FOSS
Research Centre for
Sustainable Energy

Universidad de Jaén

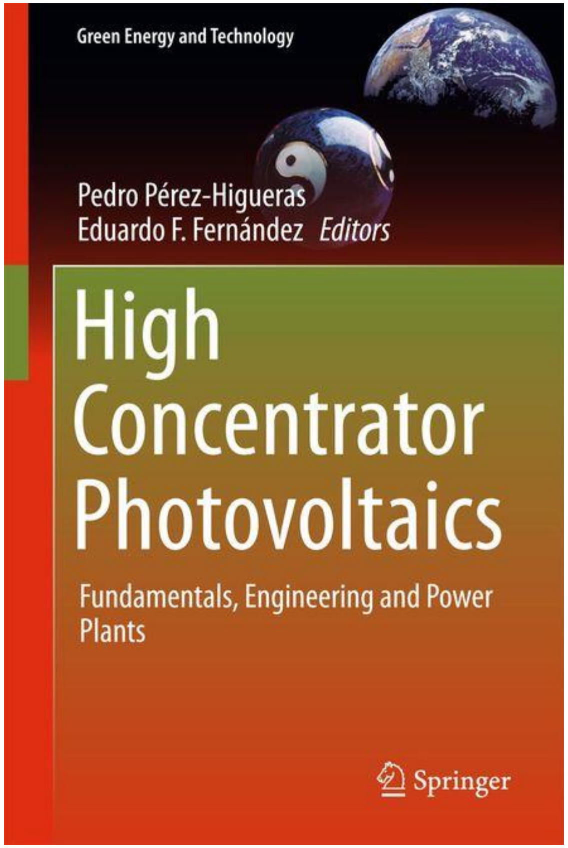
University of Cyprus
PV Technology

28/05/2018

Concentrating photovoltaics: fundamentals, modelling and levelised cost of electricity

Eduardo F. Fernández and Marios Theristis

Reference books



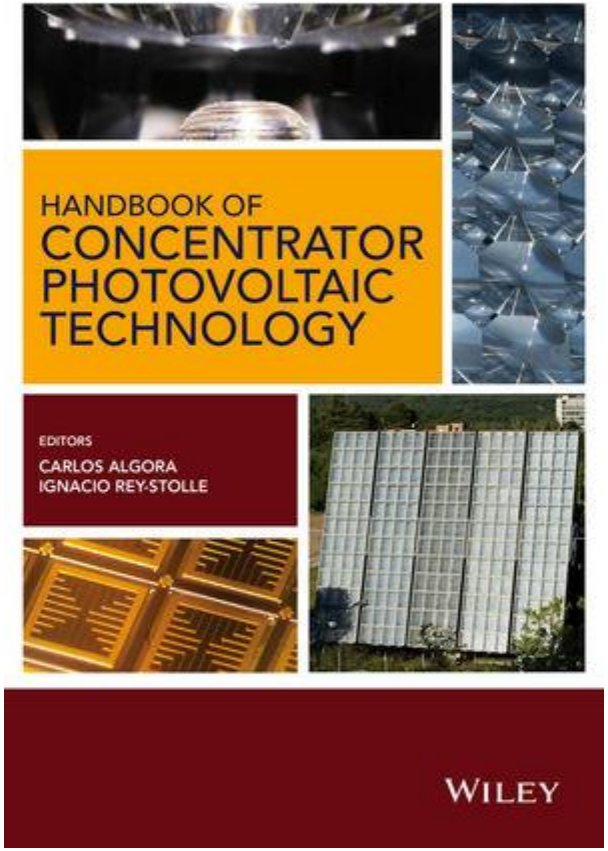
Green Energy and Technology

Pedro Pérez-Higueras
Eduardo F. Fernández *Editors*

High
Concentrator
Photovoltaics

Fundamentals, Engineering and Power
Plants

Springer



HANDBOOK OF
CONCENTRATOR
PHOTOVOLTAIC
TECHNOLOGY

EDITORS
CARLOS ALGORA
IGNACIO REY-STOLLE

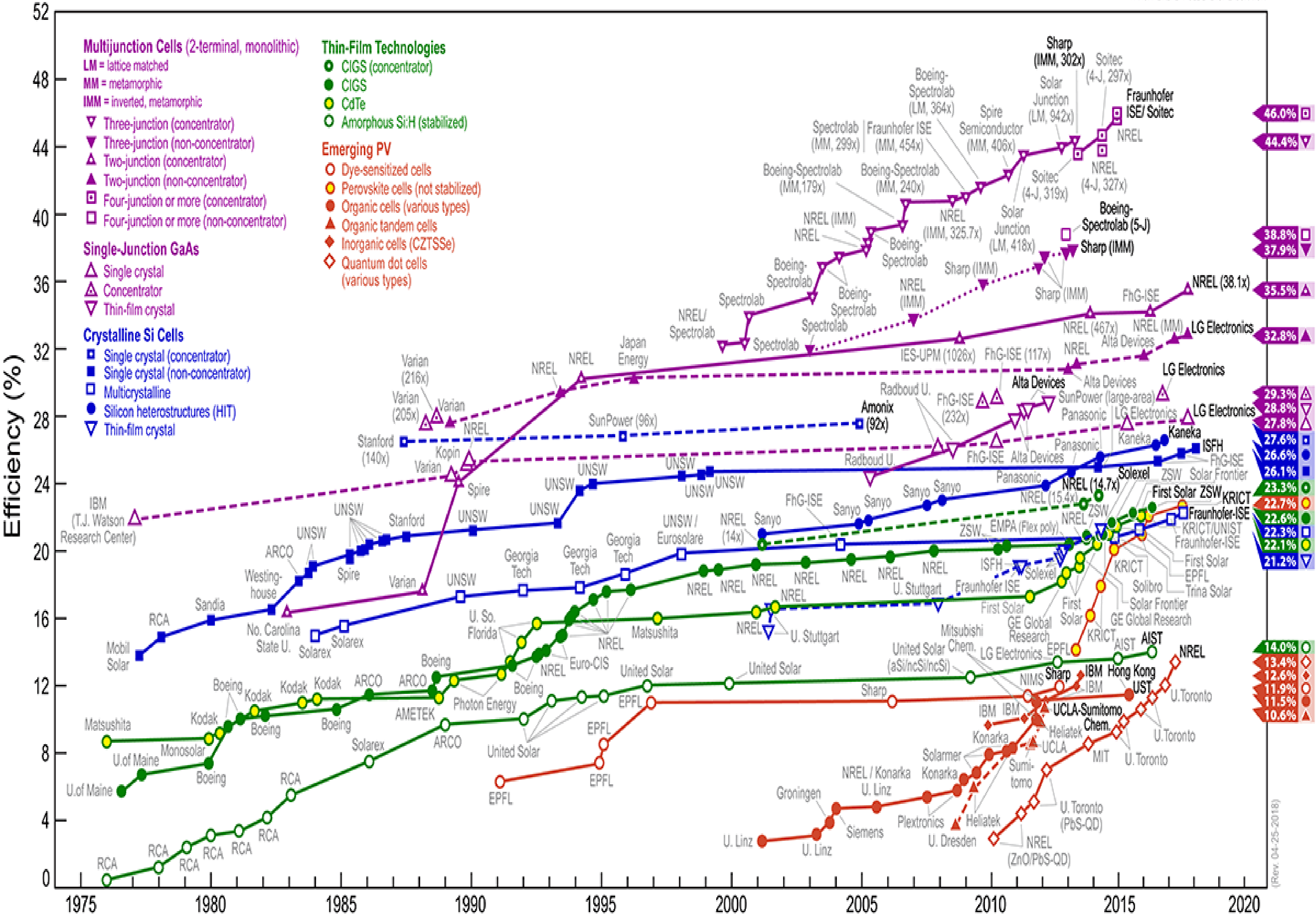
WILEY

Content

- Overview of concentrator photovoltaic technology
- Concentrator Photovoltaic system under study
- Model for estimating the energy yield of a CPV system
- Energy yield and cost of electricity assessment
- Conclusions

Best Research-Cell Efficiencies

NREL
NATIONAL RENEWABLE ENERGY LABORATORY



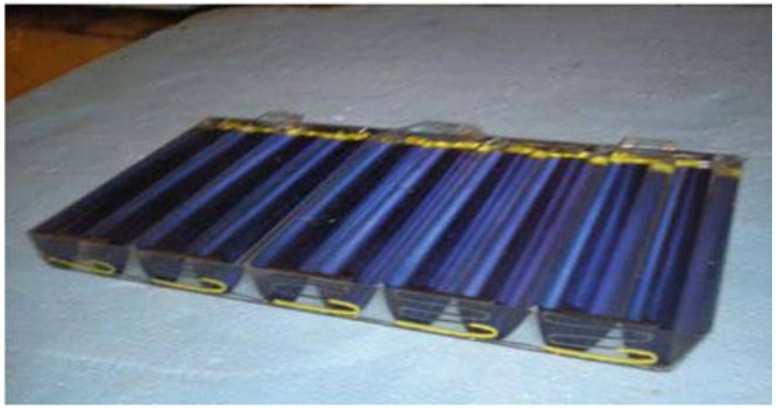
Overview of concentrator photovoltaic technology

¿What is CPV?:

$$\text{Concentration ratio } C = \frac{G_x(W/m^2)}{G_I(W/m^2)}$$

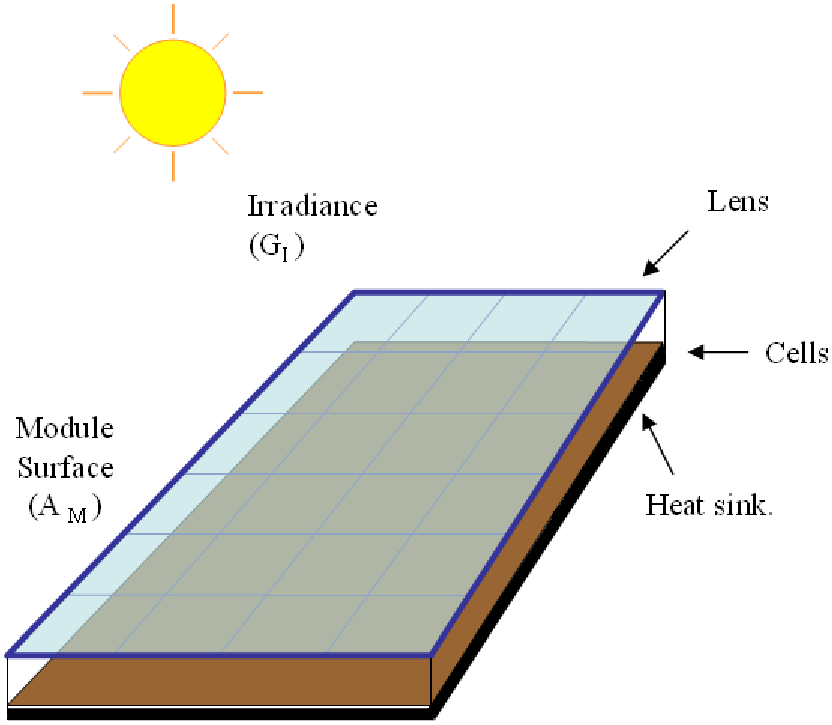
CPV (Concentrator PhotoVoltaic) systems use **optical elements to concentrate the sunlight on small and high-efficiency solar cells**. According to the concentration ratio, we may define:

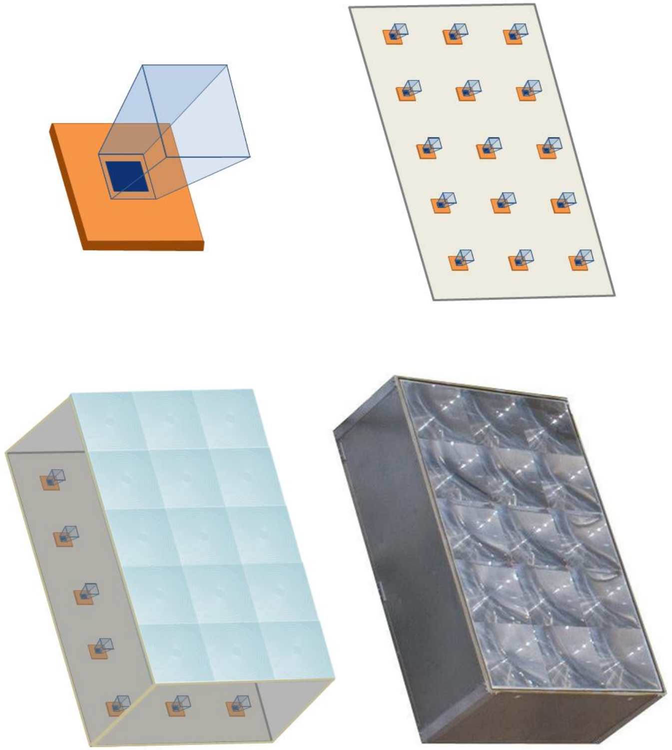
- **Low-CPV:** 1 to 40 suns.
- **Medium-CPV:** 40 to 100 suns.
- **High-CPV:** 100 to 1000 suns.



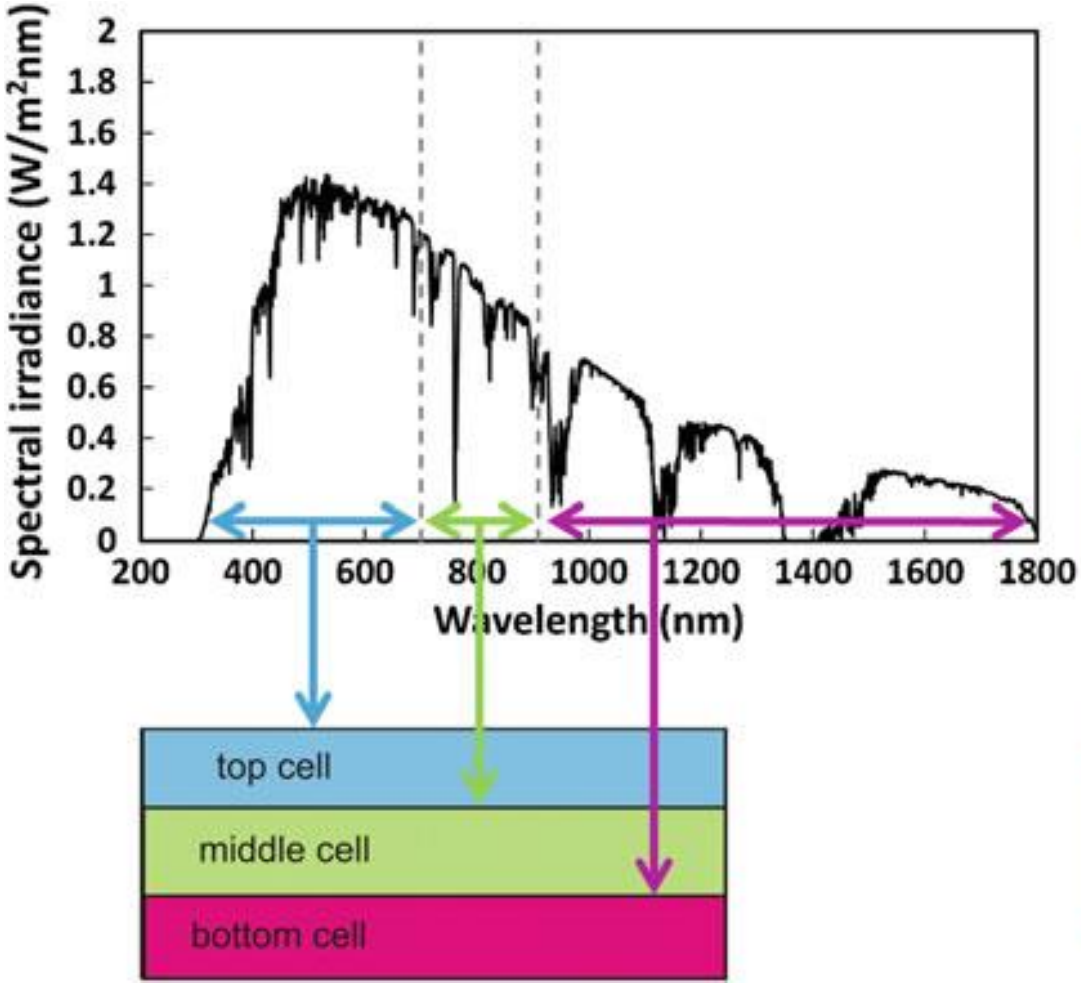
Overview of concentrator photovoltaic technology

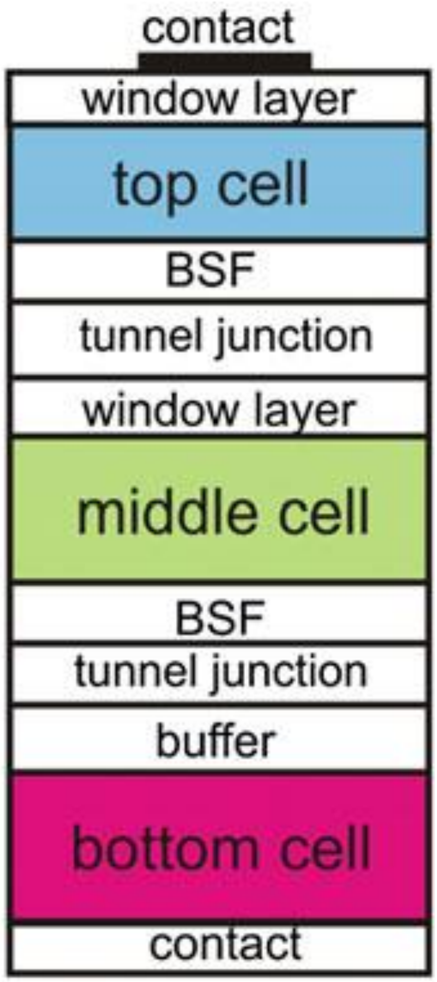
A concentrator module is the smallest, complete, environmentally protected assembly of cells and optics that accepts non-concentrated solar radiation. CPV Module is made up of a group of cells, primary optics, secondary optics (optional), cooling mechanism and housing components, such as interconnection and mounting.



