Concentrated PhotoVoltaics (CPV): a case study

S. Centro
Associated to Centro "E. Fermi", Roma
Dipartimento di Fisica e Astronomia
Università di Padova

CENTRO FERMI
Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

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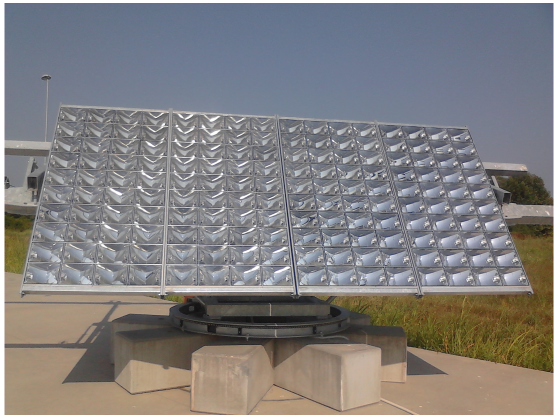

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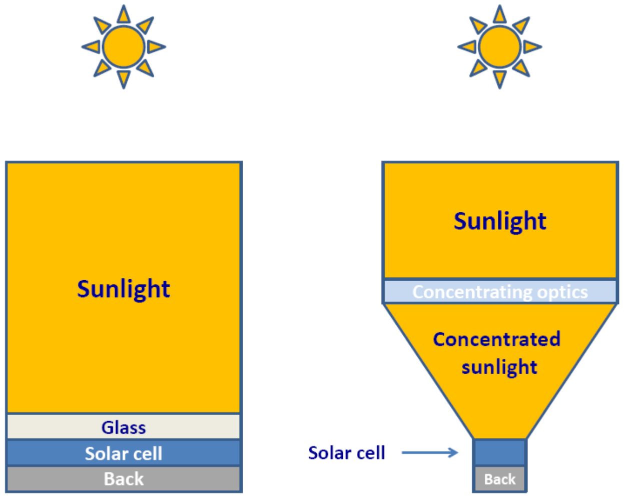
Guang MENG, *INFN technologist, electronics design of testing units*
Alessandro SACCÀ, *Centro Fermi Fellow, optical studies and design*

Introduction

- CPV «in the back of the envelope» is simple: take a small solar cell, some concentrating optics (lens or mirror) and a Sun tracker.
- Why? How?
- «Why»: reducing semiconductor surface we limit cost, moreover we can use higher efficiency solar *not-silicon cells* to have more power per square-meter. [*Silicon cells do not stand concentration!*]
- «How»: we need to control many technologies that must be sound and economically sustainable.



Motivations [1]

1. «Traditional» photovoltaics based on silicon solar cells need **large areas** due to its low (~14%) efficiency. CPV can use higher efficiency cells (triple junction, 3J, see later) that need less area for same installed power.

2. Very high (500 – 1500 X) concentration ratio allows substitution of large areas of semiconductor with **cheaper materials.**

3. **Silicon solar cells** have large efficiency dependence (-0,3 %/K) on temperature: a real problem for this technology.

4. **3J solar cells** have much smaller efficiency dependence (-0,04 %/K) on temperature: **a great advantage with high concentration that implies the necessity for the cells to stand high temperatures.**

Motivations [2]

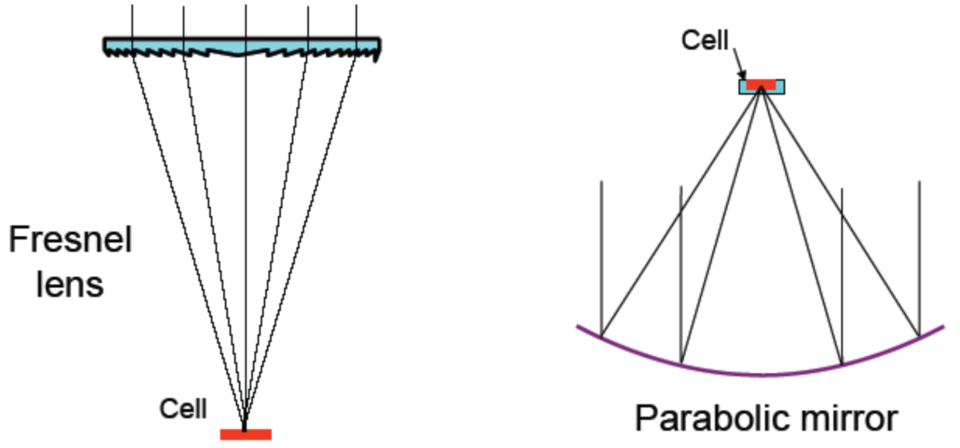
4. Silicon power plants frequently spoil large areas of land.

5. CPV although requires the use of trackers (an extra cost) allows dual land usage.

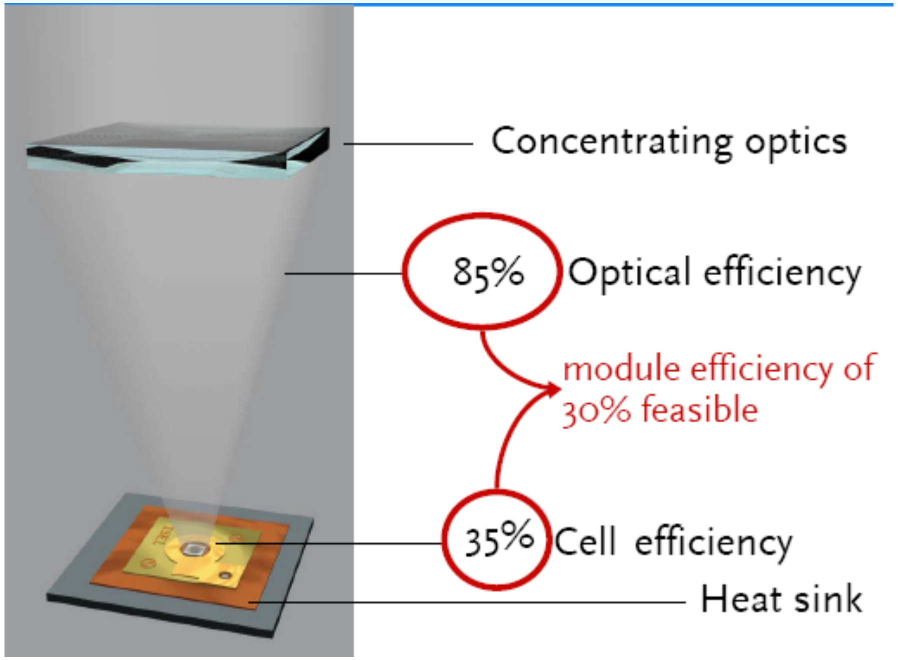
6. For CPV is possible the use of cheap materials treated with mature and reliable technologies, as molded polycarbonate, aluminum, and non-optical glass.

