, 2010

Qualification Testing



Qualification Testing of c-Si PV Modules at ASU-PTL

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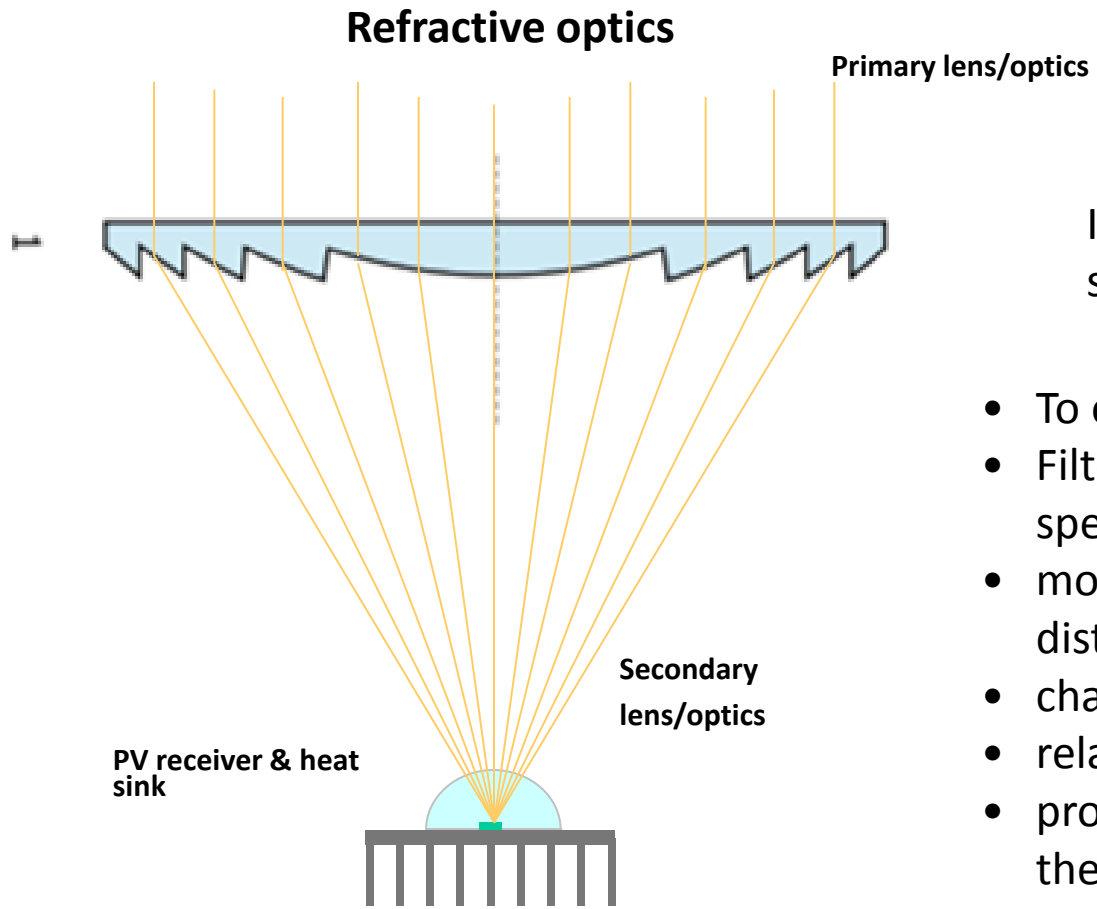
Outdoor testing

- Outdoor monitoring of climatic loads:
  - Radiation (UV, solar)
  - Humidity
  - Temperature (ambient and sample)
  - Wind and mechanical loads

- Outdoor testing of innovative PV-modules and new materials:
  - Impact of extreme, but natural loads
  - Identification of week points
  - Validation of accelerated indoor tests

Michael Köhl Fraunhofer ISE,D SPIE Conference 7048-4

PV Concentration (PV-C)

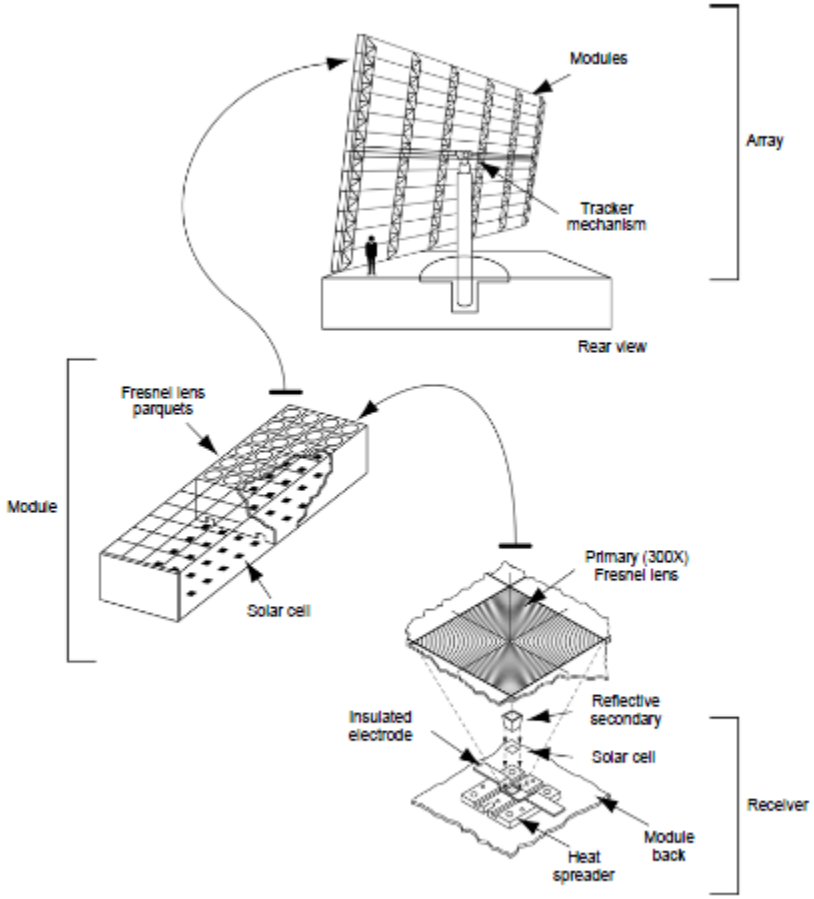


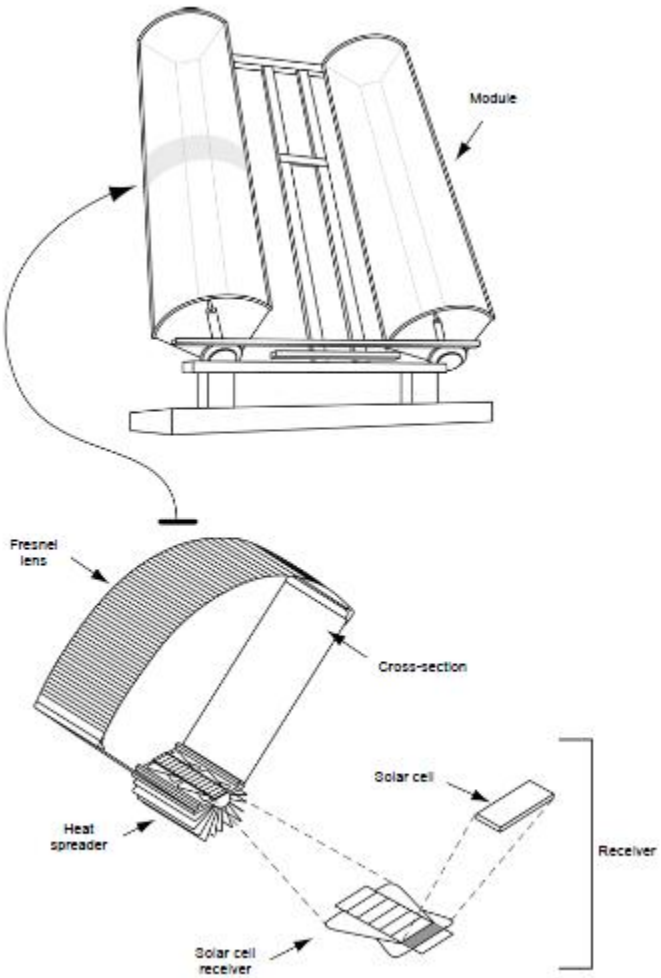
It could be profitable a secondary lens/optics (SOE):