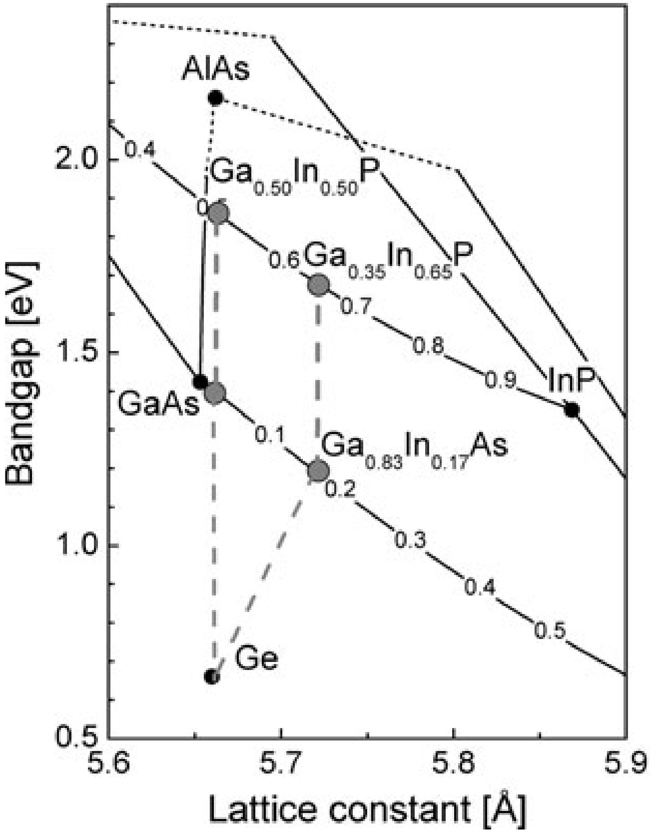


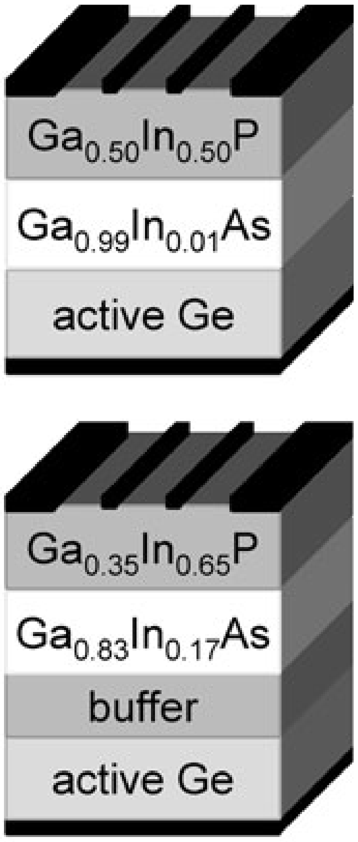
Overview: multi-junction solar cells

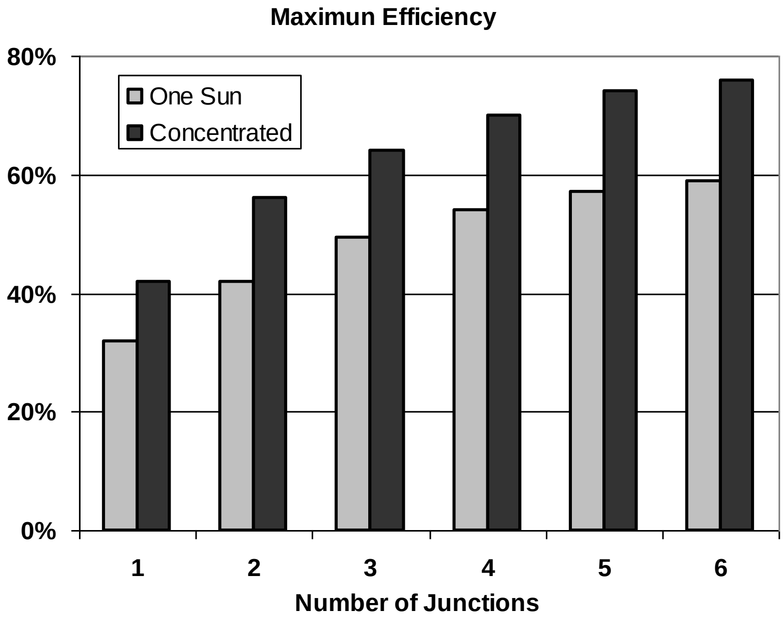




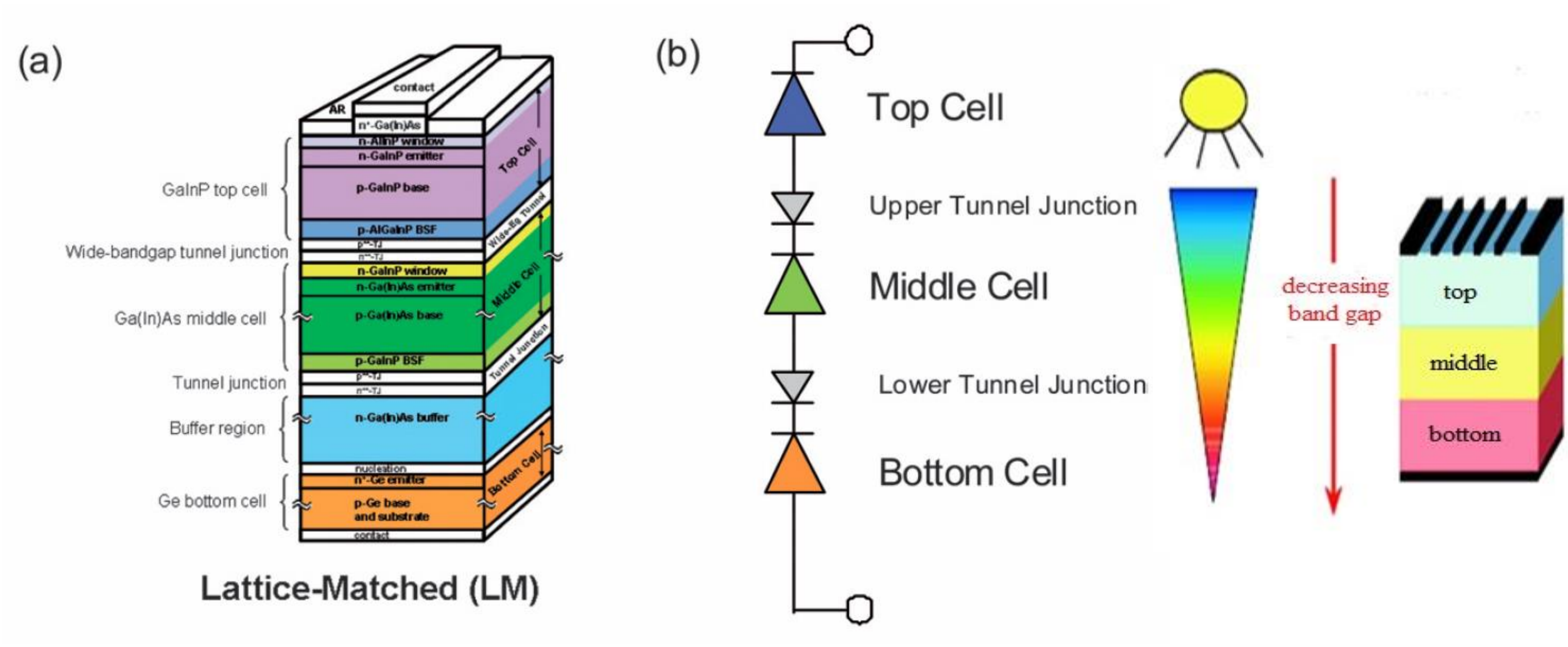
Overview: multi-junction solar cells





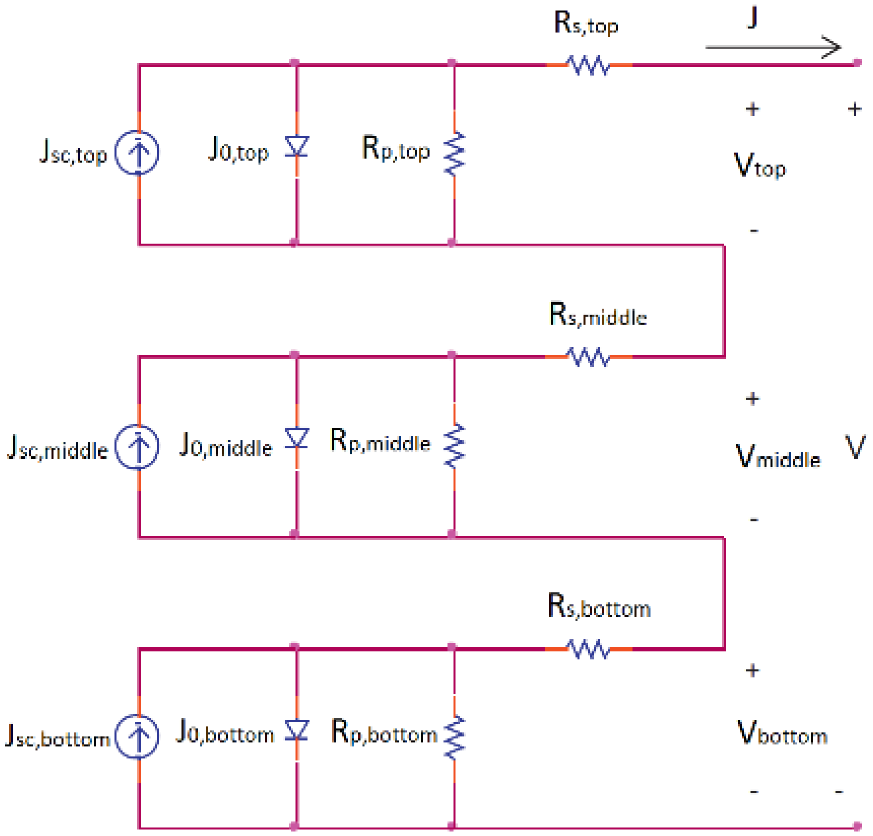


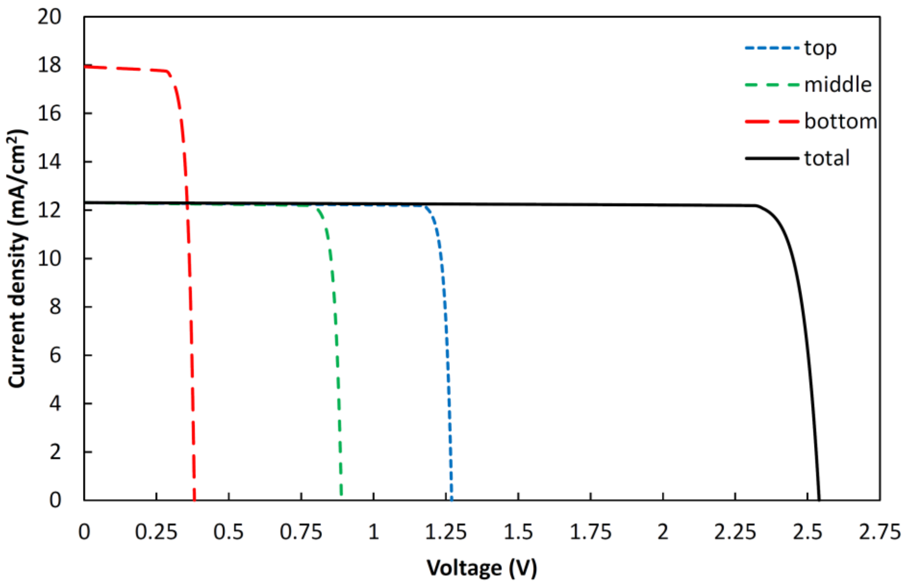
Overview: multi-junction solar cells



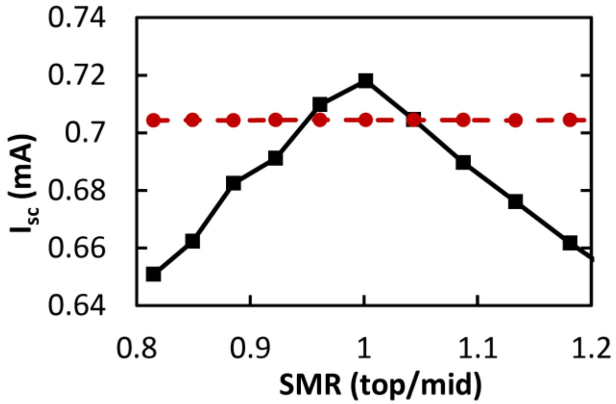
Lattice-Matched (LM)

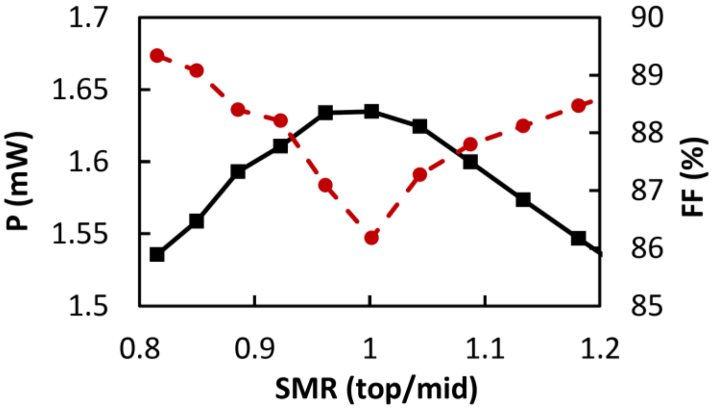
Overview: multi-junction solar cells

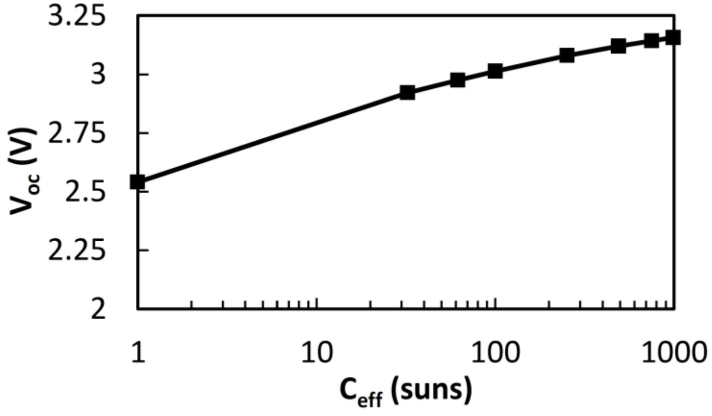


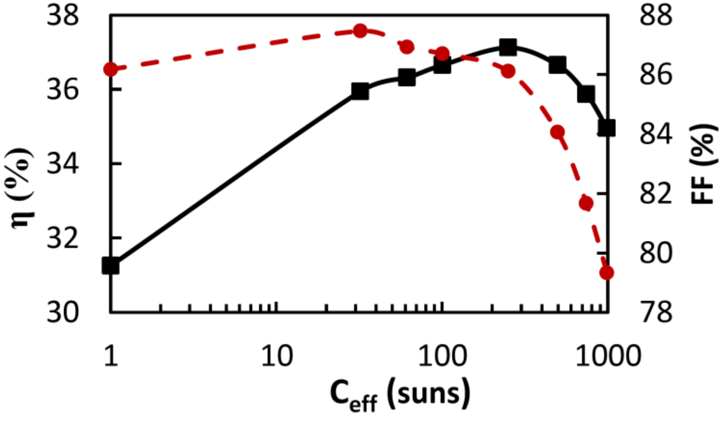


Overview: multi-junction solar cells





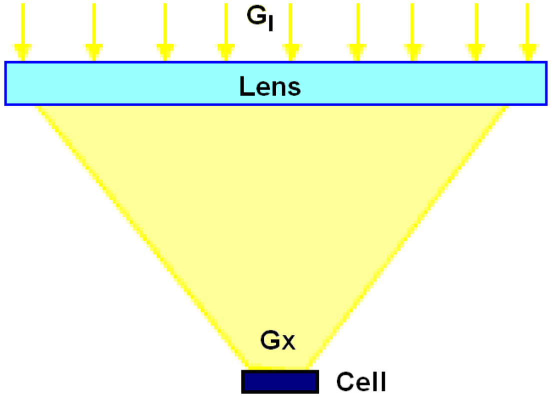


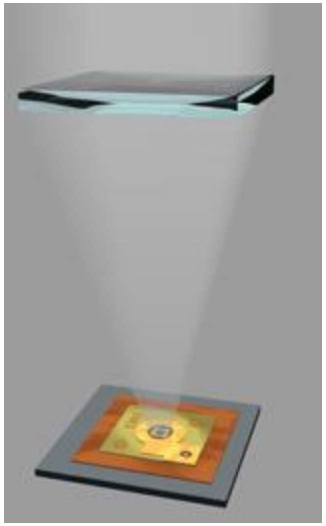


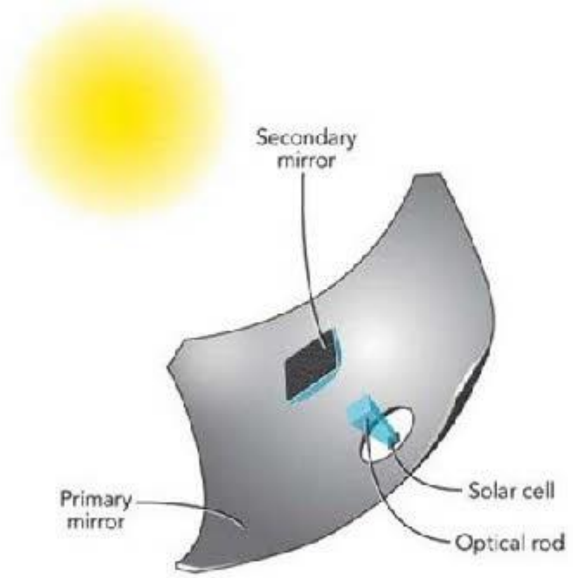
Overview: Optics

A concentrator optics is an optical device that increases the light intensity from its input to output. Typically, it is a lens or a mirror. A primary optics, POE, receives non-concentrated sunlight directly from the sun. A secondary optics, SOE, (optional) receives concentrated or modified sunlight from another optical device, such as primary optics or another secondary optics.