How it works

- Mirrors or lenses concentrate solar light on very small (<1cm^2) solar cells



Conventional simple designs

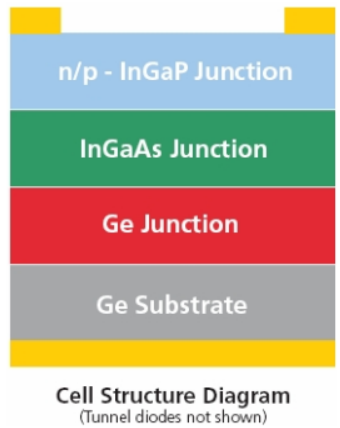


The use of high efficiency triple junction (3J) solar cells compensates for the optical losses

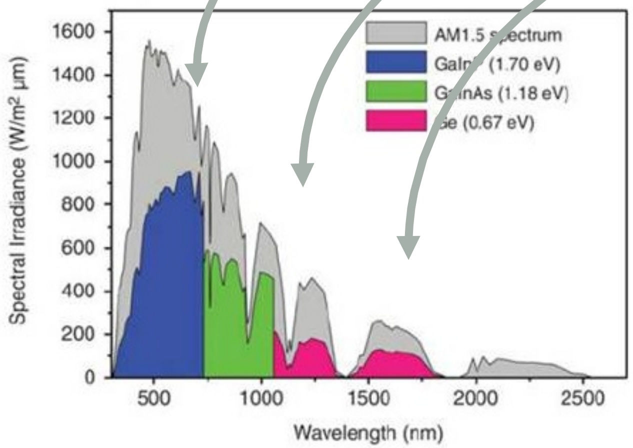
Triple junction Solar Cells [1]

They were developed for space application with huge investments. Their cost is now affordable for civil applications.

Use of three junctions enlarges the spectral sensitivity, that means higher efficiency. Moreover the efficiency has lower **temperature dependence: -0.04%/K.**



A series of three junctions, each sensitive to a different spectral range

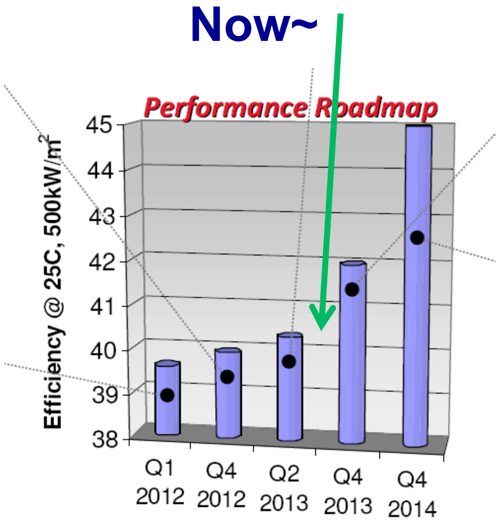


Almost the whole solar spectrum converted

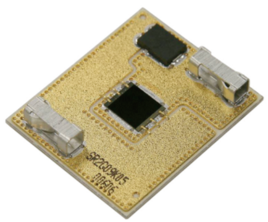
AMI1.5 Spectrum is published by the American Society for Testing and Materials and is intended as average condition in most US states for surfaces at 37° and it is conventionally accepted as the terrestrial solar spectrum that takes into account the atmosphere effects.

Triple junction Solar Cells [2]

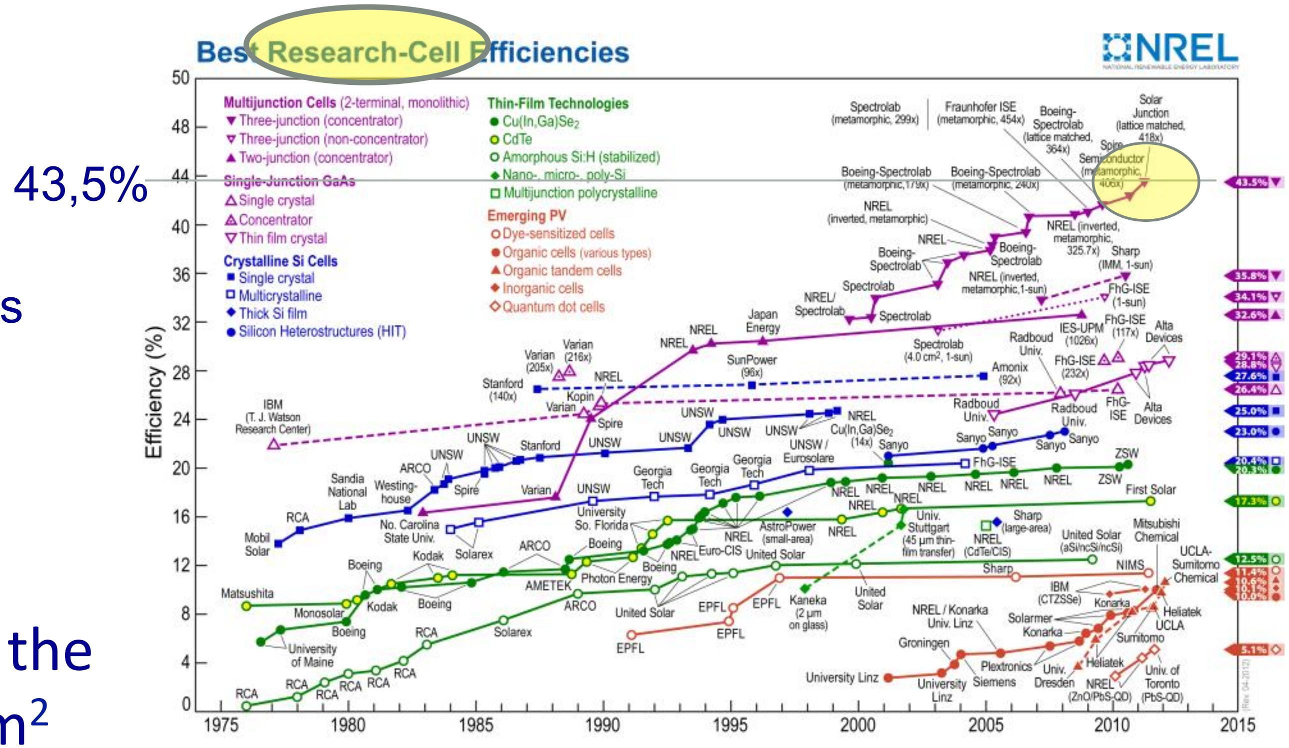
- Efficiency of R&D prototype 3J cells: 43.5 %
- Efficiency of commercially available 3J cells: 40 %