- To enhance concentration ratio
- Filtering concentrator optics spectrum
- modifying light intensity distribution
- changing light direction
- relax tracker accuracy
- protection against the missing of the focal point

PV-C Concentrators : refractive optics

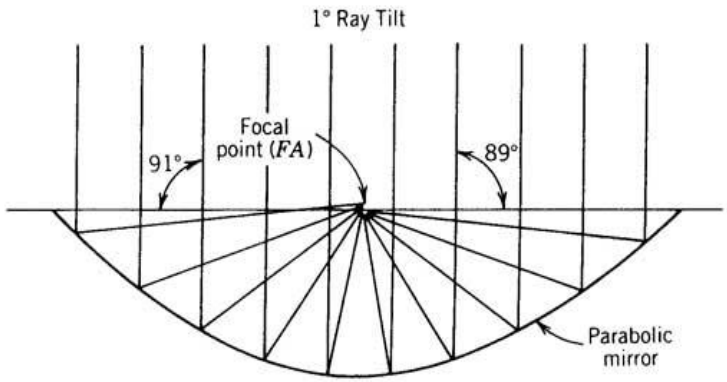
Schematic of linear-focus Fresnel lens PV concentrator

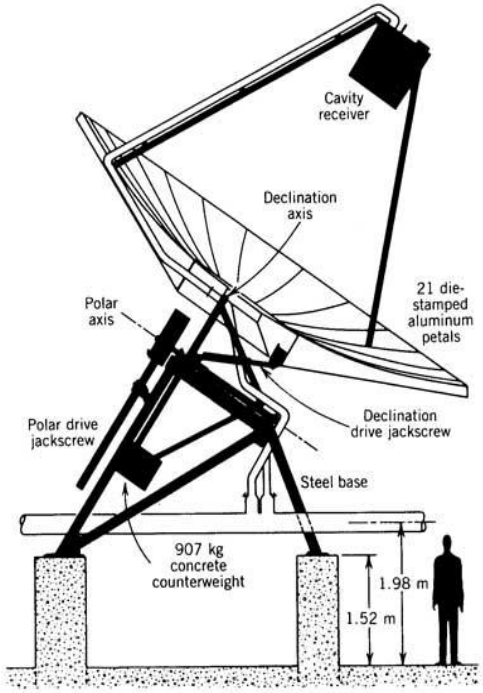




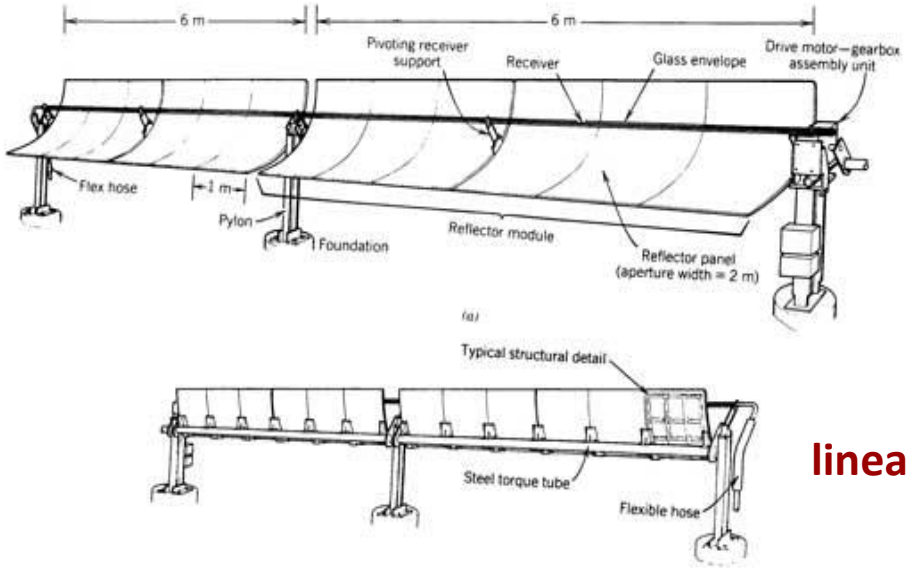
Schematic of point-focus Fresnel lens PV concentrator