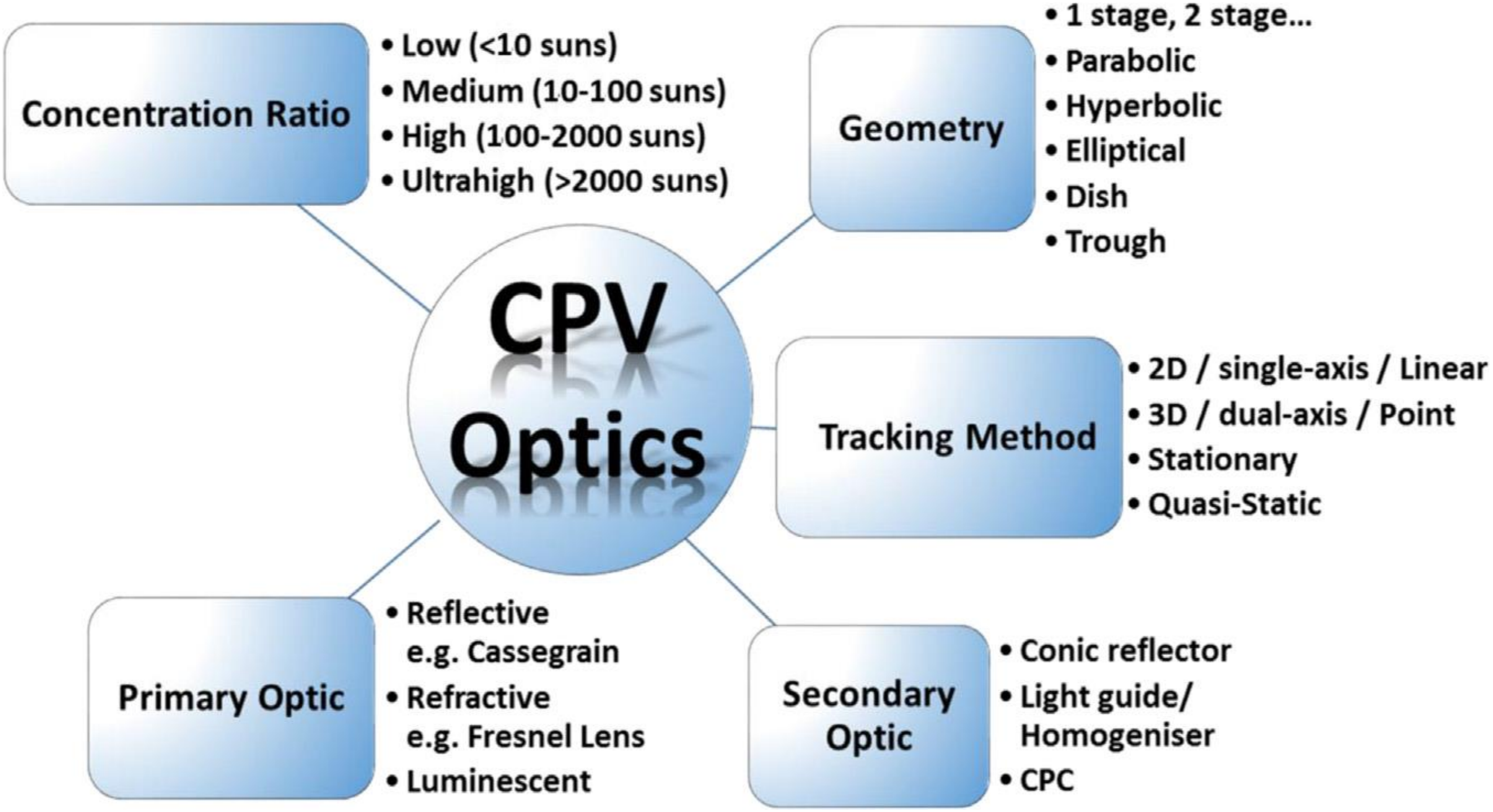
$$Concentration\ ratio\ \ C = \frac{G_x(W/m^2)}{G_I(W/m^2)}$$







Overview: Optics



CPV Optics

Concentration Ratio
- Low (<10 suns)
- Medium (10-100 suns)
- High (100-2000 suns)
- Ultrahigh (>2000 suns)

Geometry
- 1 stage, 2 stage…
- Parabolic
- Hyperbolic
- Elliptical
- Dish
- Trough

Tracking Method
- 2D / single-axis / Linear
- 3D / dual-axis / Point
- Stationary
- Quasi-Static

Primary Optic
- Reflective
  e.g. Cassegrain
- Refractive
  e.g. Fresnel Lens
- Luminescent

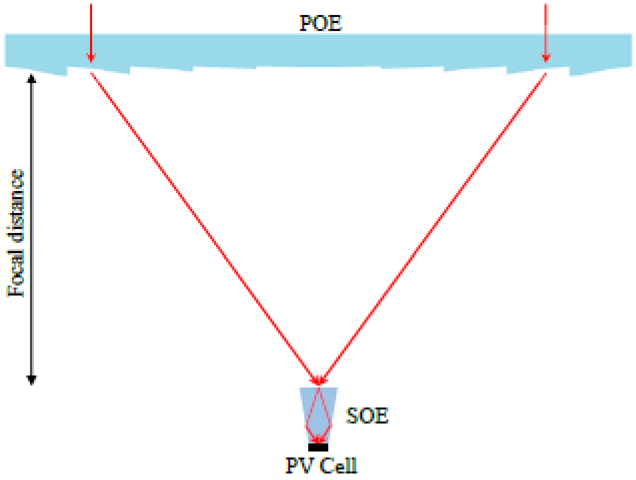
Secondary Optic
- Conic reflector
- Light guide/
  Homogeniser
- CPC

Overview: Optics

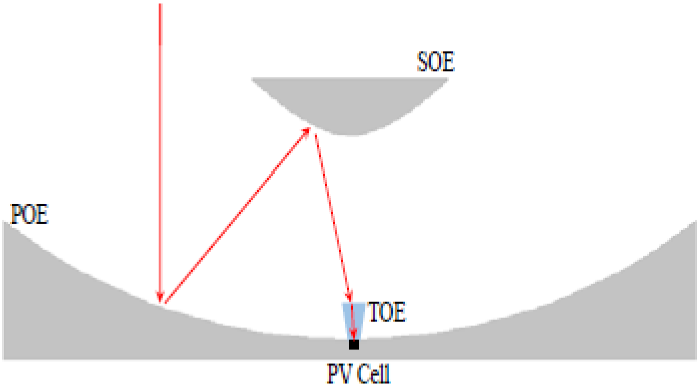
	Refractive Optics (Lenses)	Reflective Optics (Mirrors)
Point-Focus		
Line-Focus		

Overview: Optics

Main optical configurations:

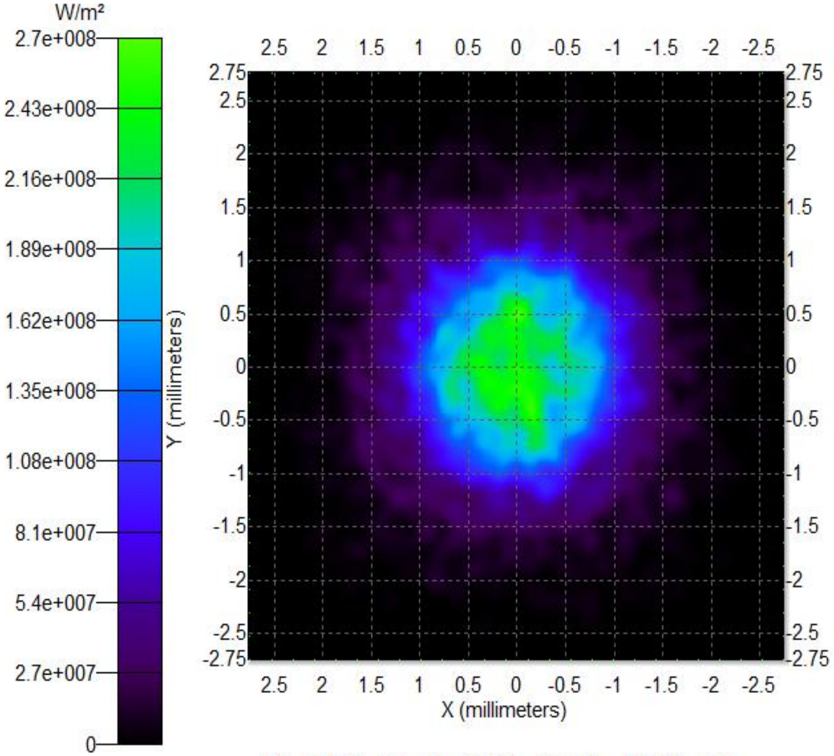


(a)

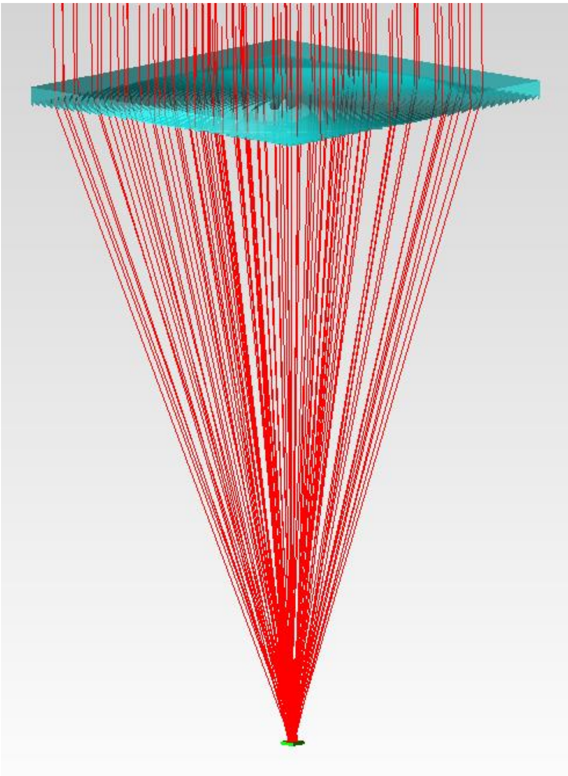


(b)

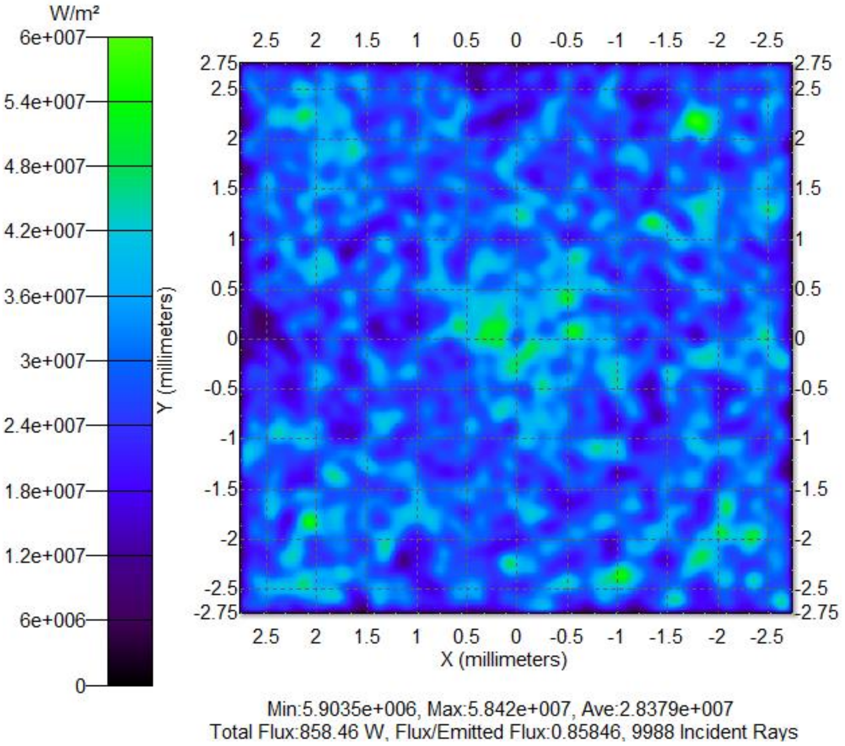
Overview: Optics [no secondary]



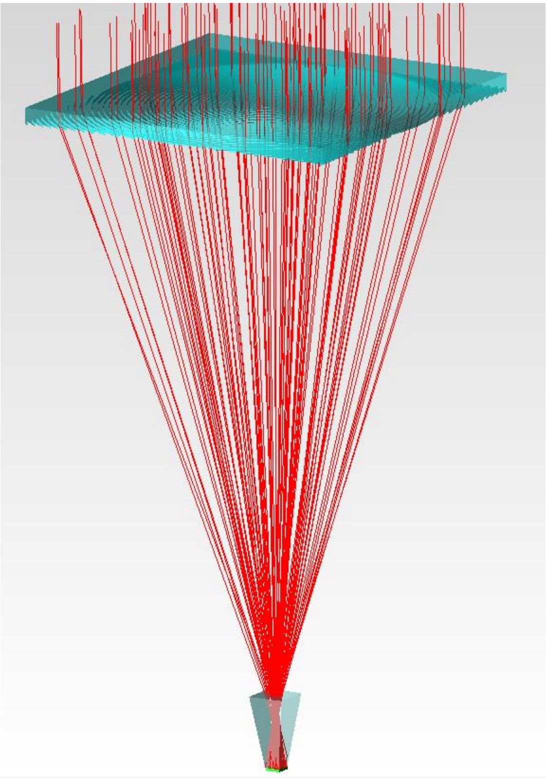
Min:2.6012e-005, Max:2.6519e+008, Ave:3.0092e+007
Total Flux:910.27 W, Flux/Emitted Flux:0.91027, 9988 Incident Rays



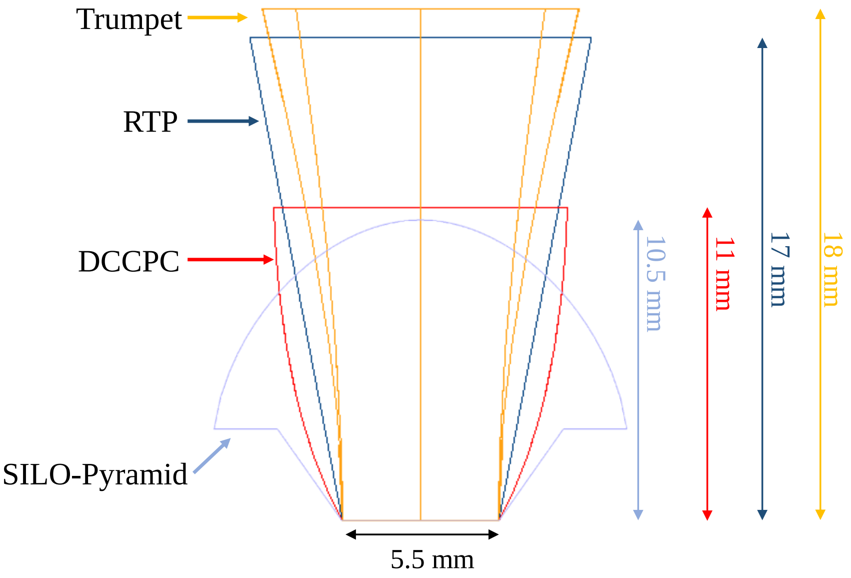
Overview: Optics [secondary]

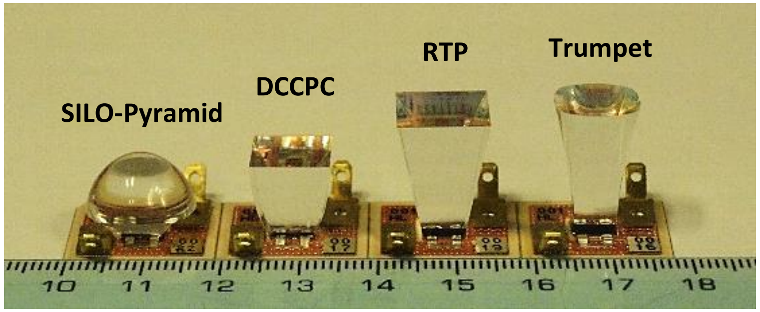


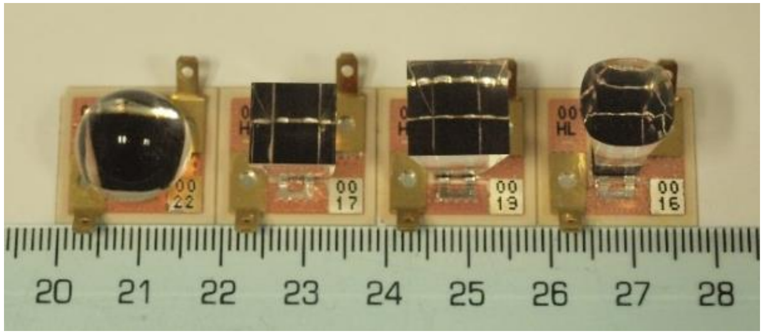
Min:5.9035e+006, Max:5.842e+007, Ave:2.8379e+007
Total Flux:858.46 W, Flux/Emitted Flux:0.85846, 9988 Incident Rays



Overview: Optics [secondary]

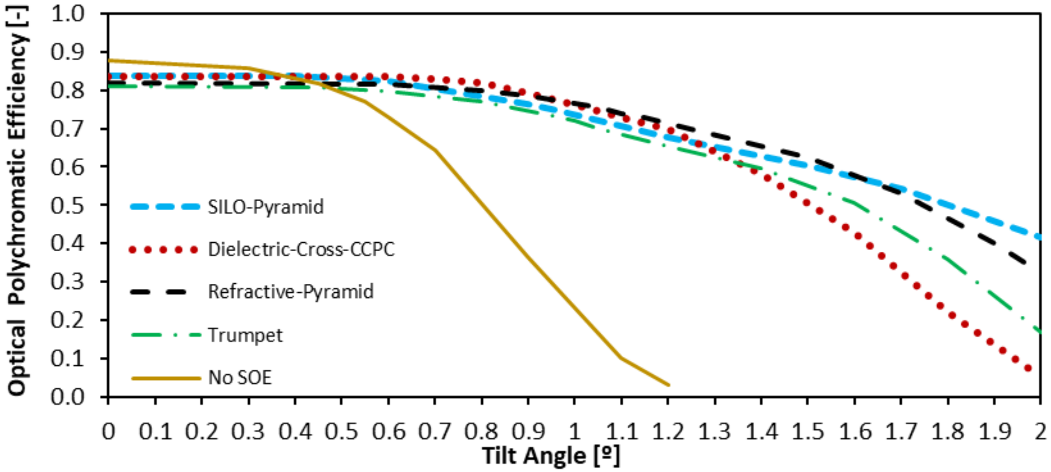




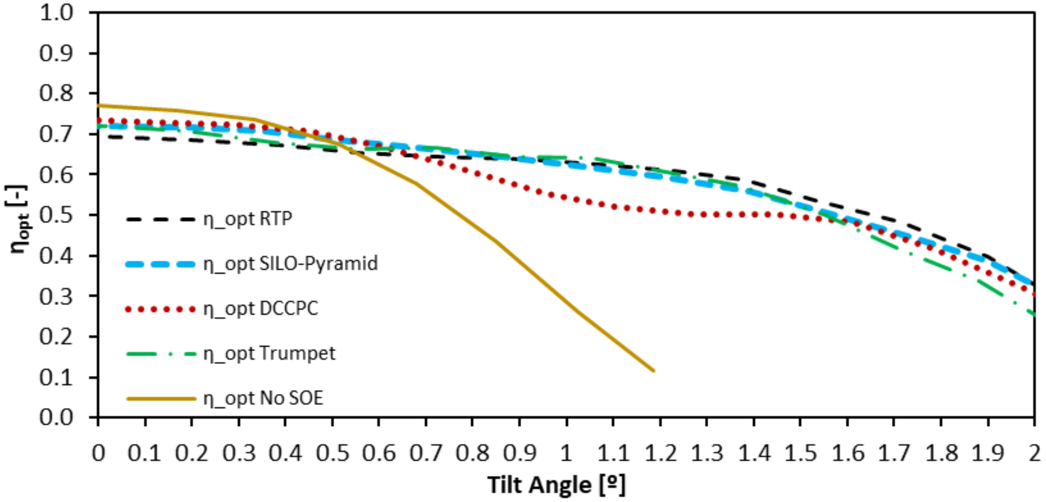


Overview: Optics [Secondary]