Road map commercial cells

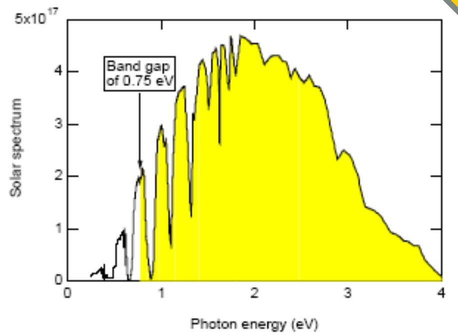


Typical dimensions of the solar cell: 5.5x5.5 mm^2

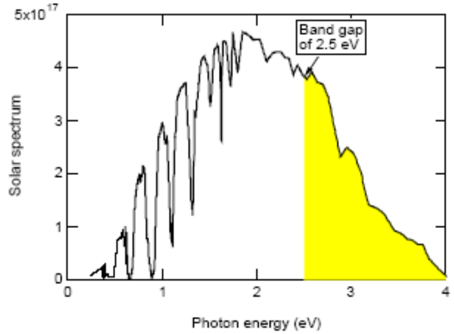


Why multijunction solar cells?

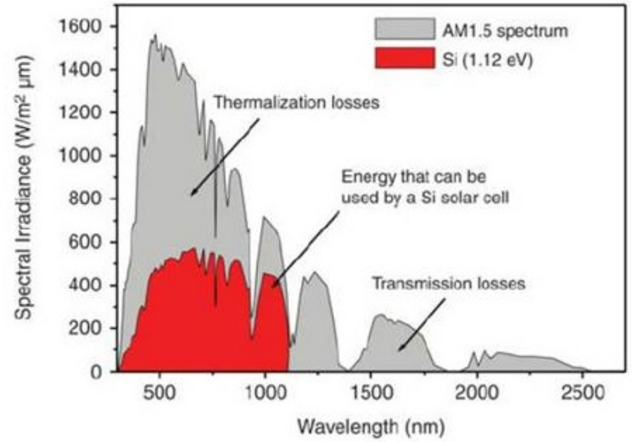
The portion of solar spectrum converted depends on energy gap:



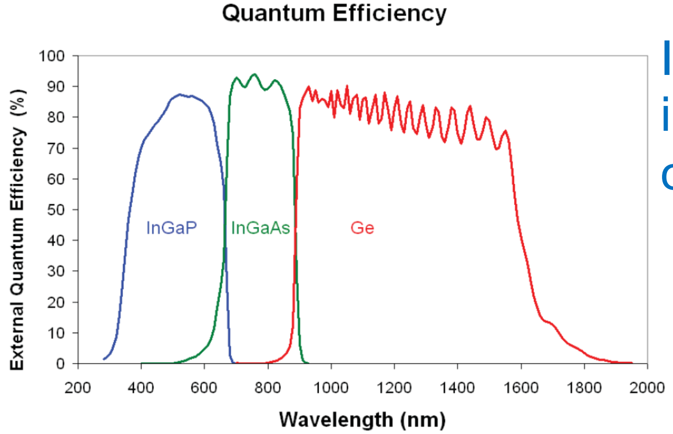
High current, but low voltage
Excess energy lost to heat



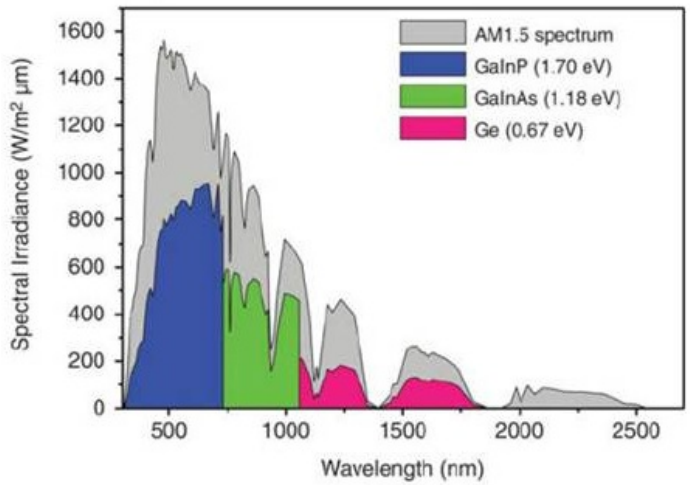
High voltage, but low current
Subbandgap light is lost



Silicon



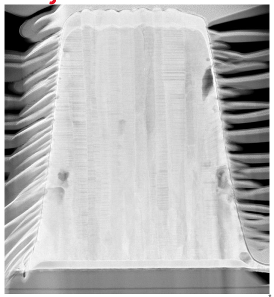
Increase efficiency increasing number of junctions:



Emcore's Solar Cell Performance Roadmap

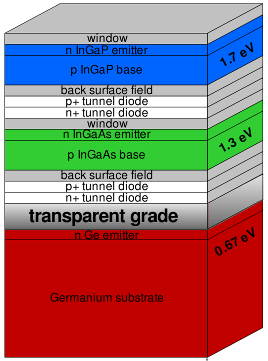
emcore
empower with light™

High Performance Metallization



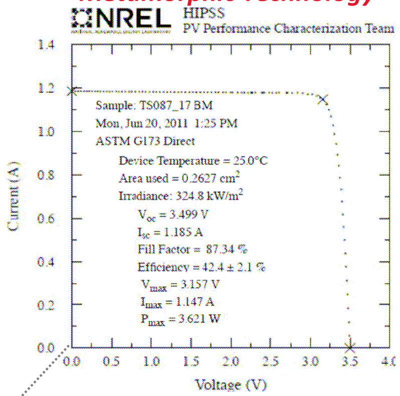
- ✓ *Prototype process demonstrated*
- ✓ *0.5 point gain achieved*

Upright Metamorphic Technology



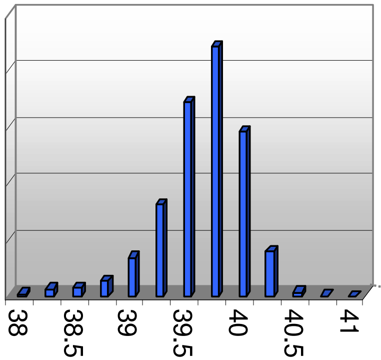
- ✓ *Leverages existing manuf. technology*
- ✓ *0.5 point anticipated gain*