PV-C Concentrators : reflective optics



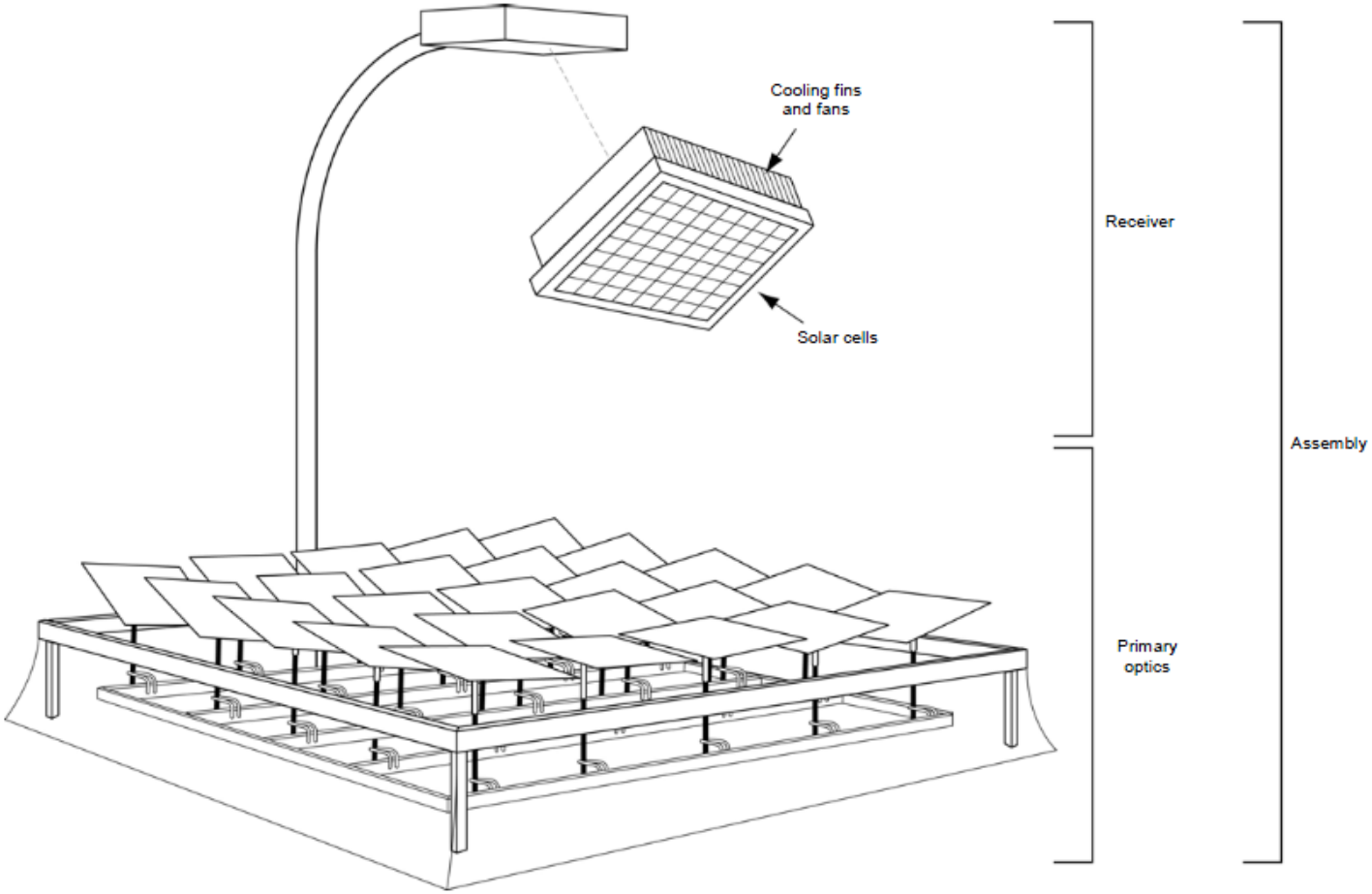


point-focus dish PV concentrator



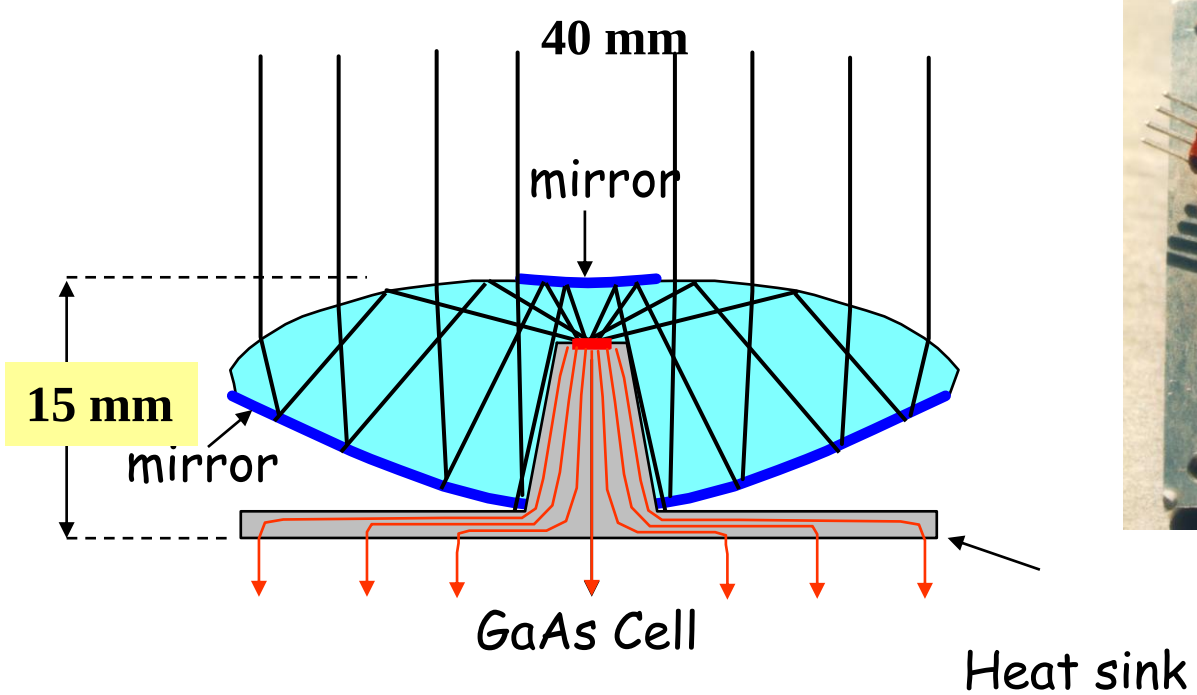
linear-focus trough PV concentrator

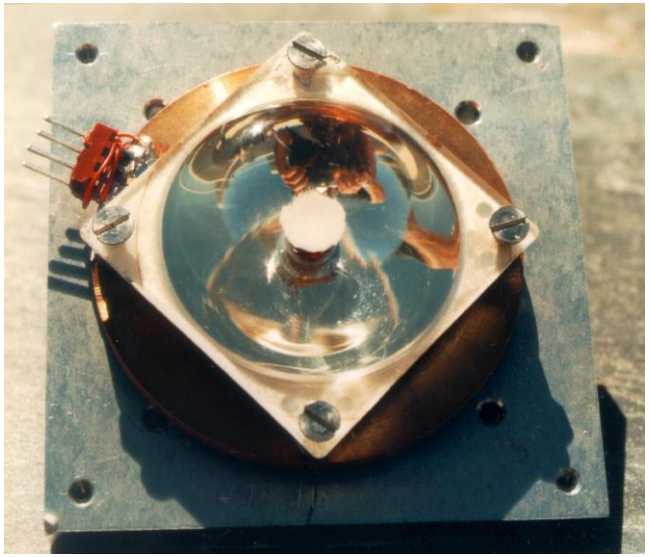
PV-C Concentrators Heliostat



Schematic of a heliostat CPV

RXI: Refractive & Reflexive & Internal Reflection





* Prototype of the HERCULES project (EU contract JOR3-CT97-0123)

Terms used for CPVs

<table>
<tr><td colspan="2">Primary optics</td><td rowspan="7">CPV Module – prefabricated and the focus point is not field adjustable, similar to most Fresnel lens systems.