Optical Simulations: Fresnel-based HCPV units equipped with refractive SOEs



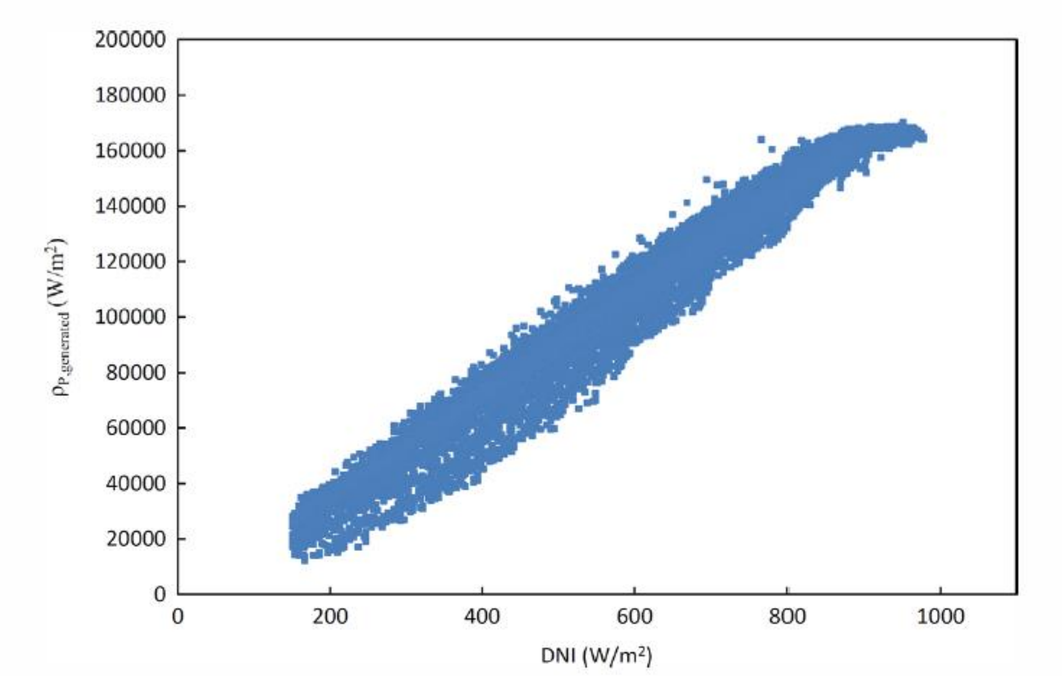
Indoor Measurements: Fresnel-based HCPV units equipped with refractive SOEs



Overview: cooling

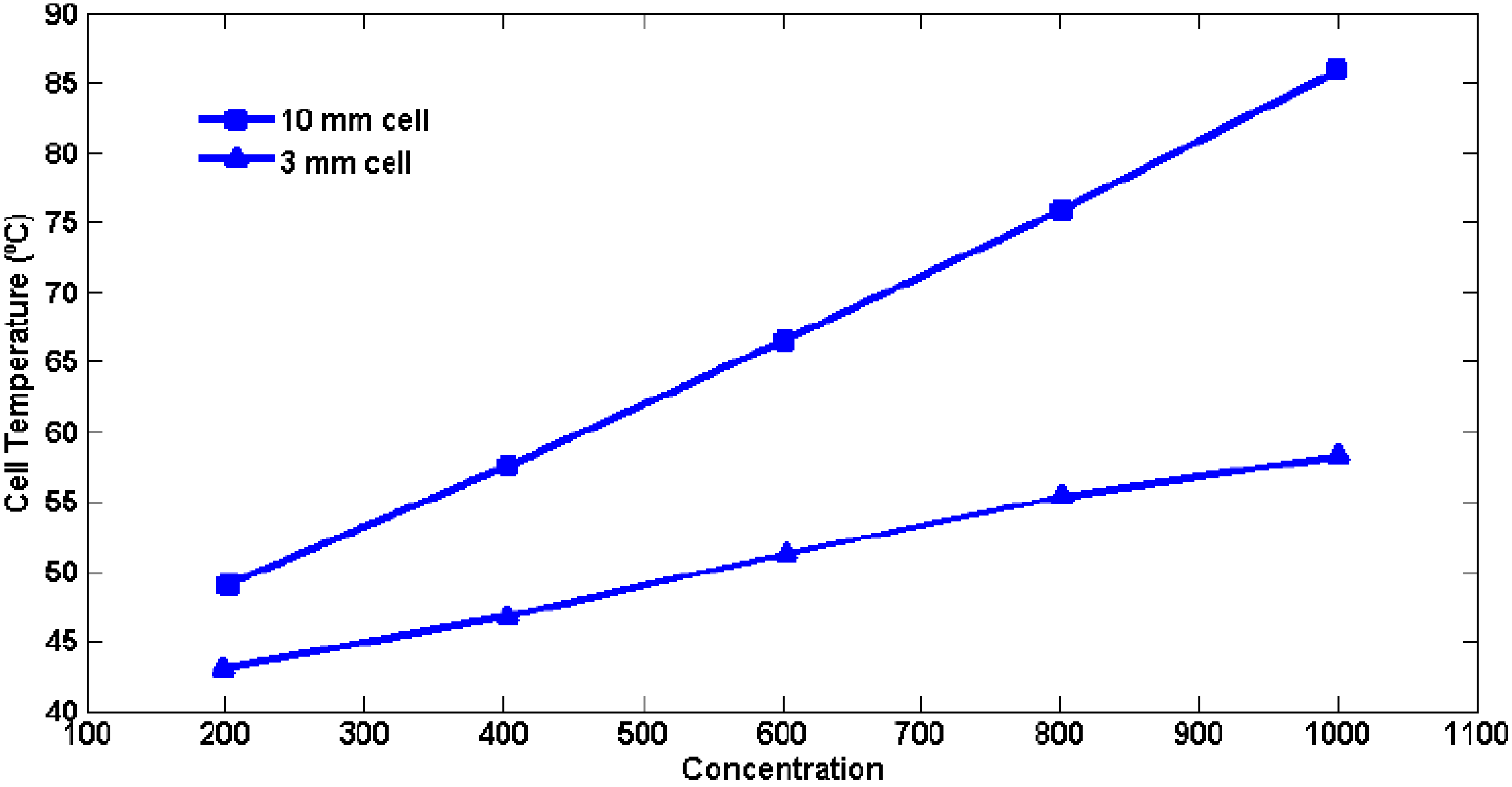
Heat power density

$$Q_{cell} = C_{geo} \cdot DNI \cdot \eta_{opt} \cdot A_{cell} \cdot (1 - \eta_{cell})$$



$$\rho_{P,generated} = DNI \times C_{geometric}\eta_{optical}\eta_{cell}$$

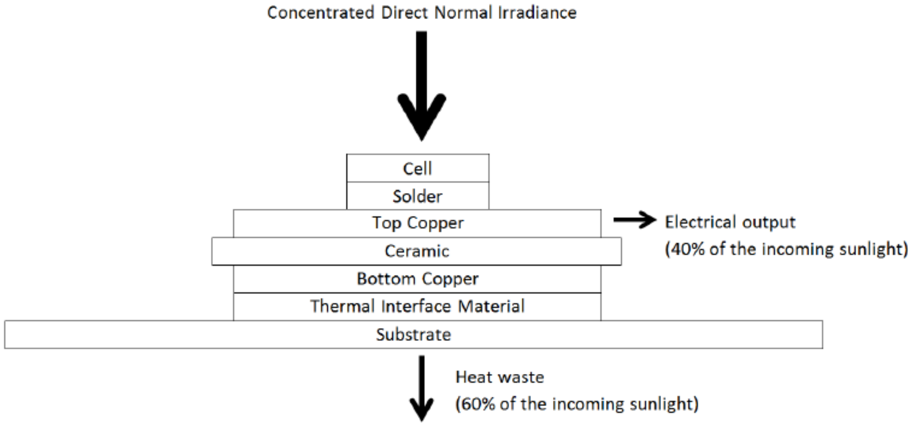
Overview: cooling



Overview: cooling

Thermal resistance:

$$R_{\text{cond}} = R_{\text{cell}} + R_{\text{solder}} + R_{\text{TopCu}} + R_{\text{dielectric}} + R_{\text{BottomCu}} + R_{\text{TIM}} + R_{\text{HS}}$$



Concentrated Direct Normal Irradiance

Cell

Solder

Top Copper

Ceramic

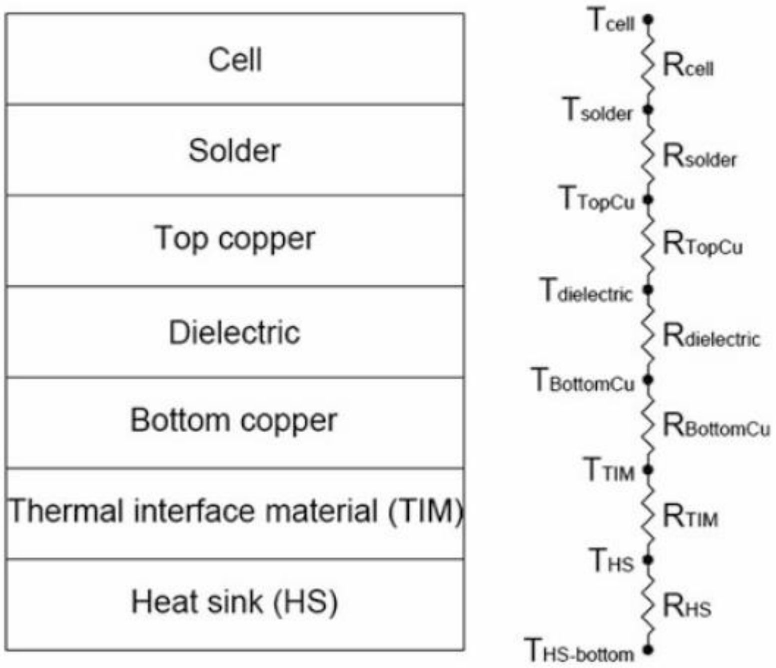
Bottom Copper

Thermal Interface Material

Substrate

Electrical output
(40% of the incoming sunlight)

Heat waste
(60% of the incoming sunlight)



Cell

Solder

Top copper

Dielectric

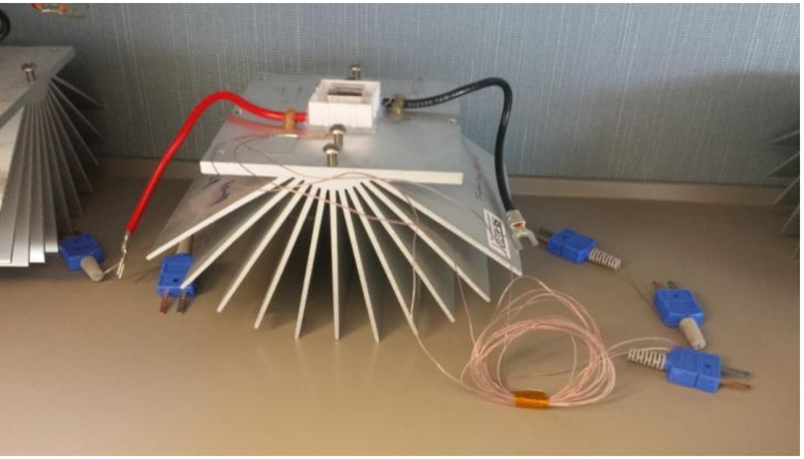
Bottom copper

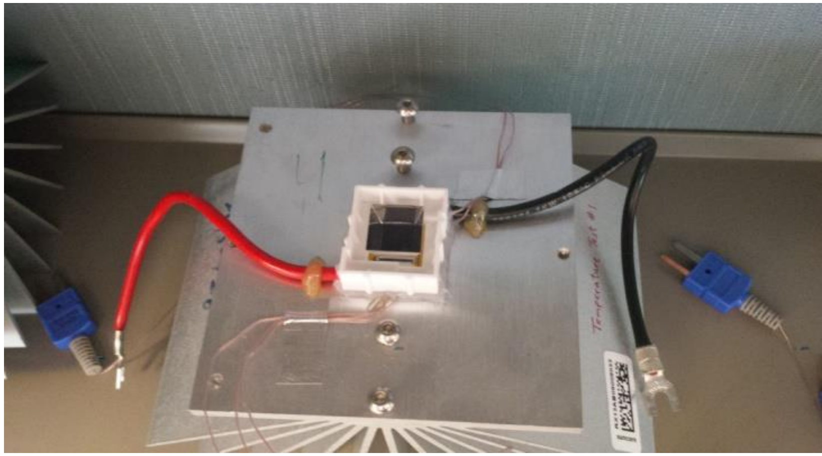
Thermal interface material (TIM)

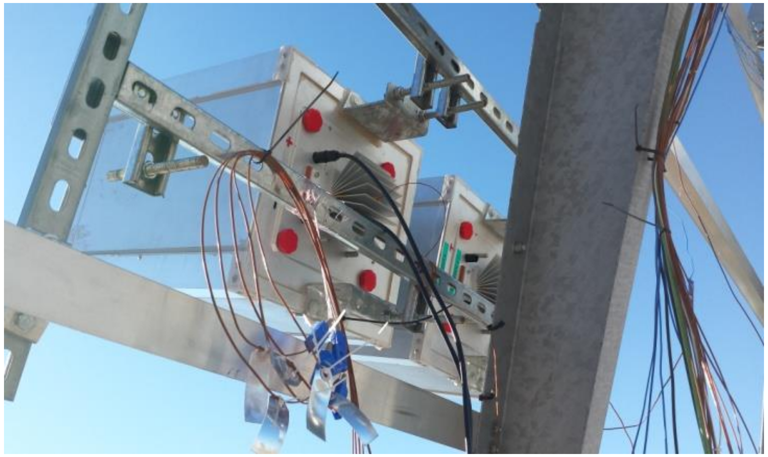
Heat sink (HS)