Triple Junction Inverted Metamorphic Technology



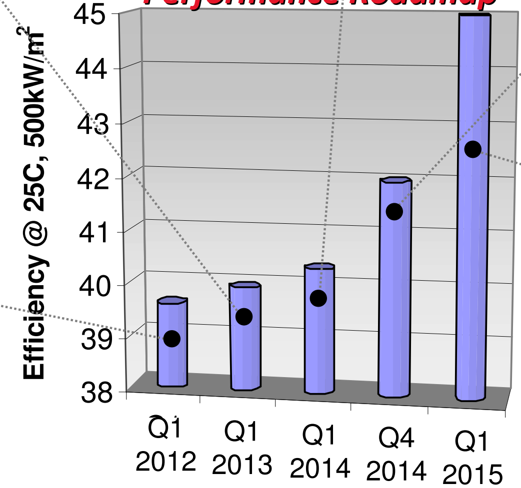
- ✓ *42.4% demonstrated and verified*
- ✓ *Ideal combination of 3 bandgaps*
- ✓ *Prototypes on sun*

CTJ-3G Baseline Technology

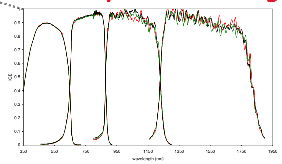


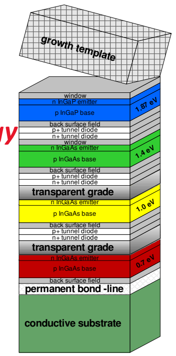
- ✓ *Sampled by customers since Q4 2011*
- ✓ *Qualification underway*

Performance Roadmap



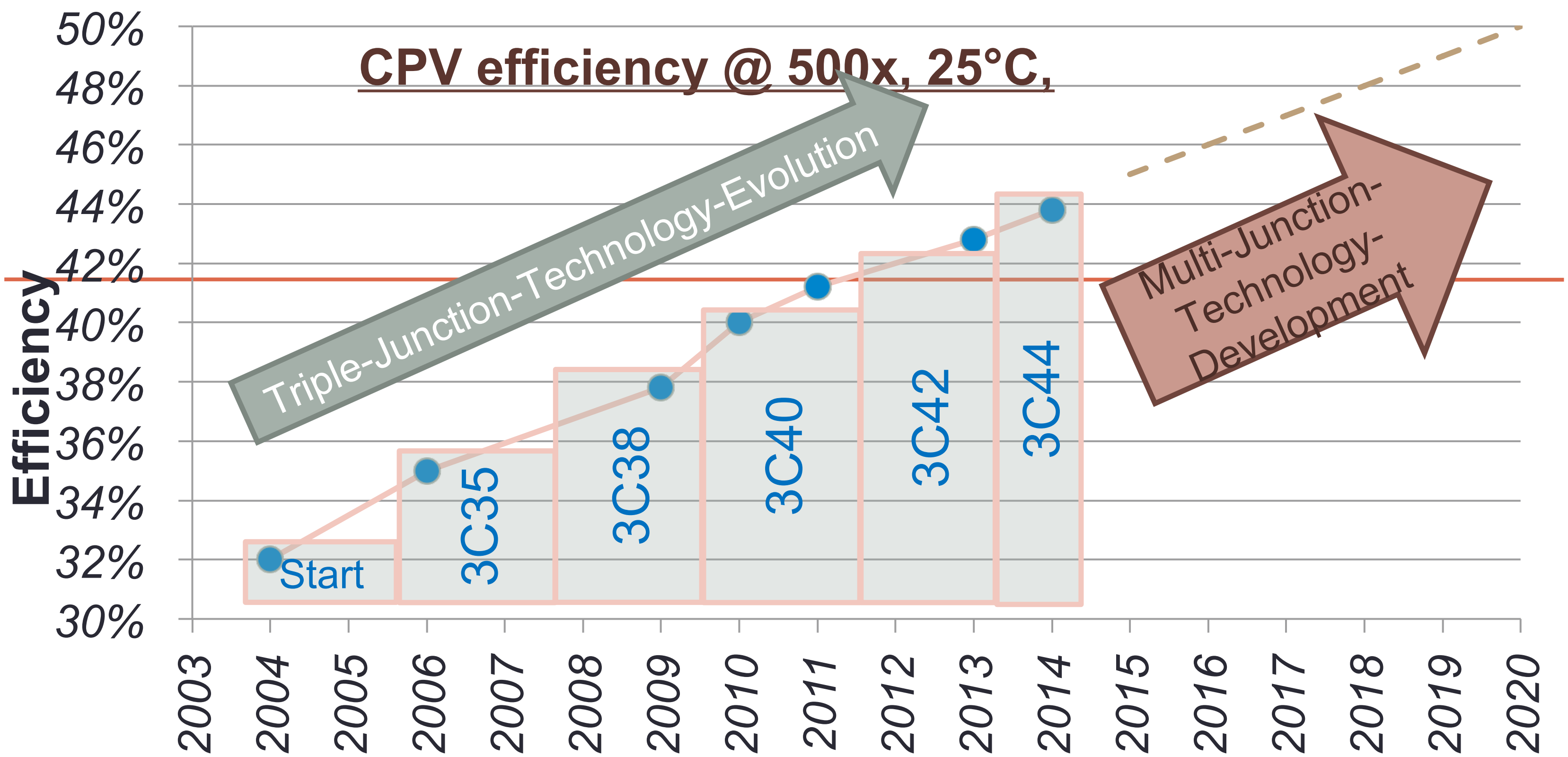
Quad Junction Inverted Metamorphic Technology





- ✓ *>45% efficiency potential*
- ✓ *Ideal combination of 4 bandgaps*
- ✓ *12% relative gain over today's cells*

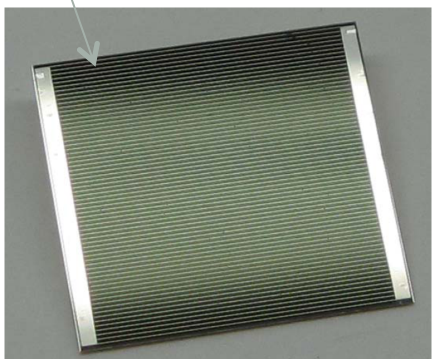
Road map


CPV efficiency @ 500x, 25°C,
Efficiency
50%
48%
46%
44%
42%
40%
38%
36%
34%
32%
30%
Triple-Junction-Technology-Evolution
Multi-Junction-Technology-Development
Start
3C35
3C38
3C40
3C42
3C44
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