CPV Assembly – needs some field installation and the focus point is field adjustable, similar to most reflective systems.</td></tr>
<tr><td>Secondary optics</td><td rowspan="4">CPV receiver</td></tr>
<tr><td>CPV cells</td></tr>
<tr><td>Electric energy transfer means</td></tr>
<tr><td>Thermal energy transfer means</td></tr>
<tr><td colspan="2">Interconnection</td></tr>
<tr><td colspan="2">Mounting</td></tr>
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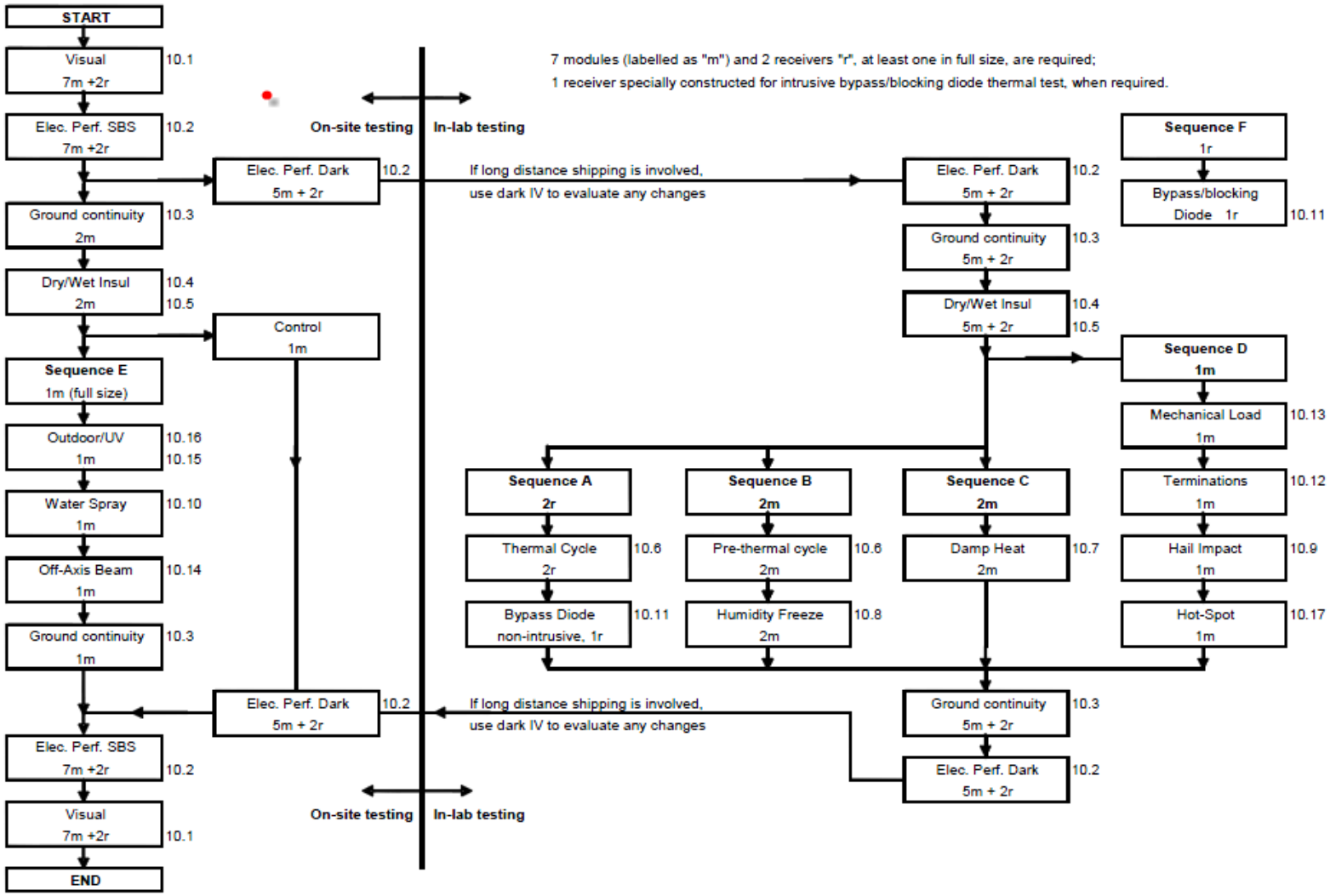
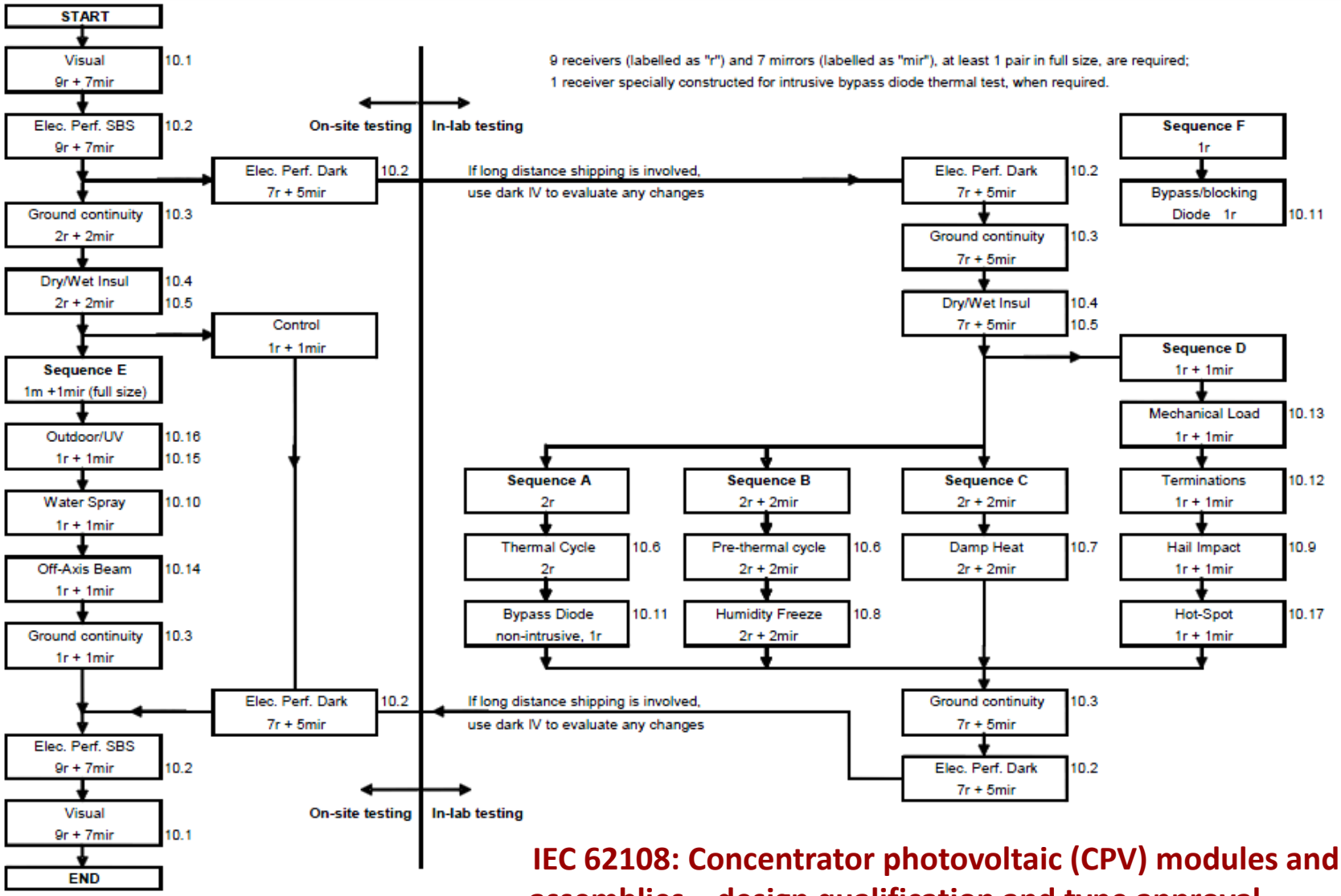
IEC 62108 : testing sequence for PV-C Module



IEC 62108: Concentrator photovoltaic (CPV) modules and assemblies – design qualification and type approval

IEC 62108 : testing sequence for PV-C Module



IEC 62108: Concentrator photovoltaic (CPV) modules and assemblies – design qualification and type approval