$$R_{\text{tot}} = \frac{T_{\text{cell}} - T_{\text{amb}}}{q_{\text{cell}}}$$

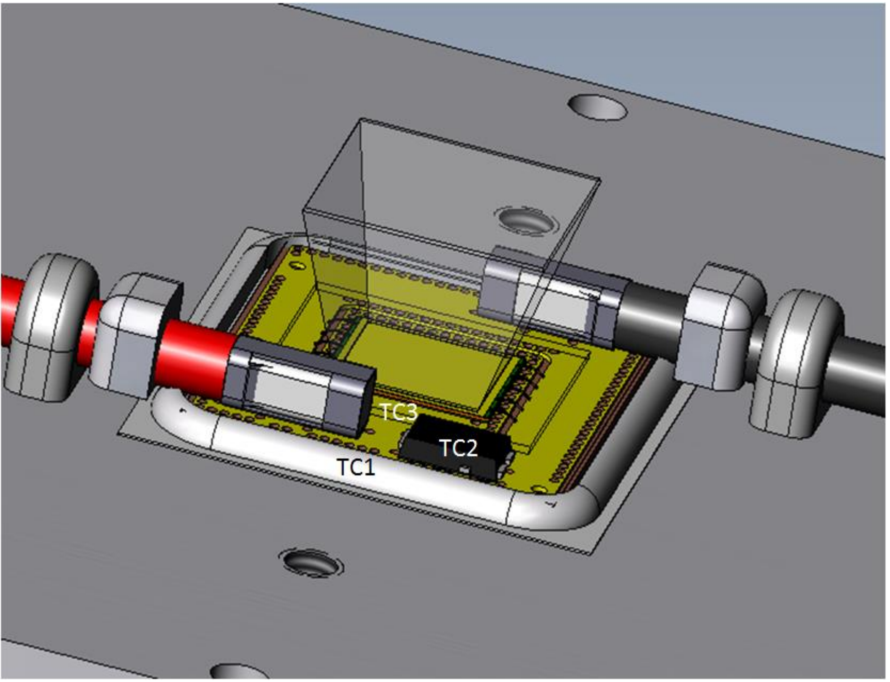
Overview: cooling

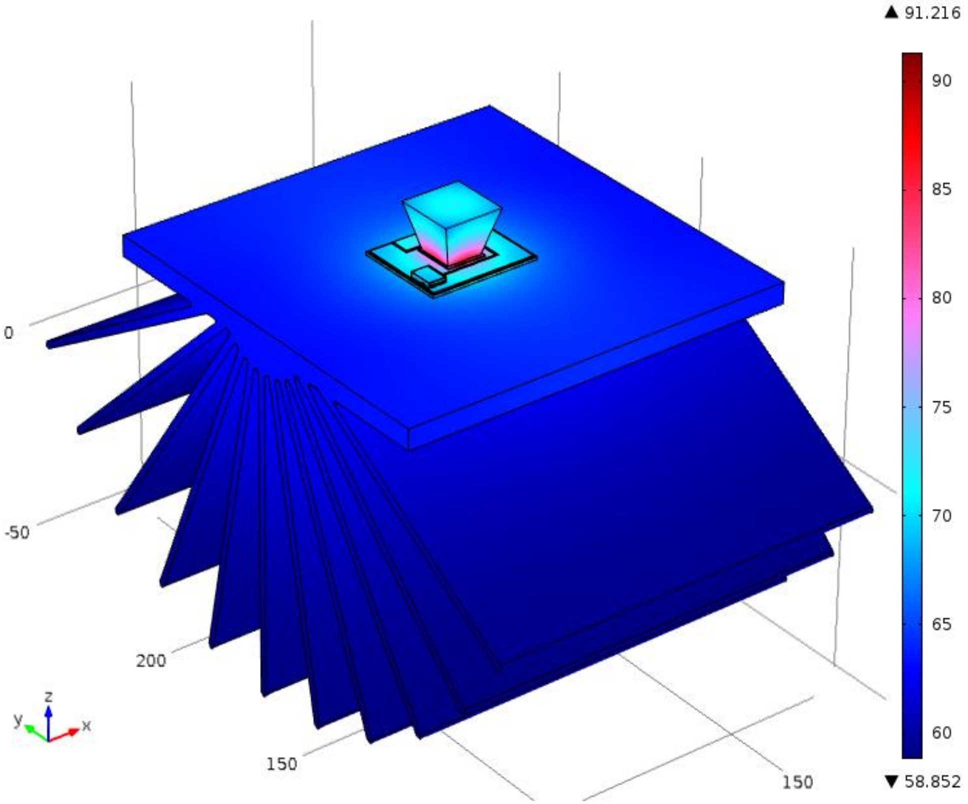




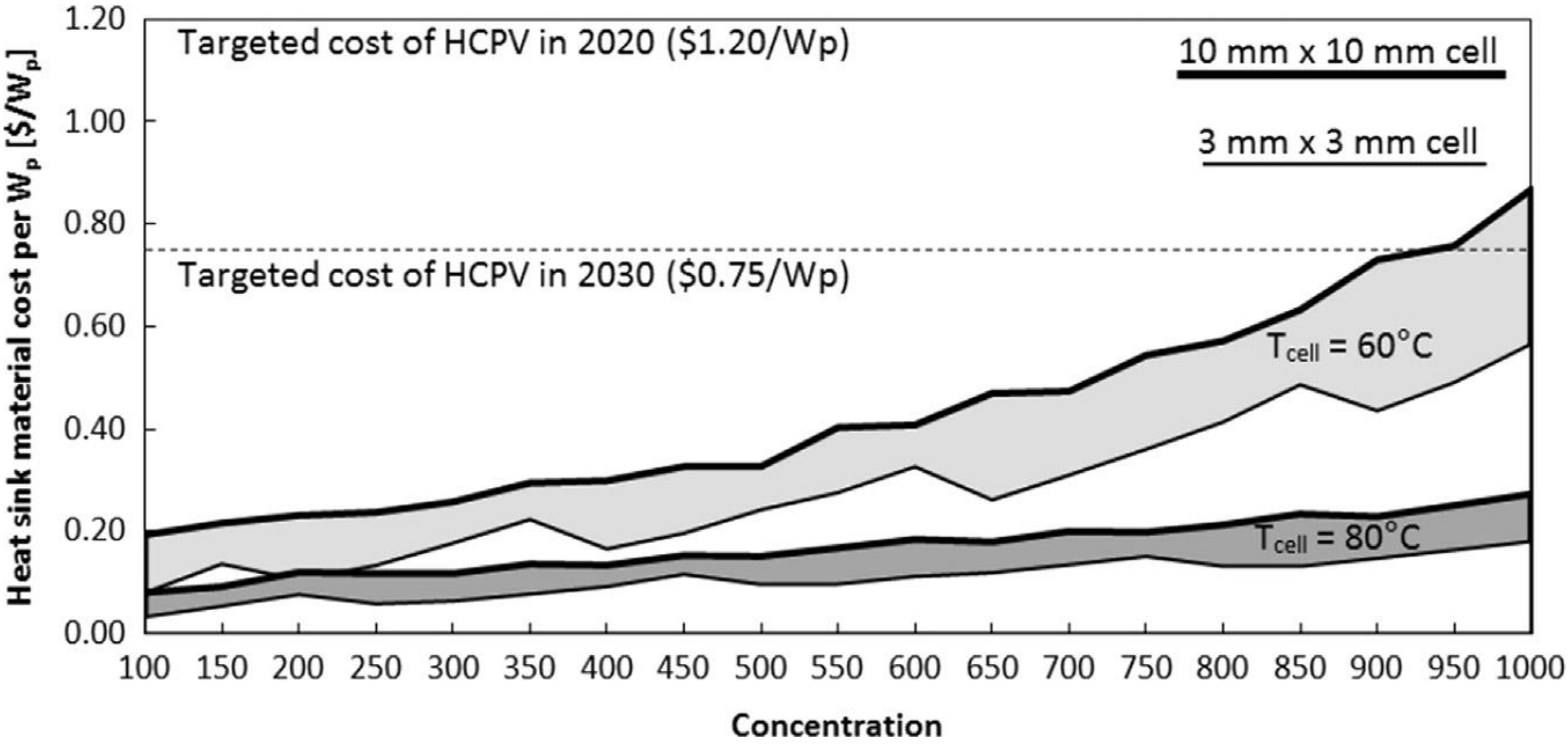


Overview: cooling





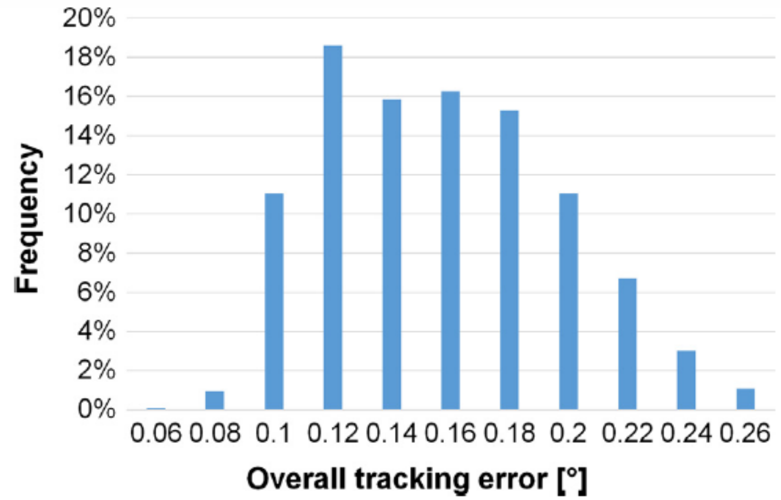
Overview: cooling



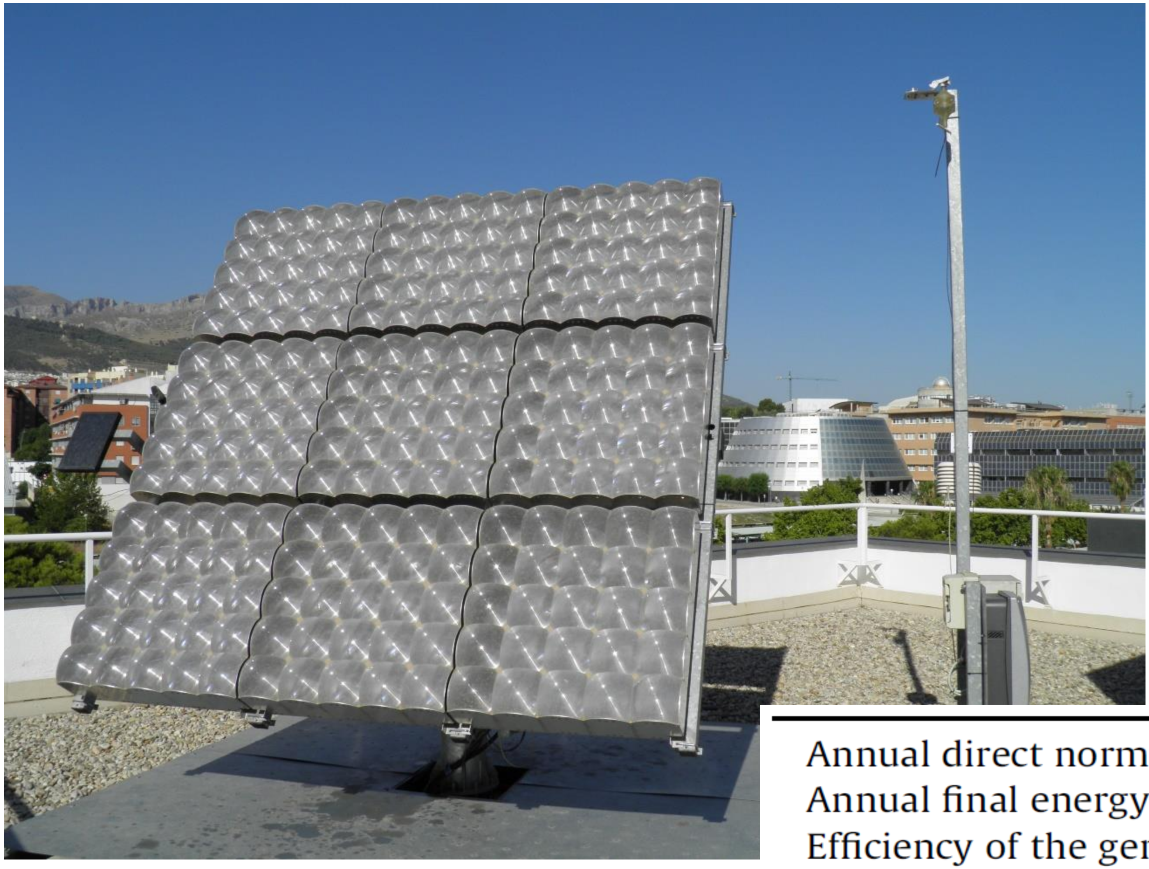
Overview: tracker

HCPV systems use high-accurate two-axis solar trackers due to the low acceptance angle of the modules, i.e. i.e. the modules must be always pointing toward the solar rays in order for the lenses to be able to focus the radiation on the small solar cell area. They may be classified in:

- Tow-axis trackers for “point-focus dish”
- Tow-axis trackers for “point-focus Fresnel Lens”:
  - Pedestal
  - Carrusel
  - “tilt and roll”

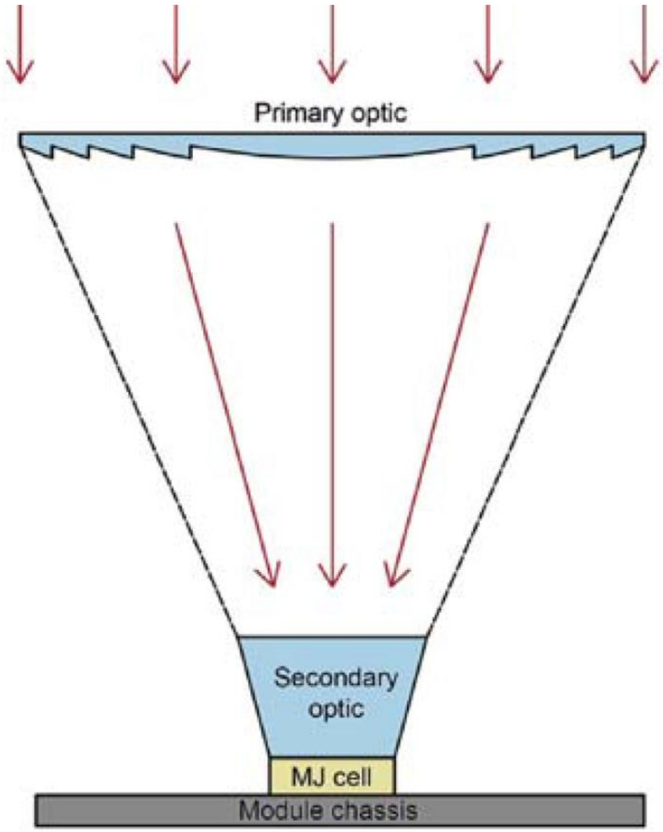


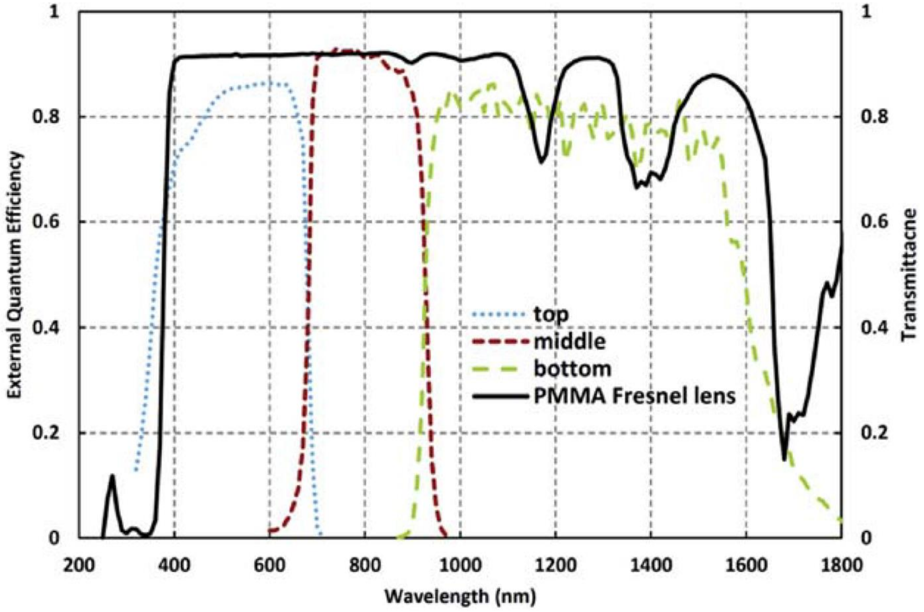
CPV system under study



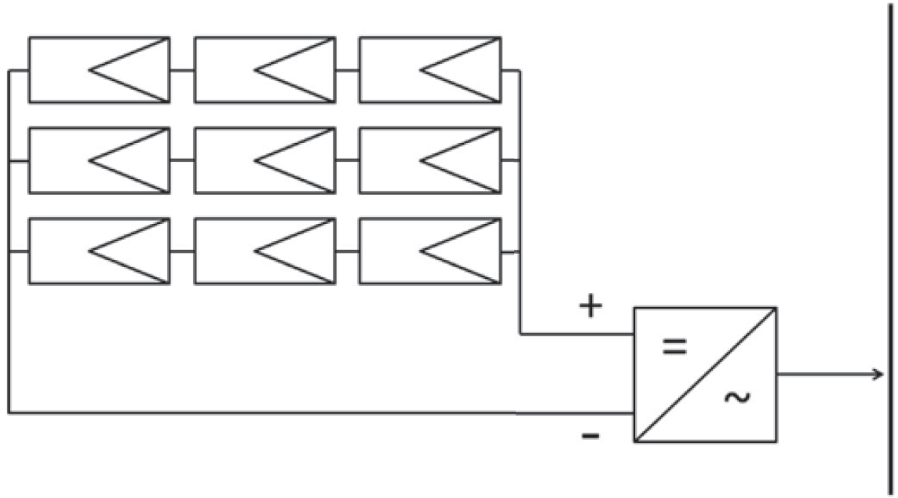
Annual direct normal irradiation (kWh/m^2 year	2214
Annual final energy yield (kWh$_{AC}$/kWp year)	1912
Efficiency of the generator (%)	20.2
Efficiency of the BOS (%)	92.9
Efficiency of the System (%)	18.8
Performance ratio (%)	86.4

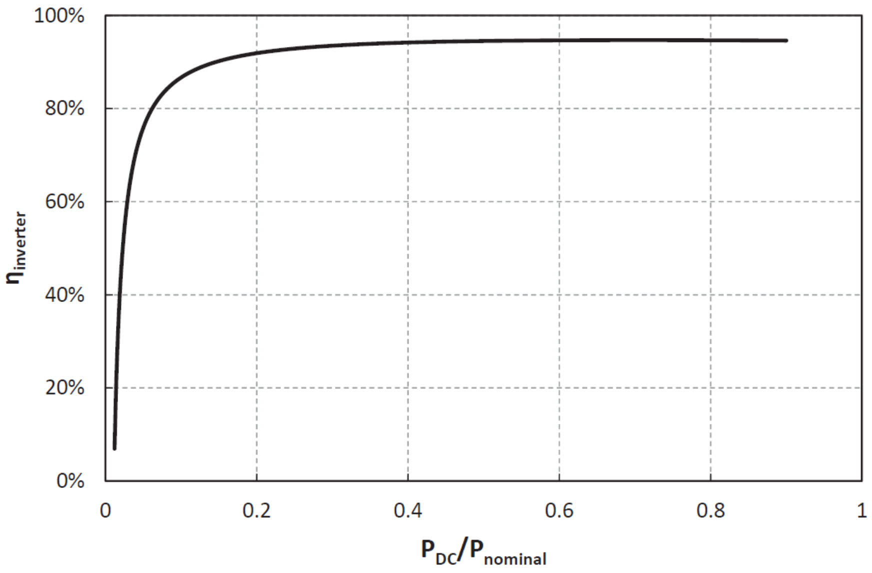
CPV system under study





CPV system under study





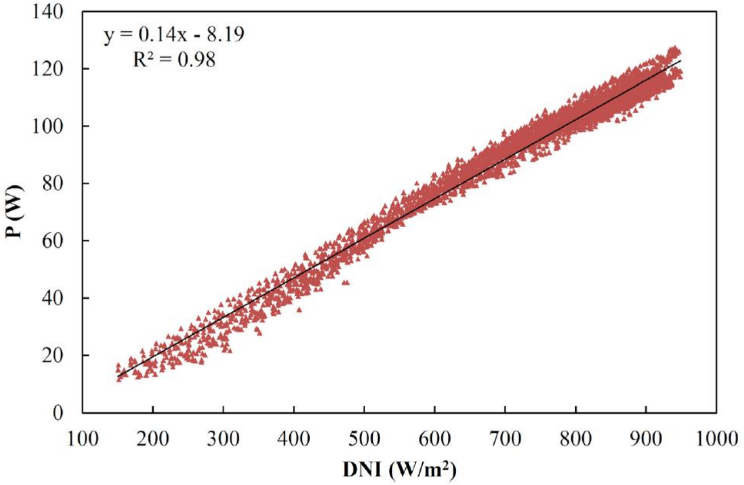
Geometric concentration	550
Primary optics	PMMA Fresnel lens
Secondary optics	Refractive truncated pyramid
Optical efficiency (%)	85
Type of solar cells	Lattice-matched GaInP/GaInAs/Ge
Number of solar cells	25 cells in series
Cooling	Passive
Area (m^2)	0.68
Length (m)	0.82
Width (m)	0.82
Depth (m)	0.24