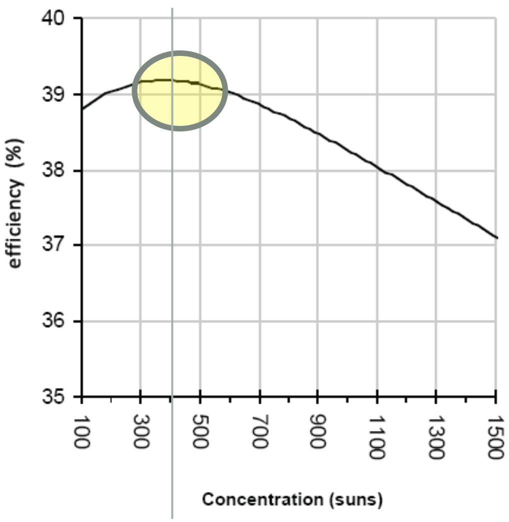
Efficiency dependence on concentration

The efficiency maximum can be optimized for different concentrations basically changing the fingers (contacts) cross-section.

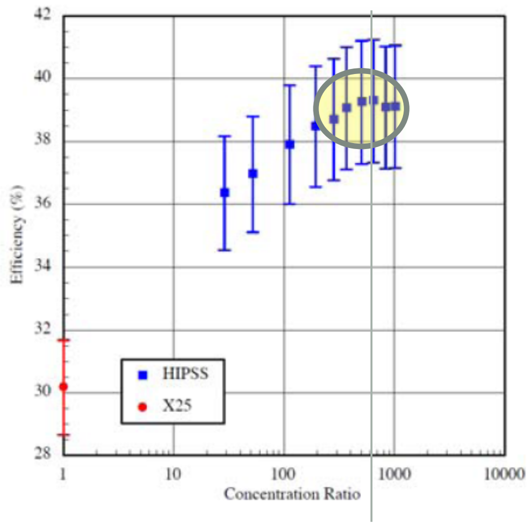
Fingers account for 5-7% of cell area: it is a good idea to keep them thin, but thinner fingers means higher ohmic resistance.
The compromise defines efficiency versus concentration.



Efficiency vs. Concentration Characteristics



Efficiency vs. Concentration Characteristics

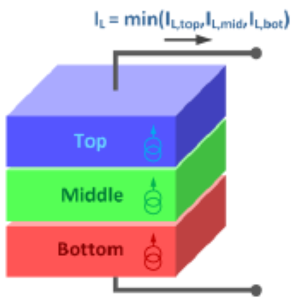


by Emcore

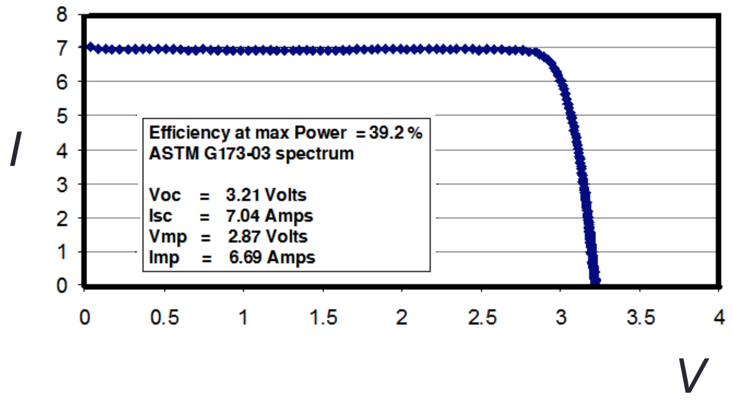
Current mismatch

- The three sub-cells (top, middle, bottom) are connected in series: this means that the sub-cell producing less current will limit the current generated by the whole cell.

- Current mismatch can be due to:
  - Spectrum mismatch: the spectrum of the light illuminating the cell is not the one for which the cell was optimized;
  - Chromatic aberration: different cell receive different power profiles;



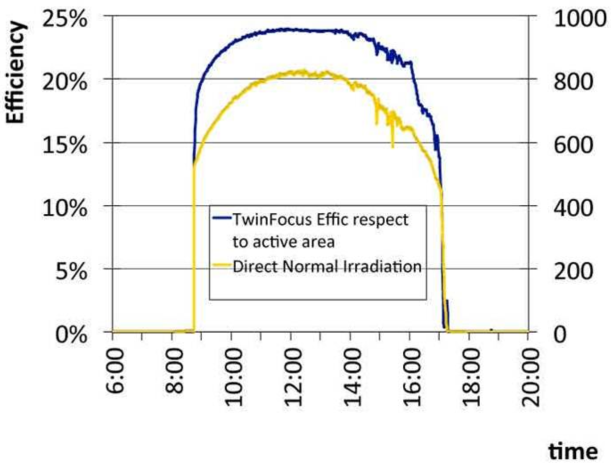
Typical Current-Voltage characteristics



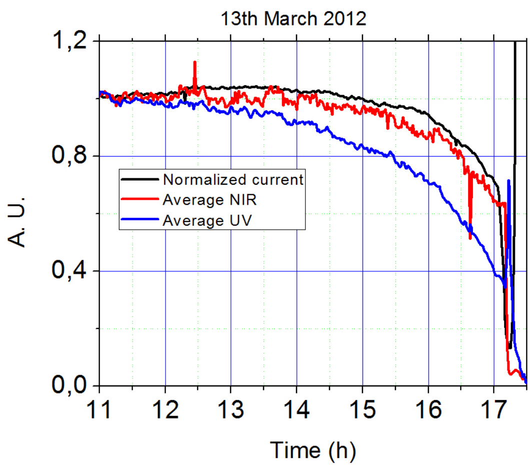
Dependence on solar spectrum

Current mismatch implies different power measurement in different regions and also at different time during the day.

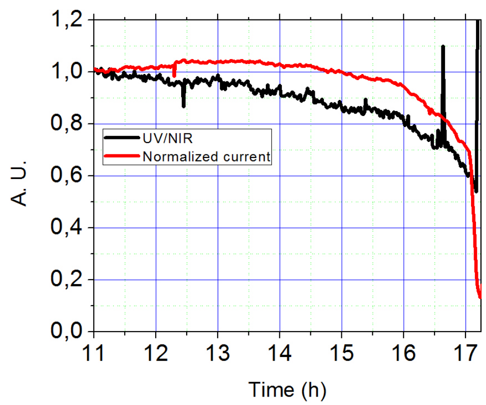
Example of a measurements performed in Northern Italy, with wind/temperature almost constant. One would expect a constant efficiency. Yet, efficiency is lower at beginning and end of the day. Relative amount of higher energy photons is lower in the second part of the afternoon, this explains why efficiency is not constant.