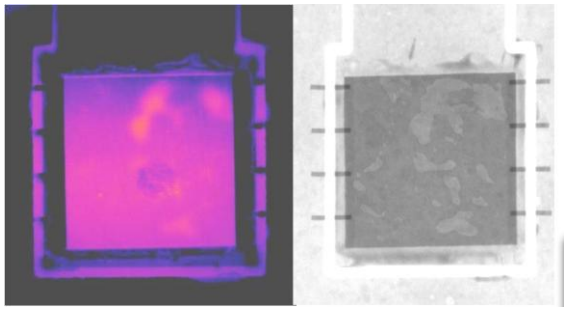
PV-C Failure analysis – vs – microelectronics FA

Analysis techniques from microelectronics for:

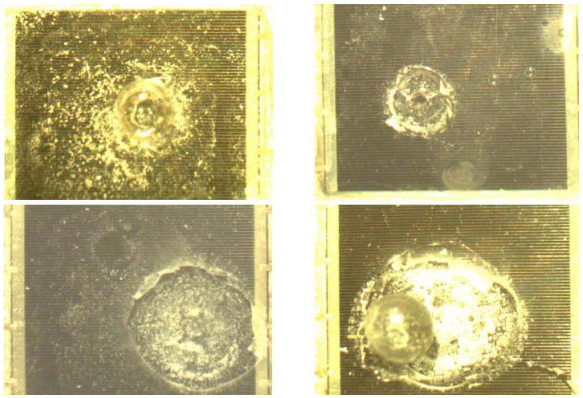
- **Electrical defects (EMMI, voltage contrast)**
- **X-ray and X-ray tomography**
- **LBIC - Light beam induced current**
- **OBIRCH - Optical Beam Induced Resistance Change)**
- **Electroluminesence imaging**
- **Photoluminesence imaging**
- **Thermal imaging**
- **Scanning Acoustic Microscopy**