Parameter	Value
Short-circuit current (A)	7.2
Open-circuit voltage (V)	228
Current at the maximum power point (A)	6.9
Voltage at the maximum power point (V)	195
Maximum power (kW)	1.35

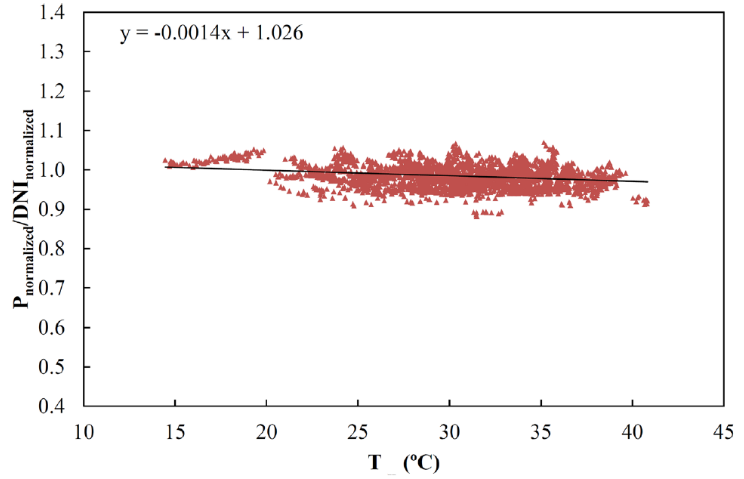
Model for estimating the energy yield of a CPV system

$$P_{module} = f_{DNI} \cdot f_{T_c} \cdot f_{S_b}$$

$$f_{DNI} = \frac{P^*}{DNI^*} \cdot DNI \longrightarrow$$



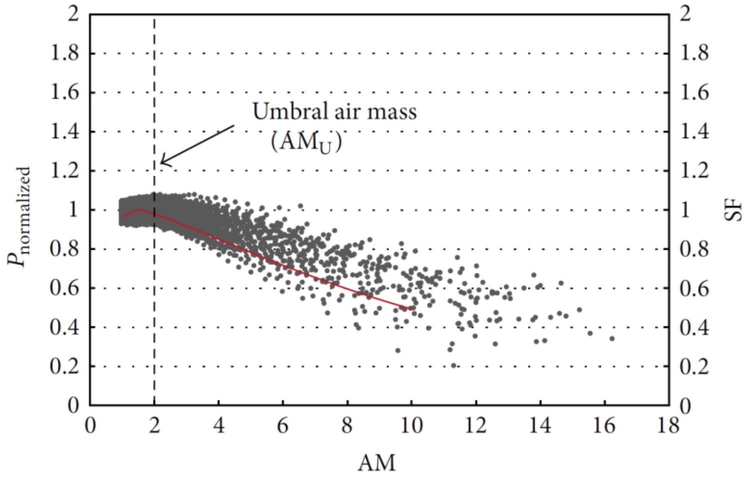
$$f_{T_c} = 1 - \delta \cdot \left(T_C - T_C^*\right) \longrightarrow$$

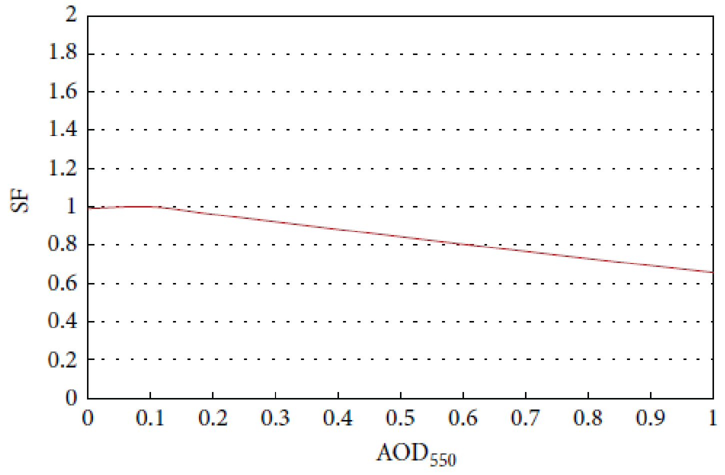


Model for estimating the energy yield of a CPV system

$$P_{module} = f_{DNI} \cdot f_{T_c} \cdot f_{S_b}$$

$$f_{S_b} = (1 - \varepsilon \cdot (AM - AM_U))(1 - \varphi \cdot (AOD_{550} - AOD_{550,U}))$$



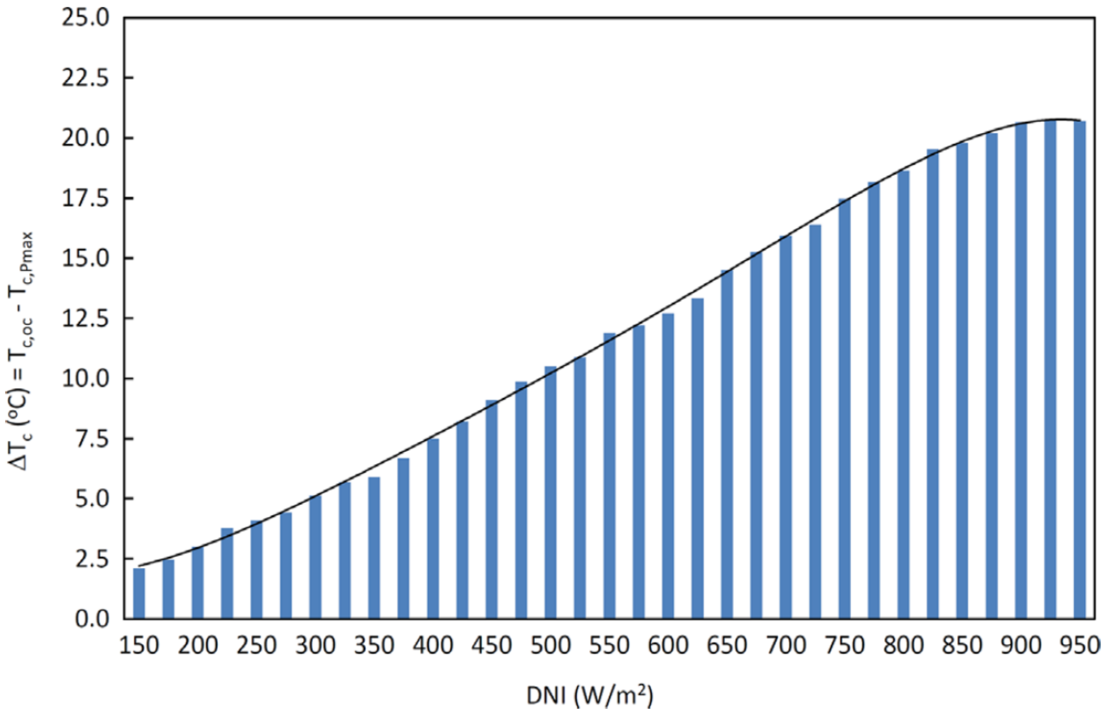


Model for estimating the energy yield of a CPV system

$$P_{module} = f_{DNI} \cdot f_{T_c} \cdot f_{S_b}$$

$$T_c = T_{air} + R_{total} \cdot DNI_{heat}$$

$$DNI_{heat} = DNI - \frac{P_{module}}{A_{module}}$$



Model for estimating the energy yield of a CPV system

$$P_{DC} = N_S N_P P_{module}(1 - L_{DC})$$

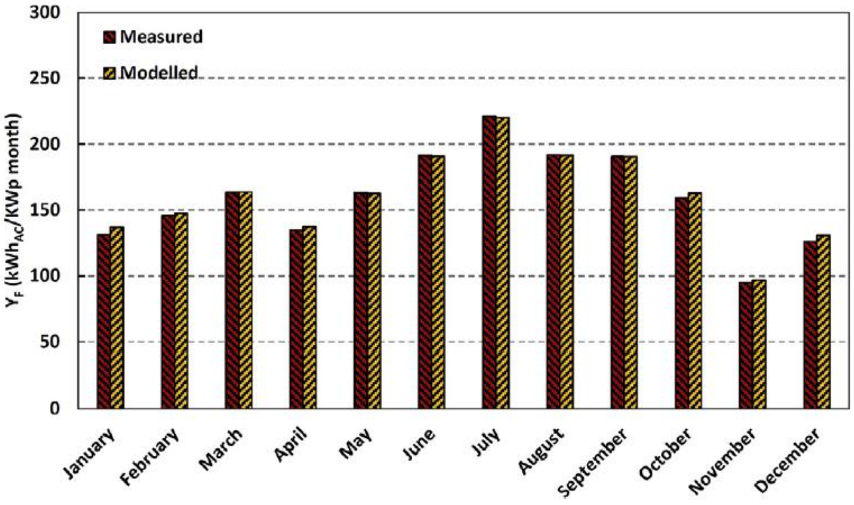
$$L_{inverter} = \frac{b_0 + b_1 p_{in} + b_2 p_{in}^2}{p_{in}}$$

$$P_{AC} = P_{DC}(1 - L_{inverter})(1 - L_{AC})$$

$$E_{AC} = \int_T P_{AC}\,dt$$

$$Y_F = \frac{E_{AC}}{P_o}$$

Coefficient	Value	Unit
R_{total}	0.059	°C/Wm^{-2}
δ	0.12	%/°C
ε	4.11	%
φ	32	%
AM_U	2.06	Dimensionless
$AOD_{550,U}$	0.25	Dimensionless
L_{DC}	4.41	%
b_0	0.010	Dimensionless
b_1	0.023	Dimensionless
b_2	0.023	Dimensionless
L_{AC}	2.11	%



	Annual Y_F (kWh$_{AC}$/kWp)	Deviation (%)
Measured	1912	0.93
Modelled	1930	

Energy yield: locations considered

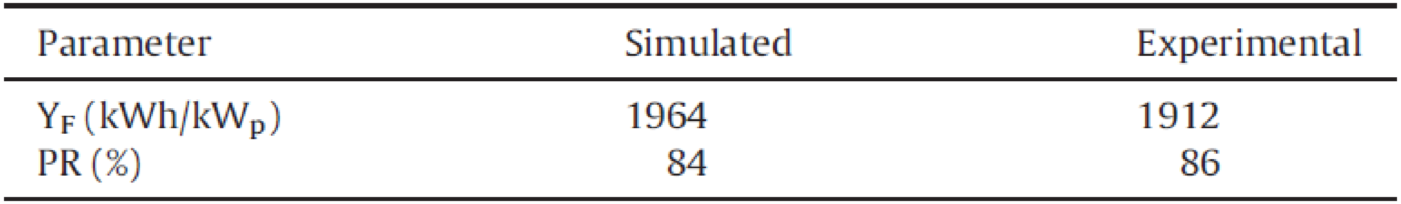
- Solar Village (Saudi Arabia): lat. N 24°54′25″, long. E 46°23′49″
- Alta Floresta (Brazil): lat. S 09°52′15″, long. W 56°06′14″
- Frenchman Flat (USA): lat. N 36°48′32″, long. W 115°56′06″
- Granada (Spain): lat. N 37′09′50″, long. W 03°36′18″
- Beijing (China): lat. N 39°58′37″, long. E 116°22′51″

Location	DNI (W/m^2)	T_{air} (°C)	AM	AOD$_{550}$
Solar Village	694	28.8	3.0	0.35
Alta Floresta	608	27.7	2.8	0.28
Frenchman Flat	704	18.4	3.3	0.07
Granada	623	19.1	3.3	0.15
Beijing	390	15.7	3.4	0.82

Energy yield: input parameters

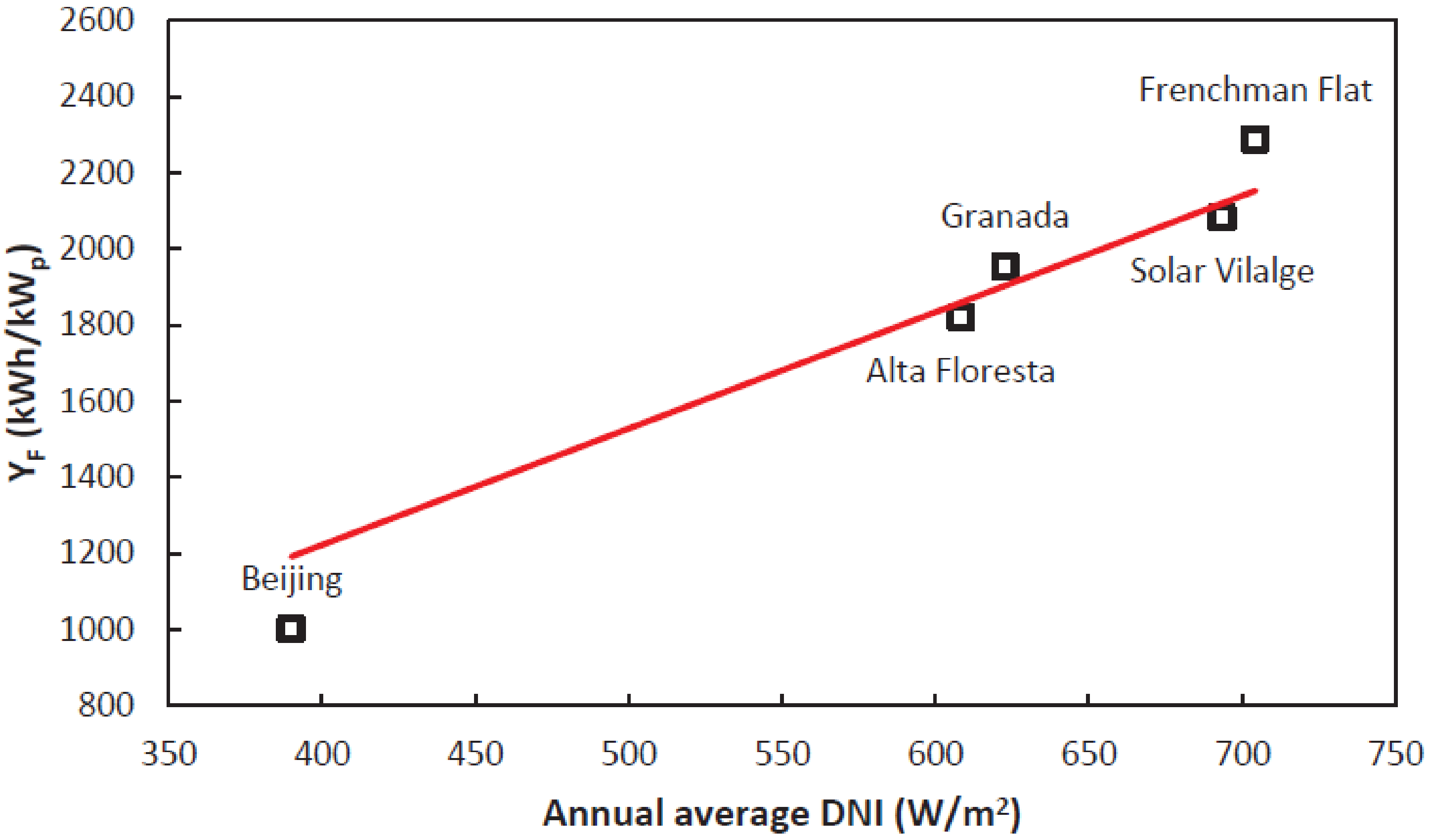
A MATLAB programming code was developed to predict the Energy Yield at each location as a function of:

1. **Direct Normal Irradiance (DNI)**: simulated with the Simple Model of Atmospheric Radiative Transfer of Sunshine (SMARTS).
2. **Air Mass (AM)**: estimated from the sun position.
3. **Aerosol Optical Depth (AOD) at 550nm**: obtained from AERONET (Aerosol Robotic Network).
4. **Air temperature (T_{air})**: simulated from the minimum, maximum and average daily values obtained from NASA by using the Erbs model.
5. **Cloud Fraction (CF):** obtained from Modis Level-3 Data Source.