Measured efficiency of a CPV module on a sunny day in march: the efficiency is not constant



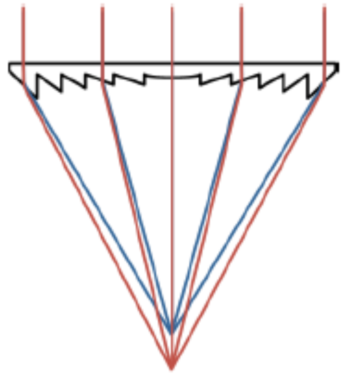
Amount of UV decreases faster than Near InfraRed NIR)



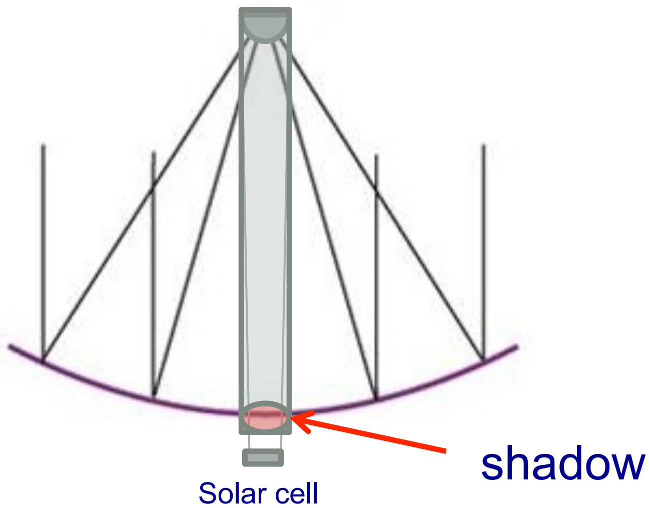
Normalized current (current/ DNI) decreases as amount of UV decreases relative to NIR

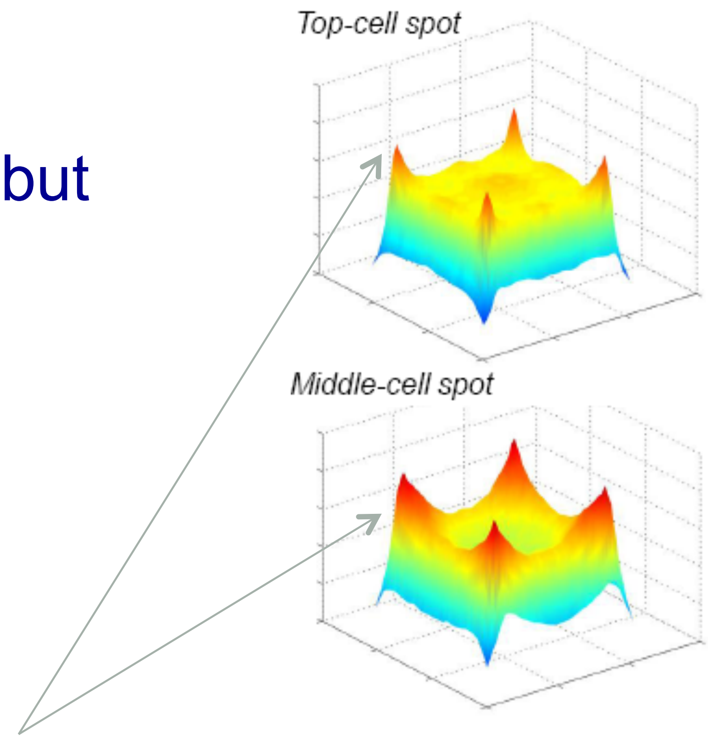
DNI: Direct Normal Irradiation

Differencies Lenses/mirrors



- Lens: no shadow cast but chromatic aberration
  - Chromatic aberration causes current mismatch
- Mirrors: in general shadow cast but no chromatic aberration

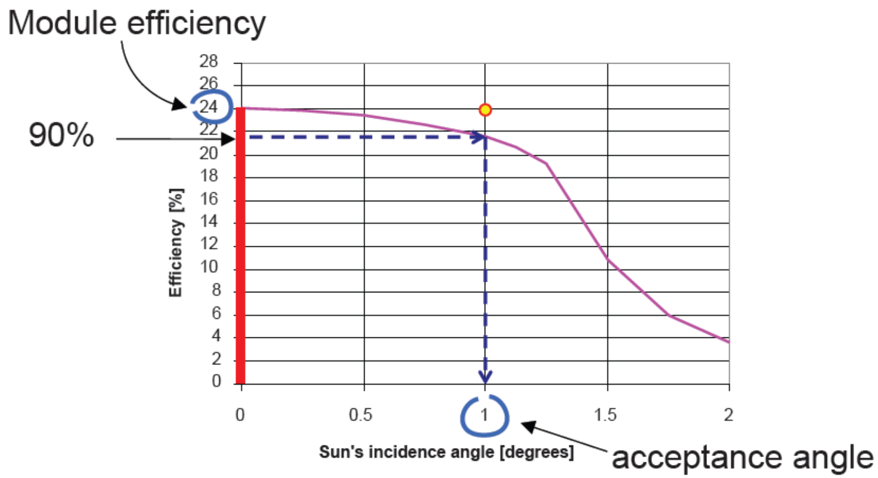




Mismatch: the top cell has a higher local concentration at boundaries than the middle cell. The excess current may not be harvested.