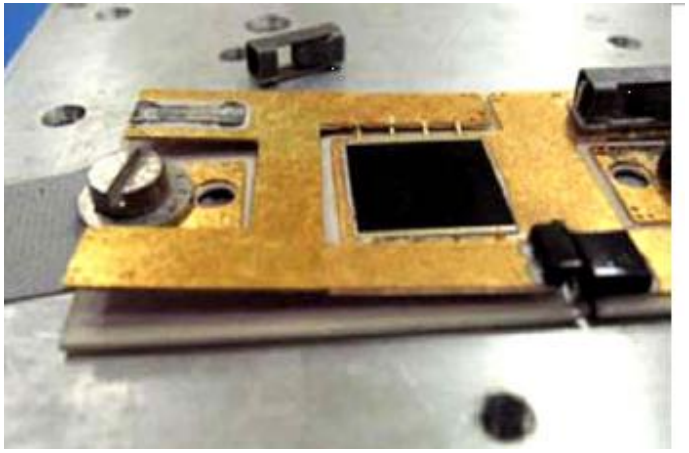
PV-C Receiver Failures

Die Attach Voids



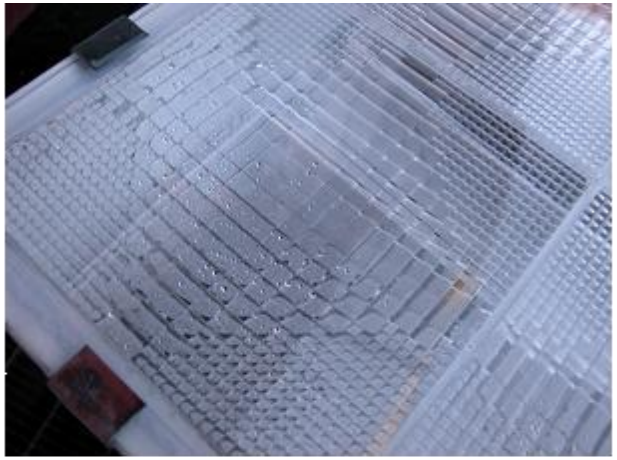
Ejected material

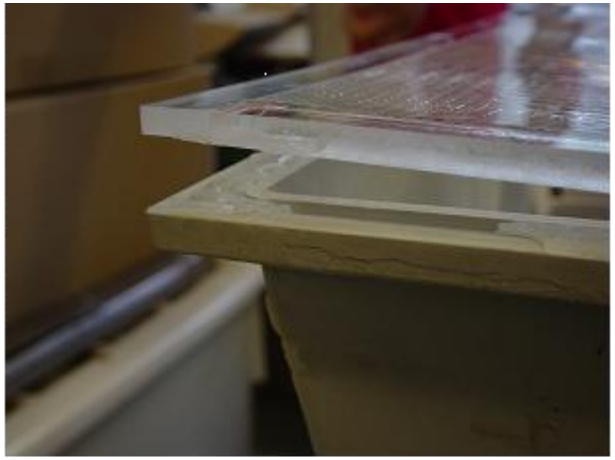


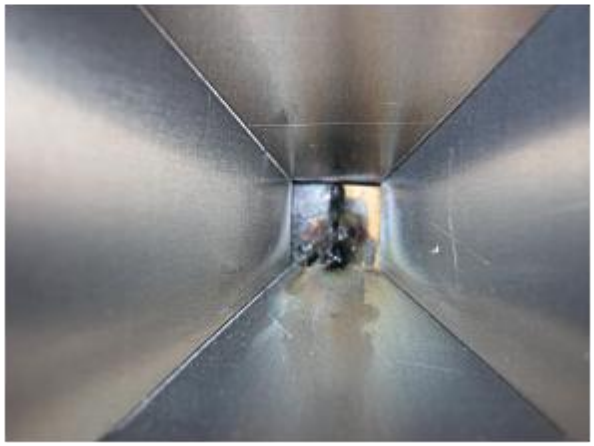


Thermal, mechanical stress

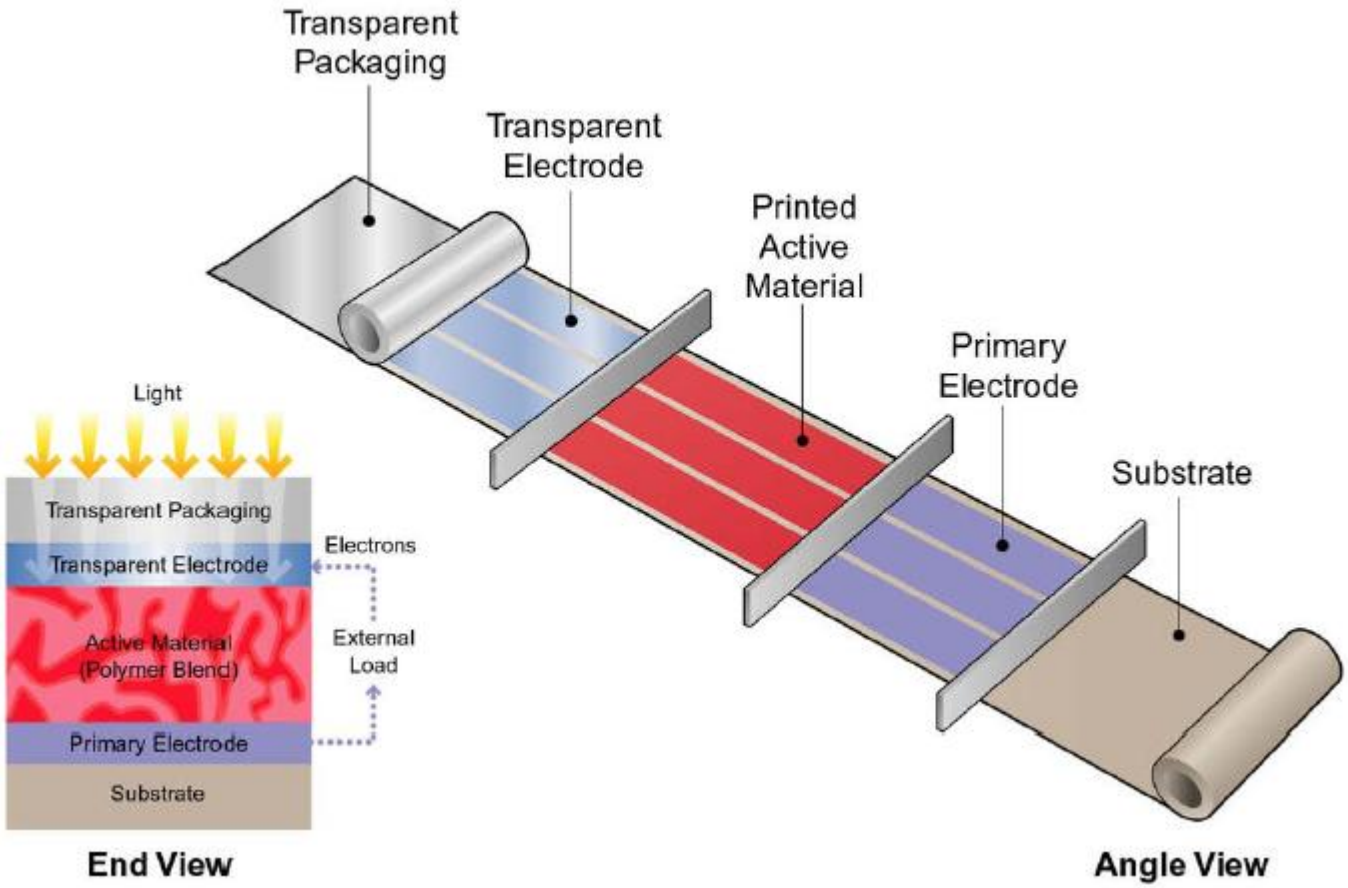
PV-C Housing Failures







Organic PV



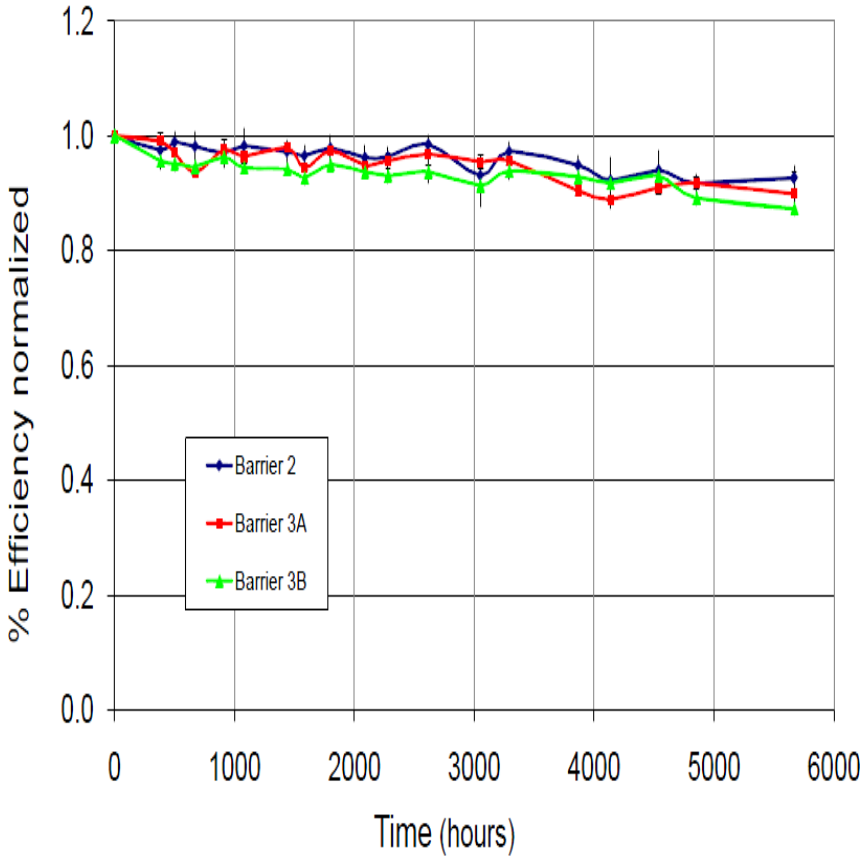
NREL Reliability Workshop February 18 & 19, 2010 Konarka Technologies Inc

Pathways for Degradation of OPV

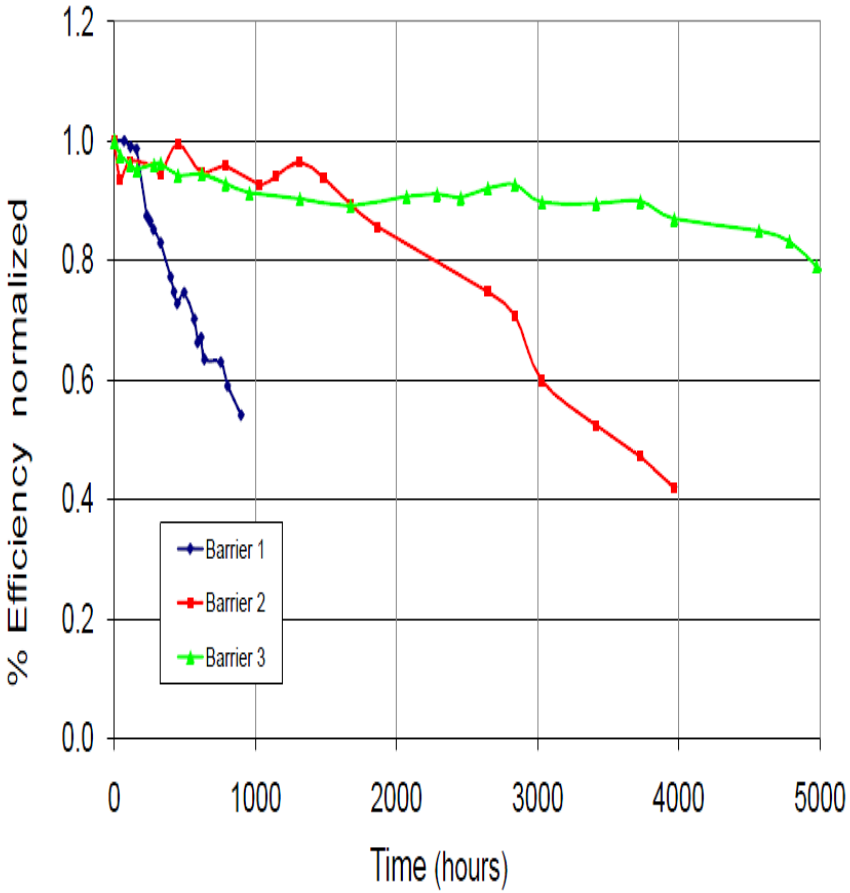
- Delamination
- Interdiffusionof Electrode Material
- Morphology Changes
- Interfacial Degradation
- Photo-oxidation of Organic Layers
- Oxidation of Electrodes
- Moisture induced degradation
- Moisture ingress failure of package