Parameter	Simulated	Experimental
Y_F (kWh/kW$_p$)	1964	1912
PR (%)	84	86

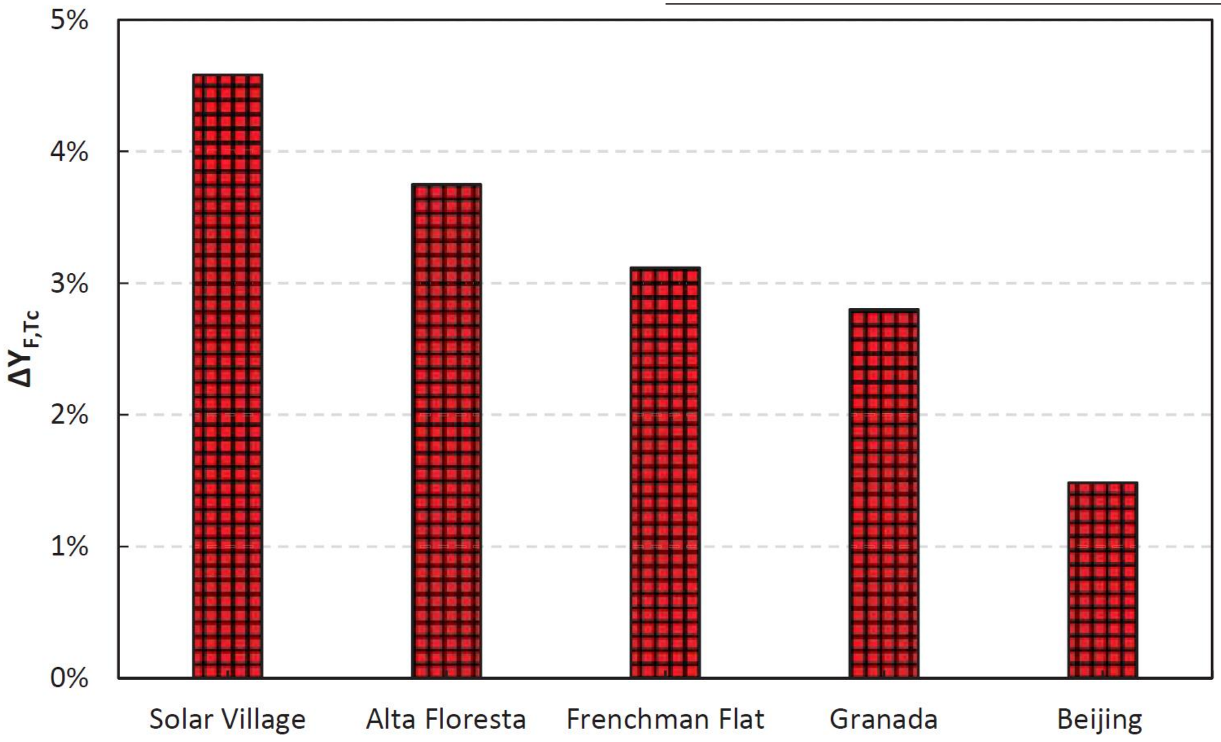
Energy yield



Energy yield: impact of cell temperature

$$\Delta Y_{F,Tc} = \left(\frac{Y_F(DNI) - Y_F(DNI, T_c)}{Y_F(DNI)}\right) \cdot 100$$

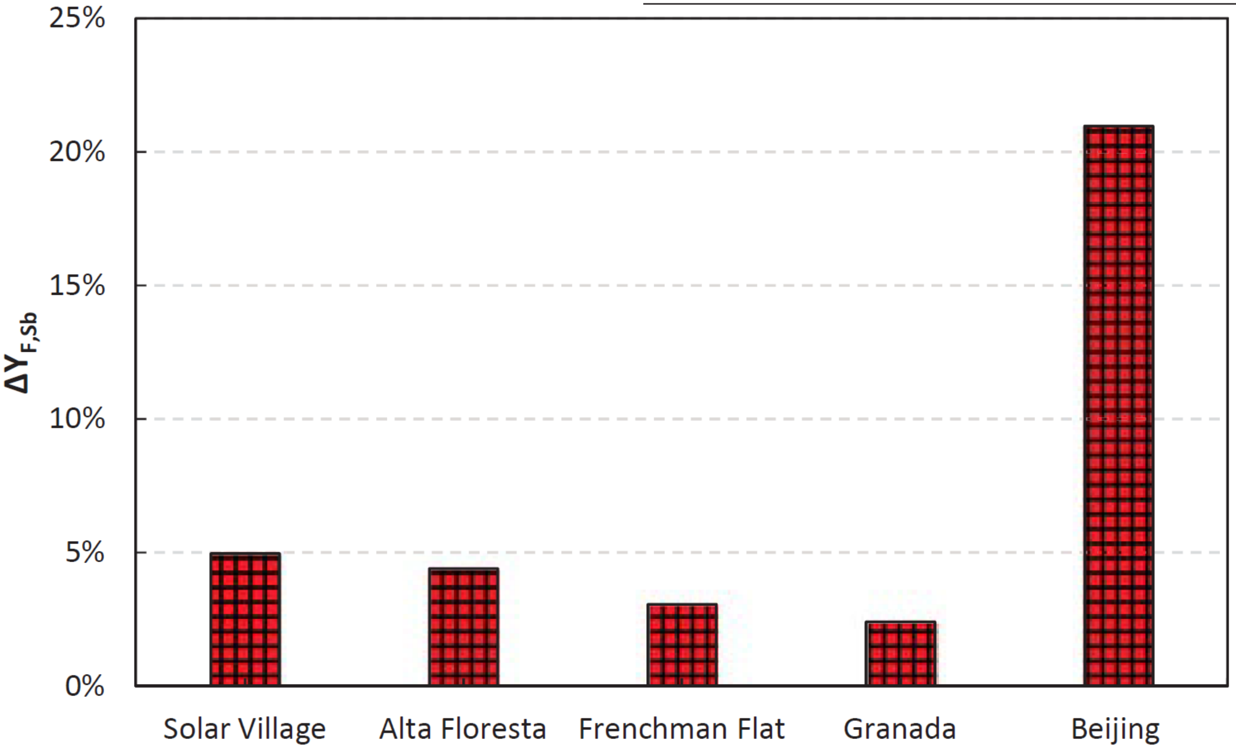
Location	DNI (W/m^2)	T$_{air}$ (°C)	AM	AOD$_{550}$
Solar Village	694	28.8	3.0	0.35
Alta Floresta	608	27.7	2.8	0.28
Frenchman Flat	704	18.4	3.3	0.07
Granada	623	19.1	3.3	0.15
Beijing	390	15.7	3.4	0.82



Energy yield: impact of spectrum

$$\Delta Y_{F,Sb} = \left(\frac{Y_F(DNI) - Y_F(DNI, S_b)}{Y_F(DNI)} \right) \cdot 100$$

Location	DNI (W/m^2)	T_{air} (°C)	AM	AOD_{550}
Solar Village	694	28.8	3.0	0.35
Alta Floresta	608	27.7	2.8	0.28
Frenchman Flat	704	18.4	3.3	0.07
Granada	623	19.1	3.3	0.15
Beijing	390	15.7	3.4	0.82



Cost of electricity

The cost has been estimated using the Levelised Cost of Electricity (LCOE) Method:

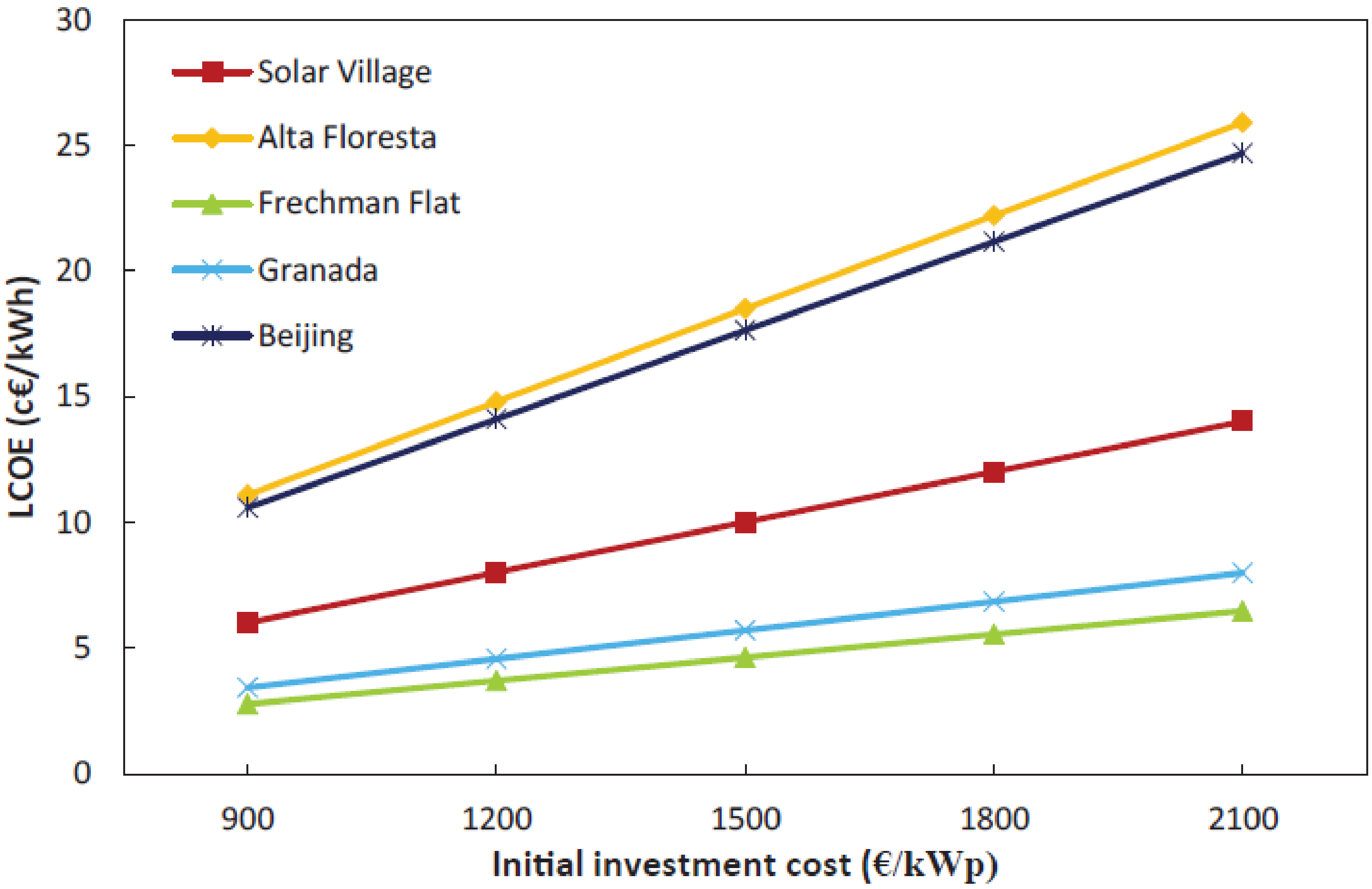
$$LCOE = \frac{LCC}{Y_F \frac{K_d\left(1-K_d^N\right)}{1-K_d}}$$

$$LCC = HCPV_I + PW[HCPV_{OM}(N)] - PW[DEP(N_d)] \cdot T$$

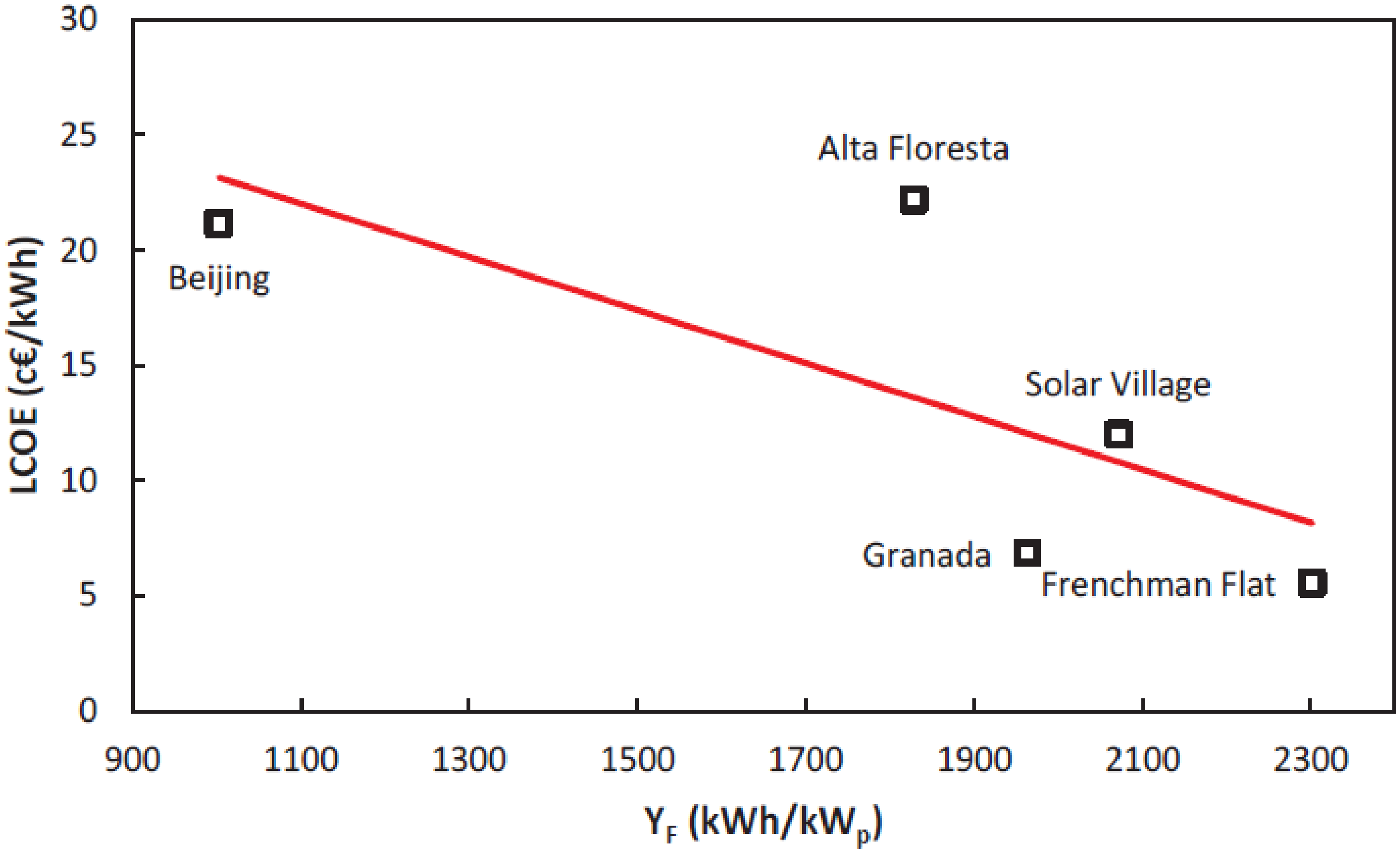
K_d is $(1 - r_d)/(1 + d)$

Factors	Location					Units
	Solar village	Alta floresta	Frenchman Flat	Granada	Beijing	
Y_F	2072	1829	2302	1964	1003	kWh/kWp
$HCPV_I$	900–2100					€/kWp
$HCPV_{AOM}$	2					%
r_d	0.5					%/year
$r_{O\&M}$	Equal to i					%/year
T	20	34	40	30	25	%
i	4.5	5.6	1.6	1.7	2.7	%
d	11.2	21.7	5.5	5.1	9.8	%
i_l	6.9	38.5	3.3	4.3	5.9	%
N_l	20					years
d_s	15.3	18.1	10	7.6	13.4	%
N	30					years

Cost of electricity

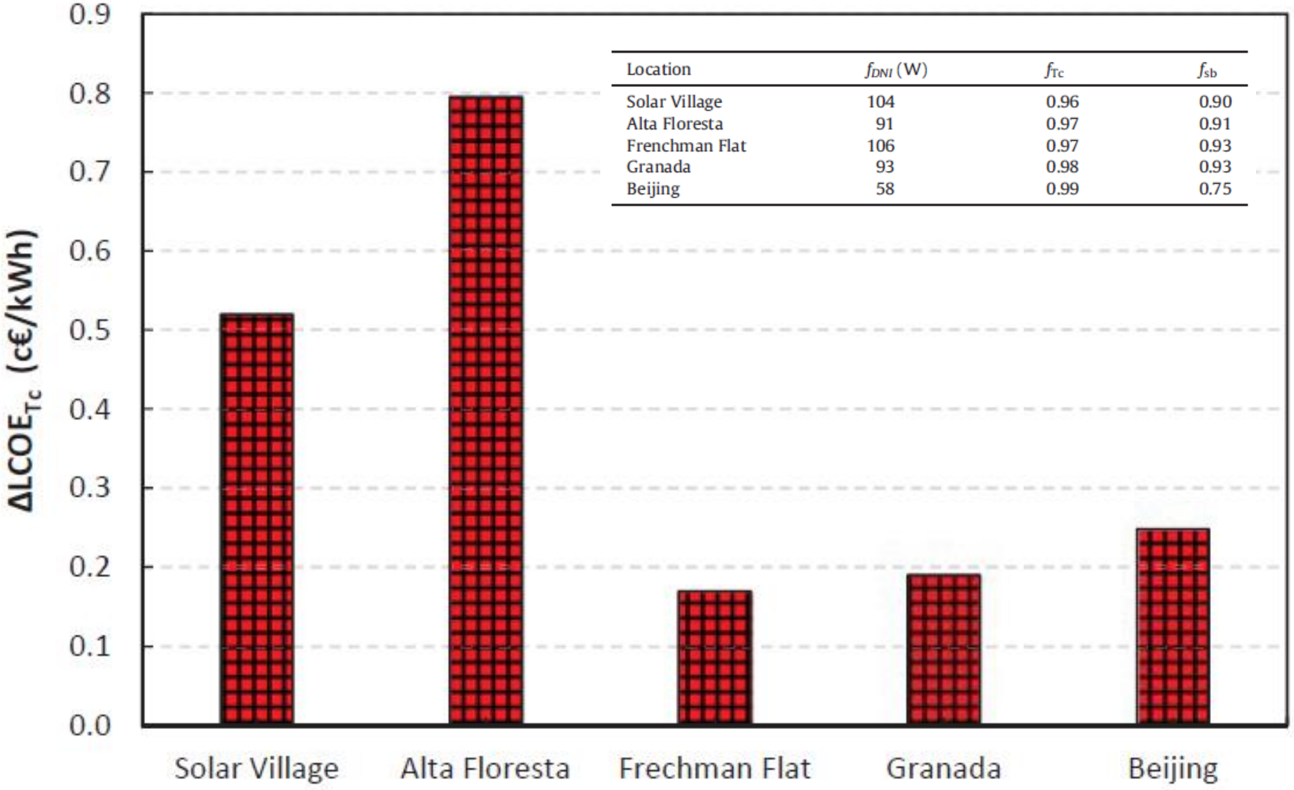


Cost of electricity



Cost of electricity: Impact of cell temperature

$$\Delta LCOE_{Tc} = LCOE(DNI, T_c) - LCOE(DNI)$$

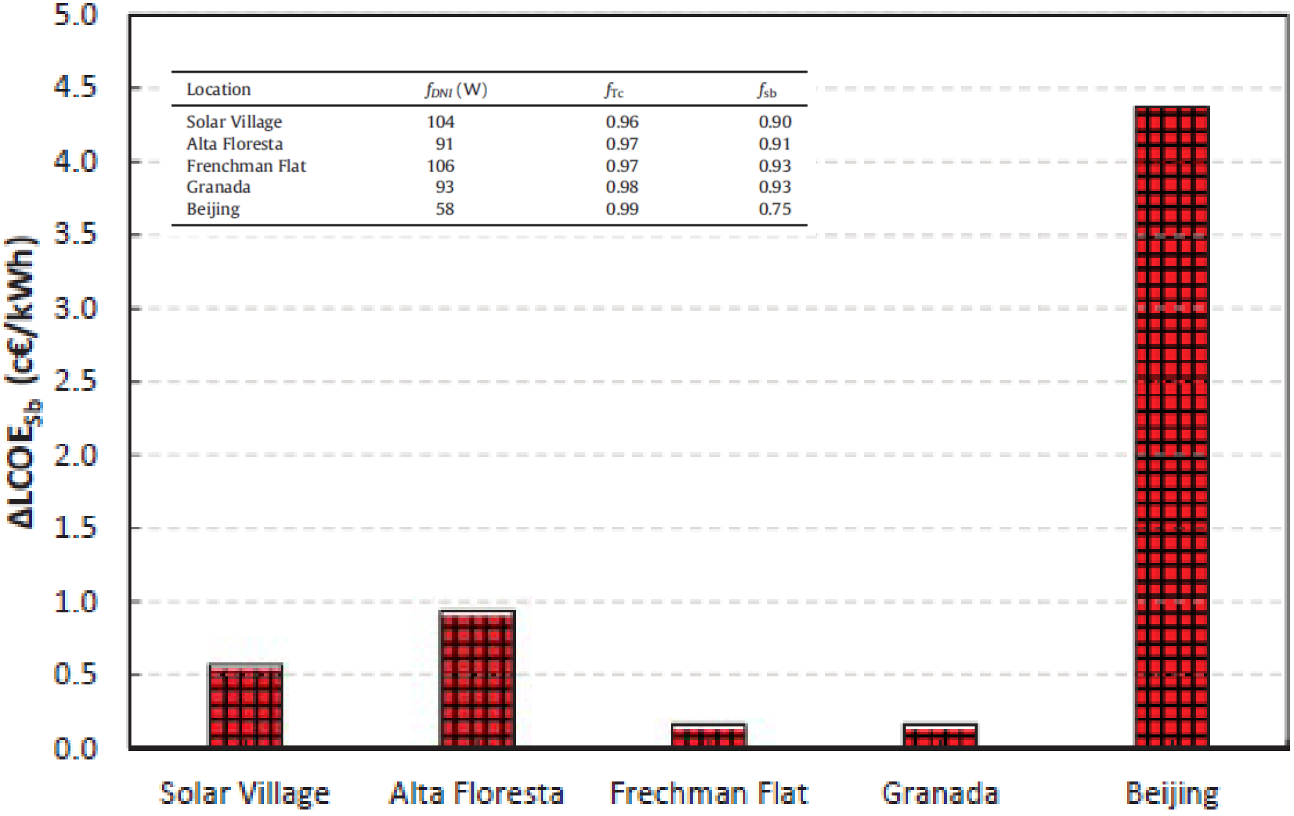


Location	f_{DNI} (W)	f_{Tc}	f_{sb}
Solar Village	104	0.96	0.90
Alta Floresta	91	0.97	0.91
Frenchman Flat	106	0.97	0.93
Granada	93	0.98	0.93
Beijing	58	0.99	0.75