Acceptance angle

Definition: the limit angle to have at least 90% of efficiency recorded with perfect alignment

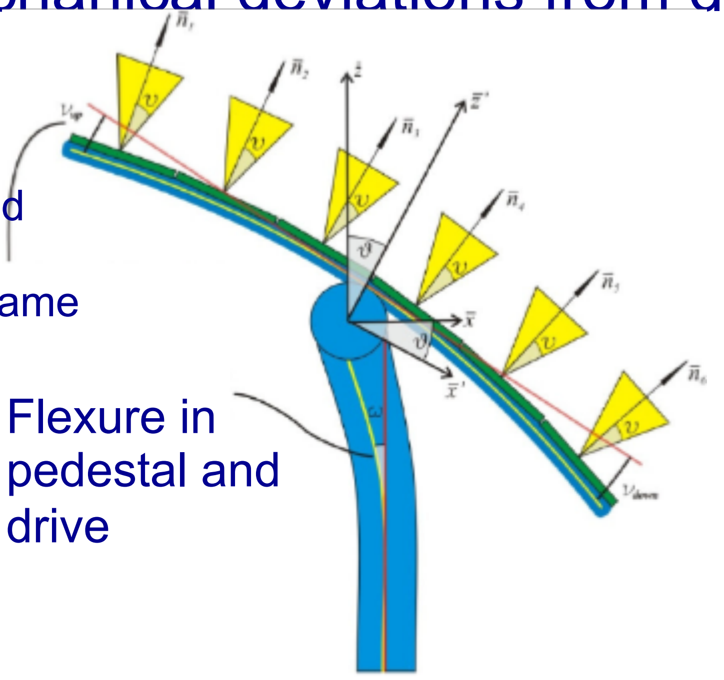


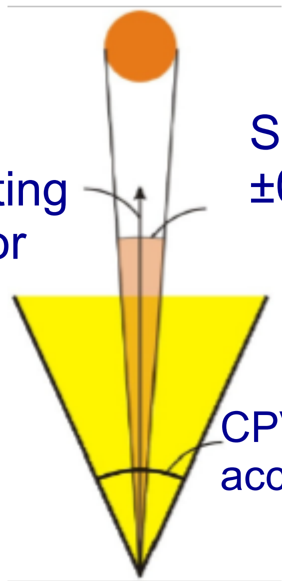
Why the acceptance angle is important:

High acceptance angle allows less stiff tracker, lower precision in optics, lower precision in assembly, lower precision in field, with a total cost reduction.

Optics: requirements

- A very uniform irradiance profile on cells is necessary to achieve high efficiency
- A wide acceptance angle is necessary to compensate mechanical deviations from design: optical mismatch





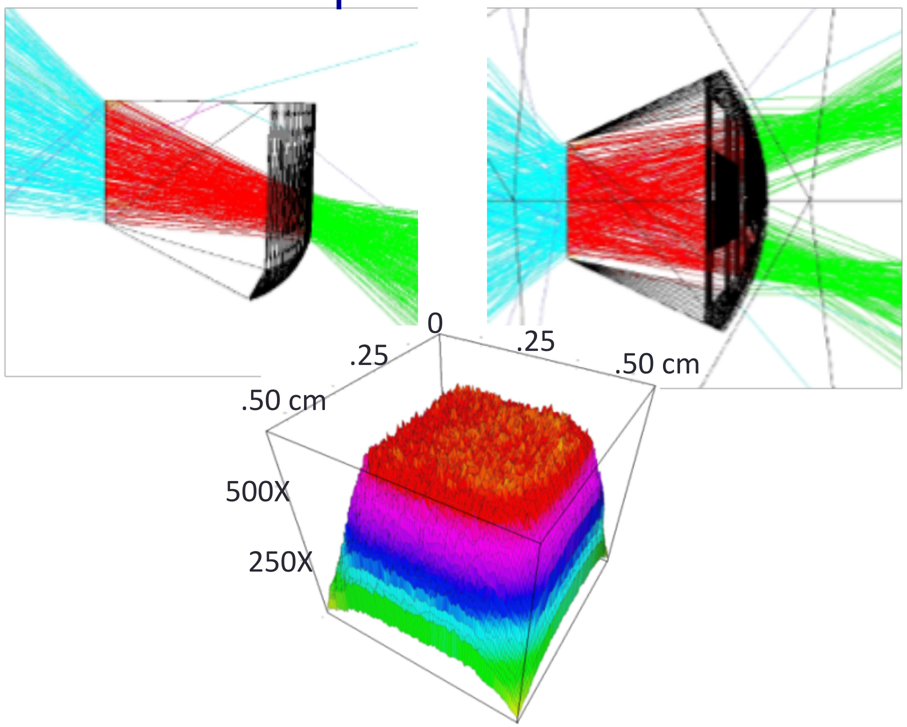
TwinFocus®: an innovative CPV solution

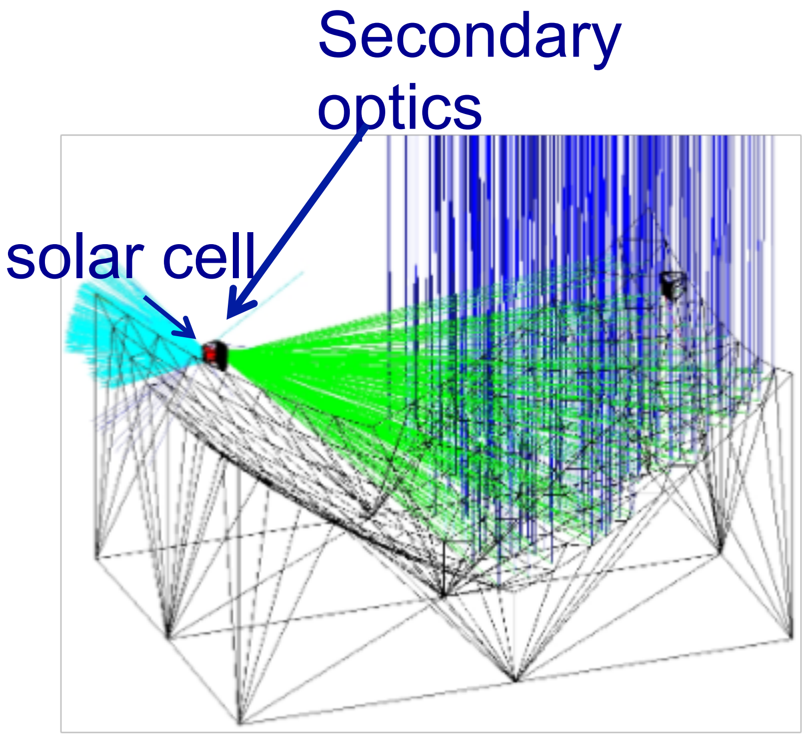
in cooperation with industries

Optics: example of simulation

- Design using ray tracing software
- Optimization using merit functions
- Large acceptance angle/uniformity