OPV Modules
Results with Various Flexible Barrier Films

65C° dry oven (open circuit, dark)

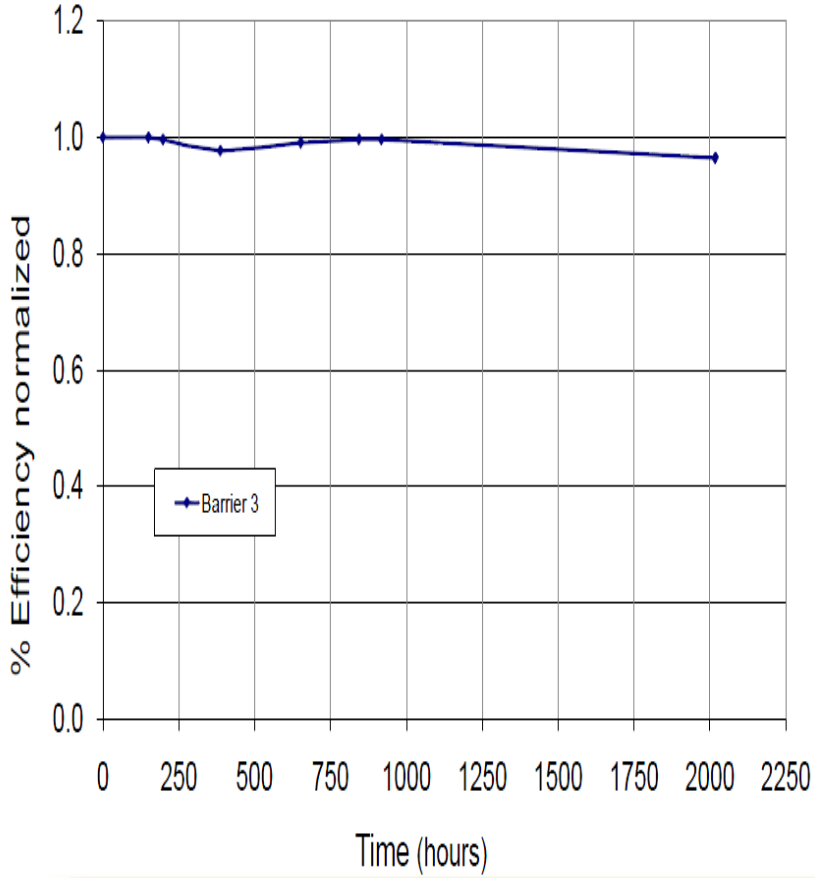


65C °/85 %RH (open circuit, dark)

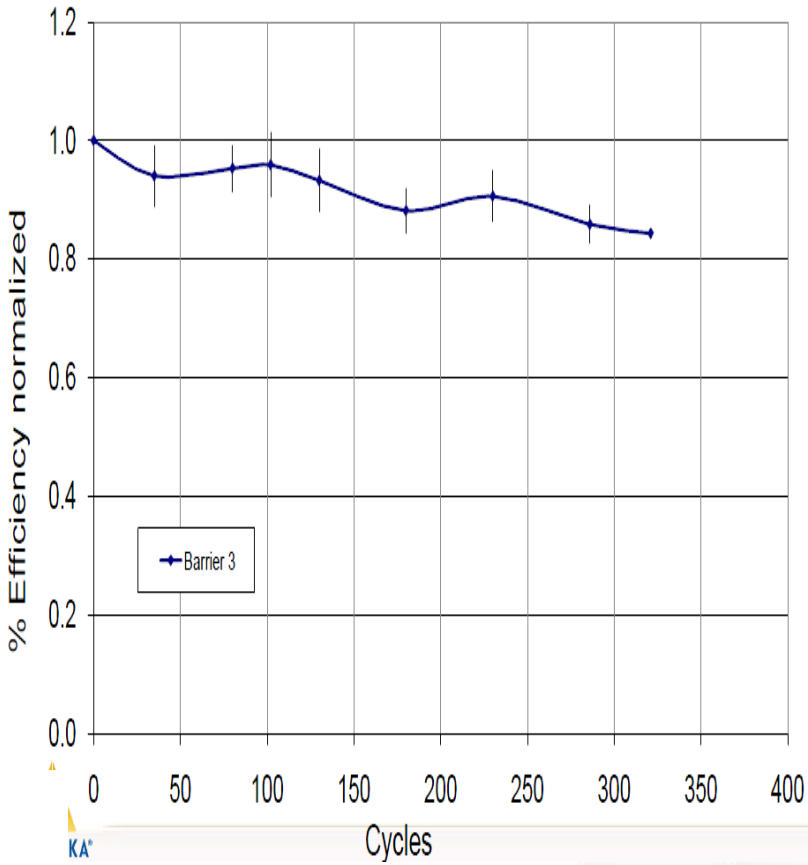


OPV Modules
Results with Various Flexible Barrier Films

Light Stability@ 1 sun, 65C



Thermal Cycling IEC 61646 10.11



Overview of failure mechanisms

Overview on cSi PV Module failure

cSi

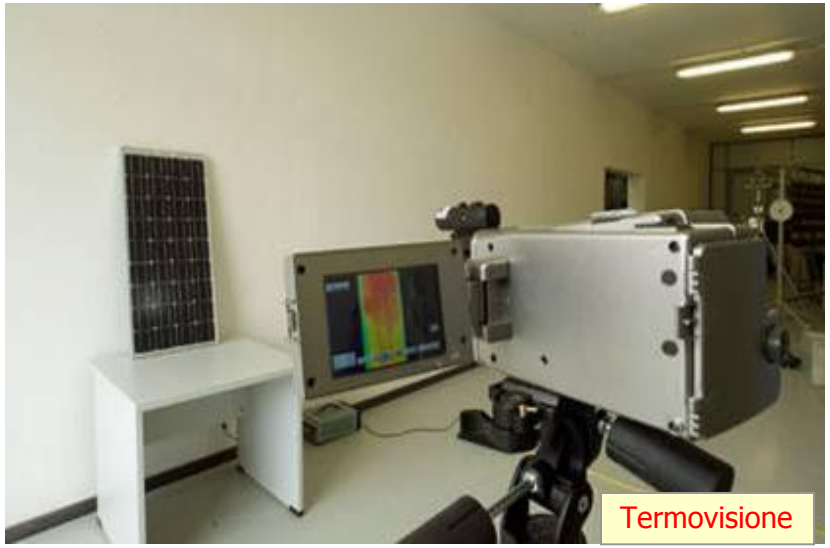
- Cracked cells (bonding processes, strain, etc.)
- Solder joint or gridline interface failure (increased series resistance)
- Reduced adhesion leading to corrosion and/ or delamination
- Slow degradation of ISC
- Fatigue of ribbon interconnect
- Junction box failure (poor solder joints, arcing, etc.)
- Busbar adhesion degradation, electrical contact, etc.
- Glass edge damage of frameless modules (though installation, handling, etc.)
- Light-induced cell degradation
- Effect of glass on encapsulant performance
- Front surface soiling
- Mechanical failure of glass-glass laminates

Reliability Concerns Associated with PV Technologies
By Nick Bosco , NREL

ENEA PV modules Qualification Laboratory

Camera di corrosione

Camere climatiche ed UV



Termovisione

Simulatore solare di classe A

Overview on Thin Film Module failure

Thin Film Silicon

- Electrochemical corrosion of SnO2:F
- Initial light degradation (a-Si)
- Annealing instabilities (a-Si)