The cost of cell temperature for a 1MWp power plant at Alta Floresta would be around 500k€

Cost of electricity: Impact of spectrum

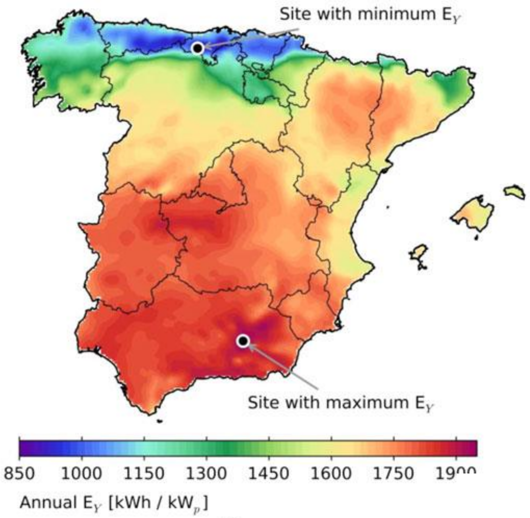
$$\Delta LCOE_{Sb} = LCOE(DNI, S_b) - LCOE(DNI)$$



Location	f_{DNI} (W)	f_{Tc}	f_{sb}
Solar Village	104	0.96	0.90
Alta Floresta	91	0.97	0.91
Frenchman Flat	106	0.97	0.93
Granada	93	0.98	0.93
Beijing	58	0.99	0.75

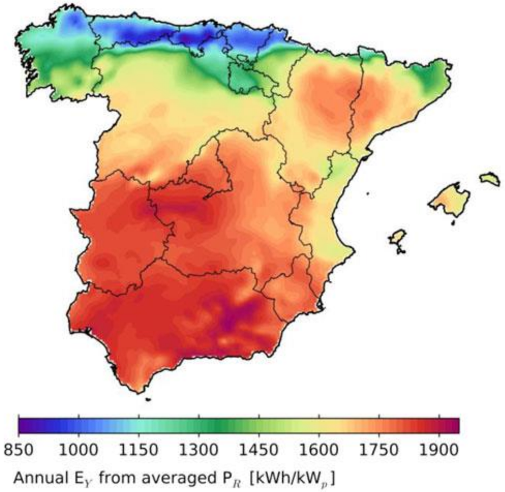
<u>The cost of spectrum for a 1MWp power plant at Beijing would be around 1.5M€</u>

Worldwide assessment: Performance ratio (PR) method



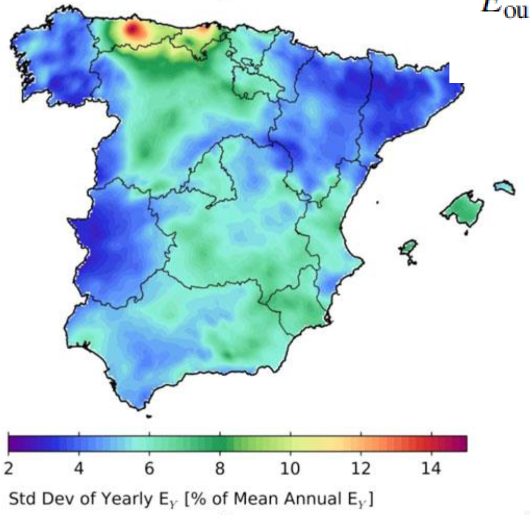
(a)

$$PR = \frac{Y_f}{Y_r} = \frac{\dfrac{E_{output,\tau}}{P_{A,CSTC}}}{\dfrac{DNI_\tau}{DNI_{CSTC}}}$$

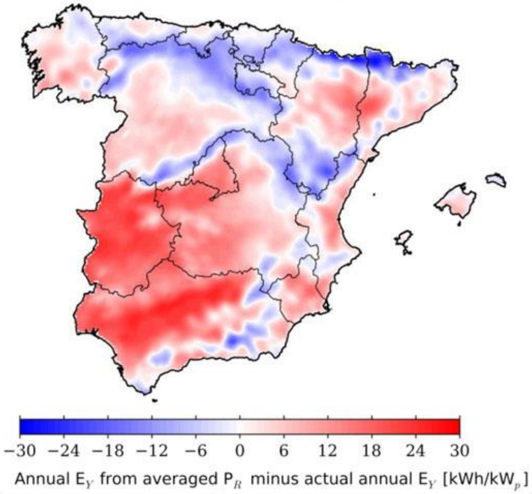


(a)

$$E_{output,annual} = PR \cdot \frac{DNI_{annual}}{DNI_{CSTC}} \cdot P_{A,CSTC}$$

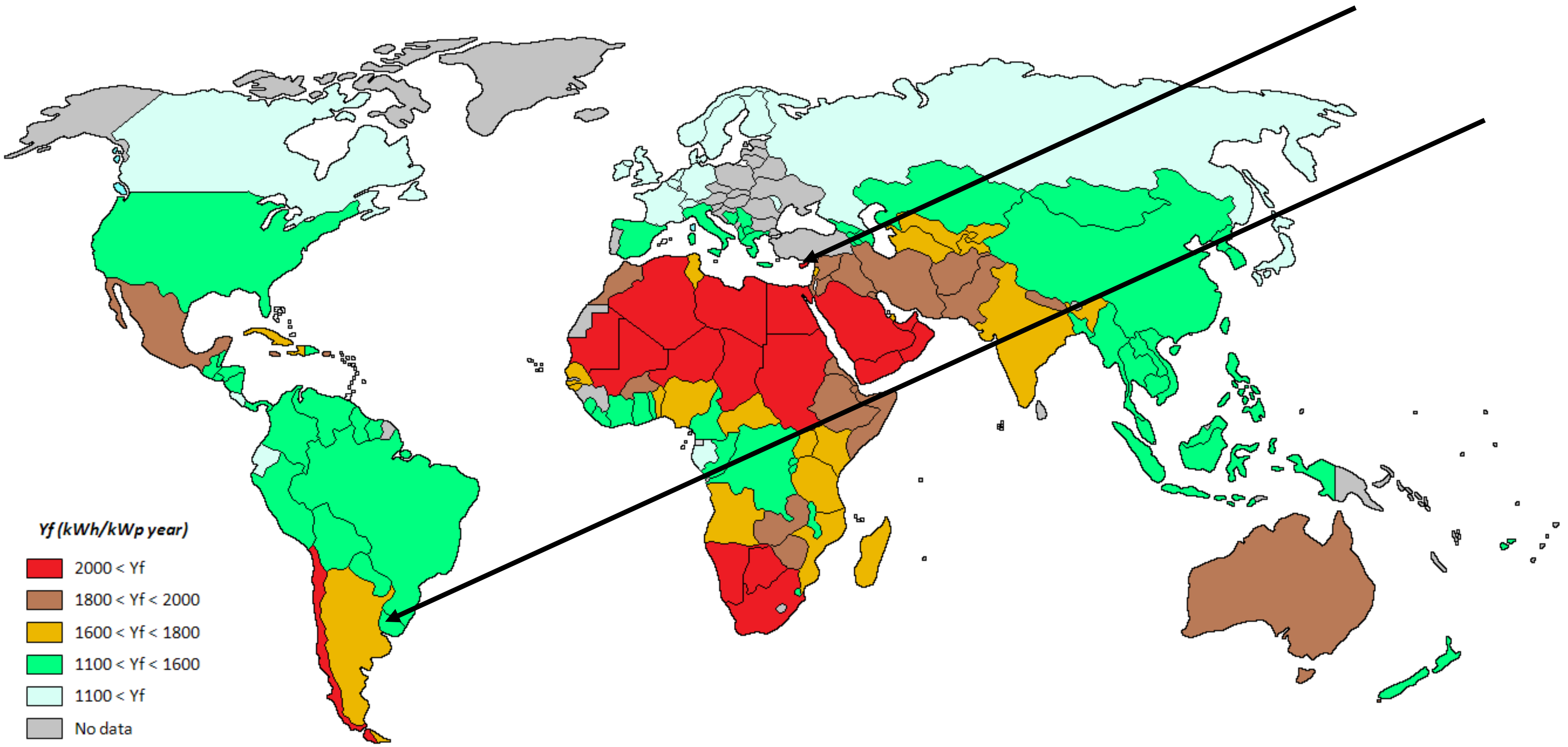


(b)

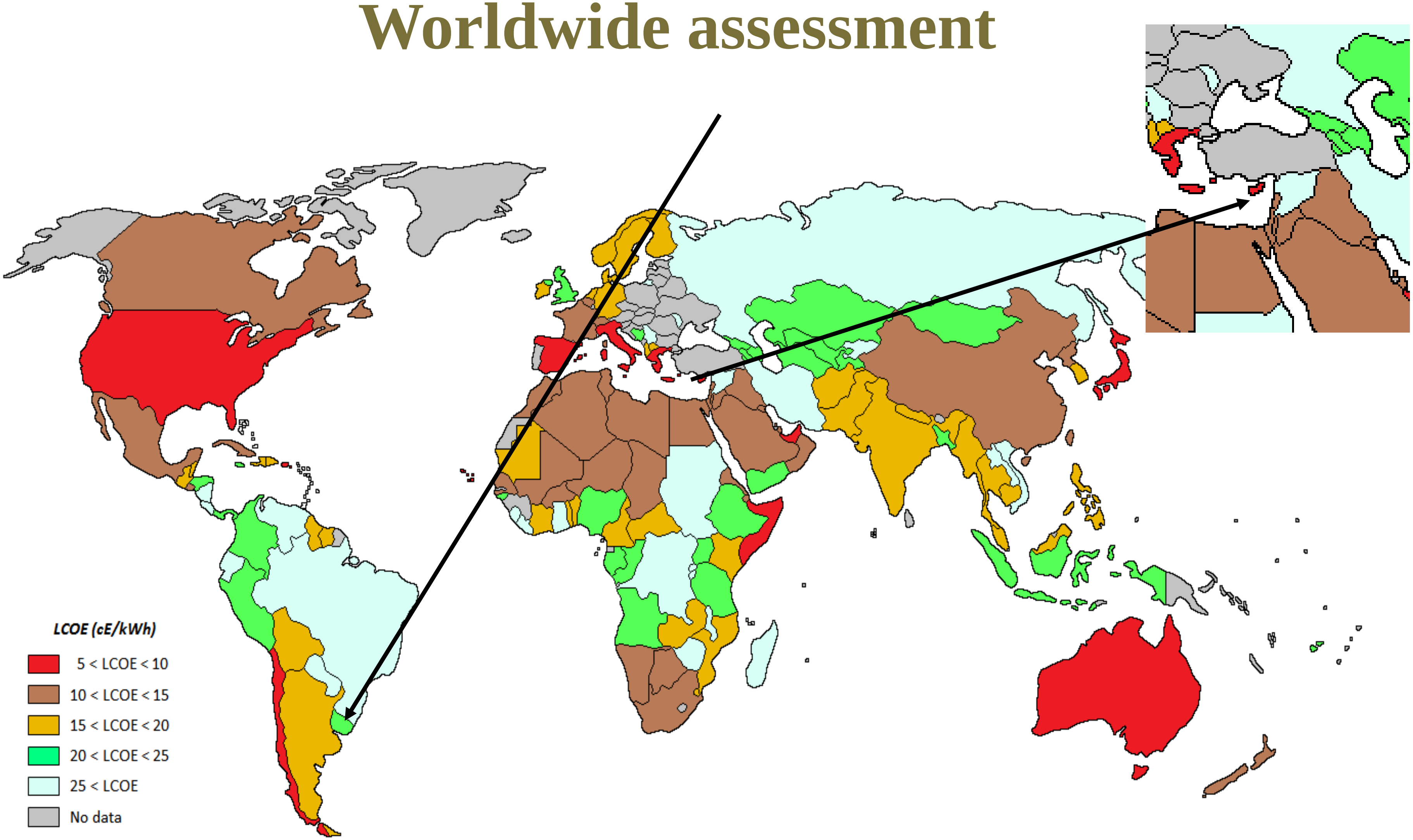


(b)

Worldwide assessment



Worldwide assessment



Conclusions

- The cell temperature and spectral losses range, respectively, from 1.8% to 4.6% and from 2.4% to 5%.

- The LCOE tends to decrease with the Energy Yield with values ranging from 2.7c€/kWh to 24.7c€/kWh.

- A higher Energy Yield does not always lead to a lower LCOE due to the impact of the economic variables at each location.

- CPV systems are expected to produce more than 2000 kWh/kWp at locations with a higher average DNI of around 650 W/m^2.

- The LCOE for the state-of-the-art CPV systems can be below 10c€/kWh in many locations.

FOSS
Research Centre for
Sustainable Energy

Universidad de Jaén

University of Cyprus
PV Technology

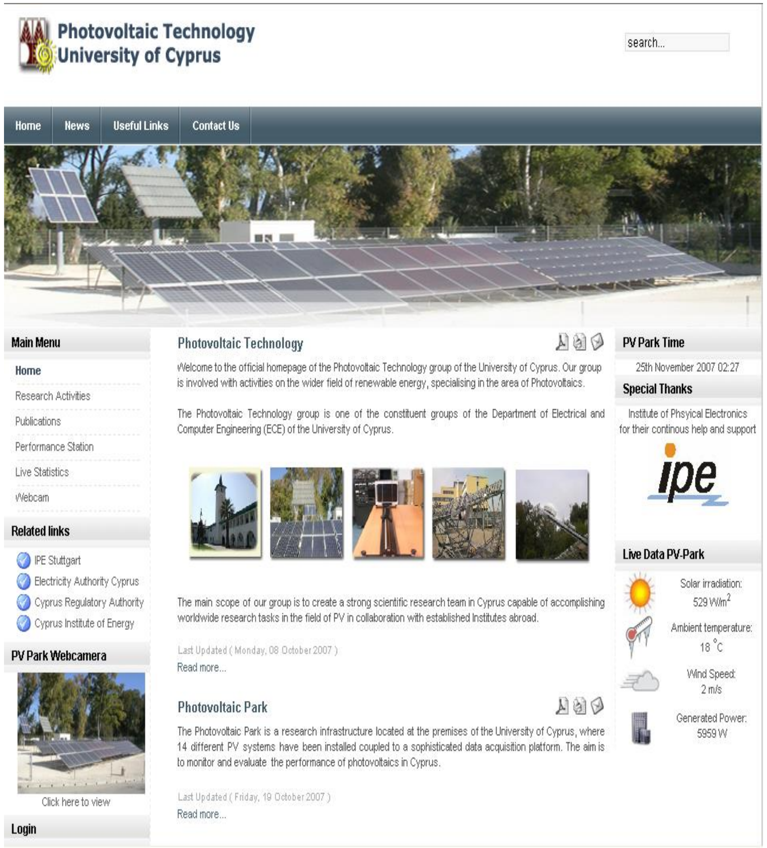
28/05/2018

Thank you for your attention!

Contact information:

Eduardo F. Fernández, PhD
Senior Researcher
Universidad de Jaén
eduardo.fernandez@ujaen.es

Marios Theristis, PhD
Postdoctoral Researcher
University of Cyprus
theristis.marios@ucy.ac.cy



Photovoltaic Technology

Welcome to the official homepage of the Photovoltaic Technology group of the University of Cyprus. Our group is involved with activities on the wider field of renewable energy, specialising in the area of Photovoltaics.

The Photovoltaic Technology group is one of the constituent groups of the Department of Electrical and Computer Engineering (ECE) of the University of Cyprus.

The main scope of our group is to create a strong scientific research team in Cyprus capable of accomplishing worldwide research tasks in the field of PV in collaboration with established Institutes abroad.

Last Updated (Monday, 08 October 2007)
Read more...

Photovoltaic Park

The Photovoltaic Park is a research infrastructure located at the premises of the University of Cyprus, where 14 different PV systems have been installed coupled to a sophisticated data acquisition platform. The aim is to monitor and evaluate the performance of photovoltaics in Cyprus.

Last Updated (Friday, 19 October 2007)
Read more...

25th November 2007 02:27

Institute of Phsyical Electronics for their continous help and support

Solar irradiation: 529 W/m^2
Ambient temperature: 18 °C
Wind Speed: 2 m/s
Generated Power: 5959 W