CdTe

- layer integrity- back contact stability [25]
- Cell layer integrity- interlayer adhesion and delamination;
- electrochemical corrosion of SnO2:F Fill-factor loss (increased series resistance and/ or recombination)
- Busbar adhesion degradation, electrical contact, etc.
- Shunt hot spots at scribe lines before and after stress
- Weak diodes, hot spots, nonuniformities before and after stress

Reliability Concerns Associated with PV Technologies
By Nick Bosco , NREL

Overview on Thin Film PV Module failure

CIGS

- Cell layer integrity – contact stability
- Cell layer integrity – interlayer adhesion
- Fill-factor loss (increased series resistance and/or recombination)
- Busbar failure – mechanical (adhesion) and electrical
- Notable sensitivity of TCO to moisture
- Moisture ingress failure of package
- Cell–to-cell interconnect (discrete cells)
- Notable sensitivity of TCO to moisture; need to pass damp heat test (non-shingle specific)
- Shunt hot spots at scribe lines before and after stress [30]
- Weak diodes, hot spots, nonuniformities before and after stress
- Edge shunting

Reliability Concerns Associated with PV Technologies
By Nick Bosco , NREL

Overview on OPV Module failure

OPV

- Delamination of layers
- Photolytic Instability
- Moisture induced degradation
- Moisture ingress failure of package
- O2 induced degradation
- Thermal instability of donors and acceptor

Reliability Concerns Associated with PV Technologies
By Nick Bosco , NREL

Overview on C-PV Module failure

CP-V

- Depolymerization, bubble formation, and yellowing of silicone encapsular under high flux and high temperature with thermal cycling for long period time
- Soiling and delamination of anti reflective coatings on internal optical components
- Cell damage from thermal runaway (may be caused by solder voids?)
- Loss of efficiency of optics
- Poor solder joints between string ribbons and wires inside junction boxes - arcing
- Potential issues with highly non-uniform illumination
- Defect migration, …(especially for lattice mismatched)
- Corrosion and diffusion of silver gridlines/contacts

Reliability Concerns Associated with PV Technologies
By Nick Bosco , NREL

Overview on C-PV Module failure

CP-V

- Electromigration due to high current under high concentration (tunnel junction)
- Inverter reliability (ability to withstand rapid changes in current)
- Module thermal fatigue (including high frequency and amplitude), materials, interconnects, cell attachment, adhesive failure
- Operational integrity of the mechanical parts of the trackers (for high concentration systems)
- High Al content AlInP can be sensitive to oxidation

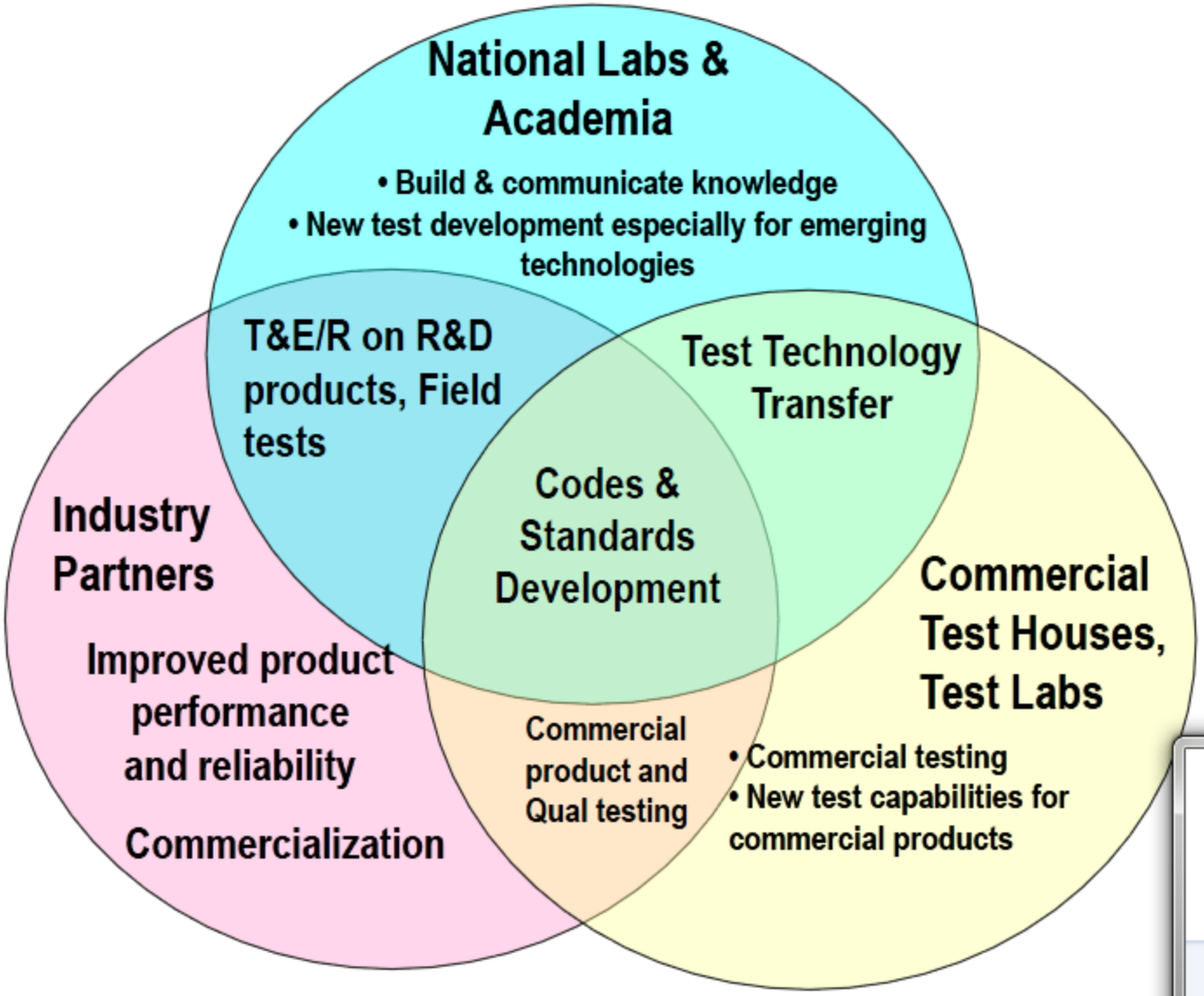
Reliability Concerns Associated with PV Technologies
By Nick Bosco , NREL

General Issues Across all Technologies

all Technologies

- Corrosion leading to loss of grounding
- Quick connector reliability
- Improper insulation leading to loss of grounding
- Delamination
- Glass fracture
- Bypass diode failure
- Inverter reliability
- Moisture ingress

Reliability Concerns Associated with PV Technologies
By Nick Bosco , NREL


National Labs & Academia
• Build & communicate knowledge
• New test development especially for emerging technologies
T&E/R on R&D products, Field tests
Test Technology Transfer
Industry Partners
Improved product performance and reliability
Commercialization
Codes & Standards Development
Commercial product and Qual testing
Commercial Test Houses, Test Labs
• Commercial testing
• New test capabilities for commercial products

Conclusion

- 1st PV generation PV Module (wafer based modules) are very stable components
- 2nd generation PV module are improving long term reliabilityd
- Emerging tecnologies need a new approches on reliability

ESREF 2010

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Thanks for your attention