Pictures show optical simulations



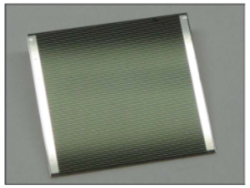


The very uniform irradiation profile on cell

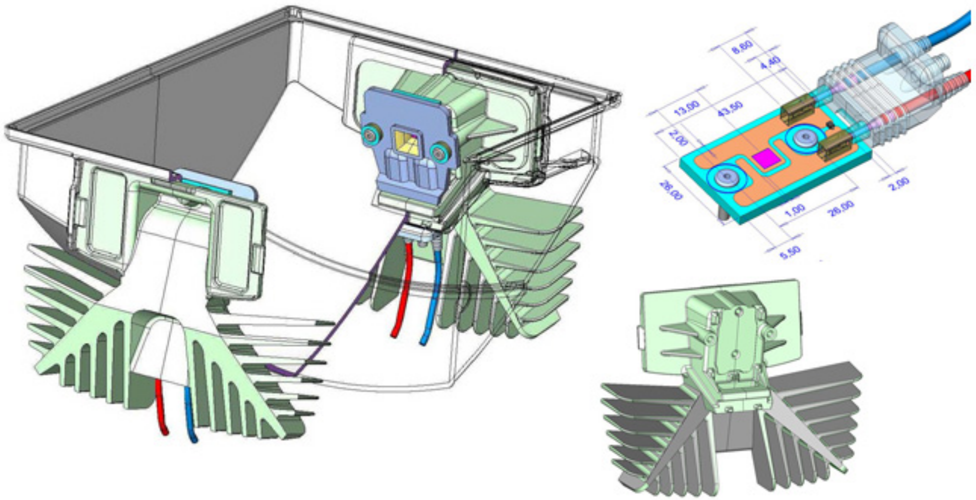
TwinFocus®

- ✓ Area of mirrors: 22x18x14 cm^3
- ✓ Area cell 0.3 cm^2 (x2)
- ✓ Geometrical concentration: ~580 X

- 3J solar cells
- Parabolic concentrators
- Injection molding of thermoplastic materials
- Sun tracker



Four test stations (~5 kWp each) in operation since 2012 demonstrate the validity of the project



Efficiency depends on temperature

- Voltage is linear with temperature, but: Power = Voltage x Current.
- Temperature coefficient and voltage depend on concentration (X) and on temperature;

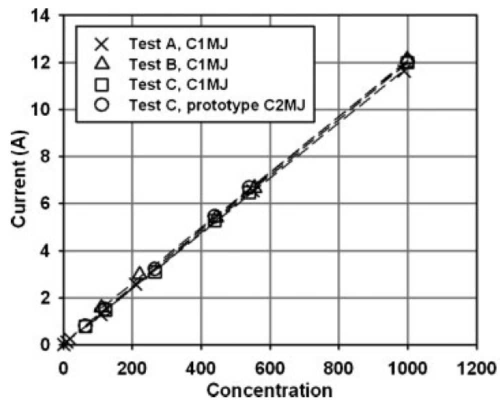
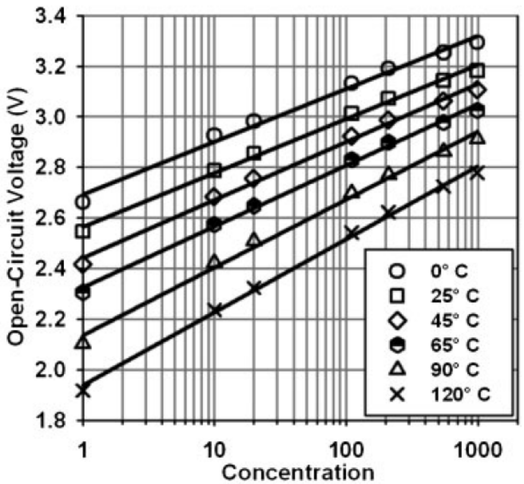


Figure 3. Short-circuit current at 25°C. The three-junction cells are linear with respect to single-junction calibration standards



These plots may be used to evaluate the temperature of the cells: a diode is in fact a thermometer. Useful during validation of design.

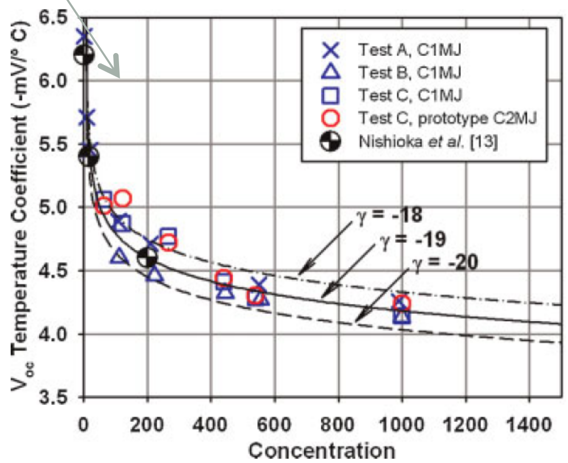


Figure 6. Open-circuit voltage temperature coefficients for multijunction cells. (The voltage decreases with increasing temperature.) Theoretical values using the simple diode assumption for several values of γ are shown

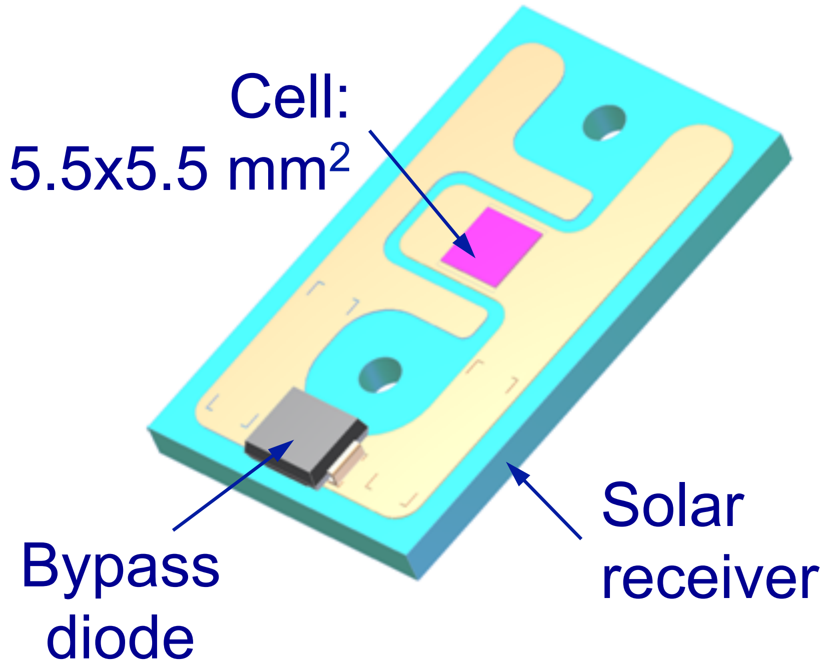
Prog. Photovolt: Res. Appl. 2008; **16**:503–508

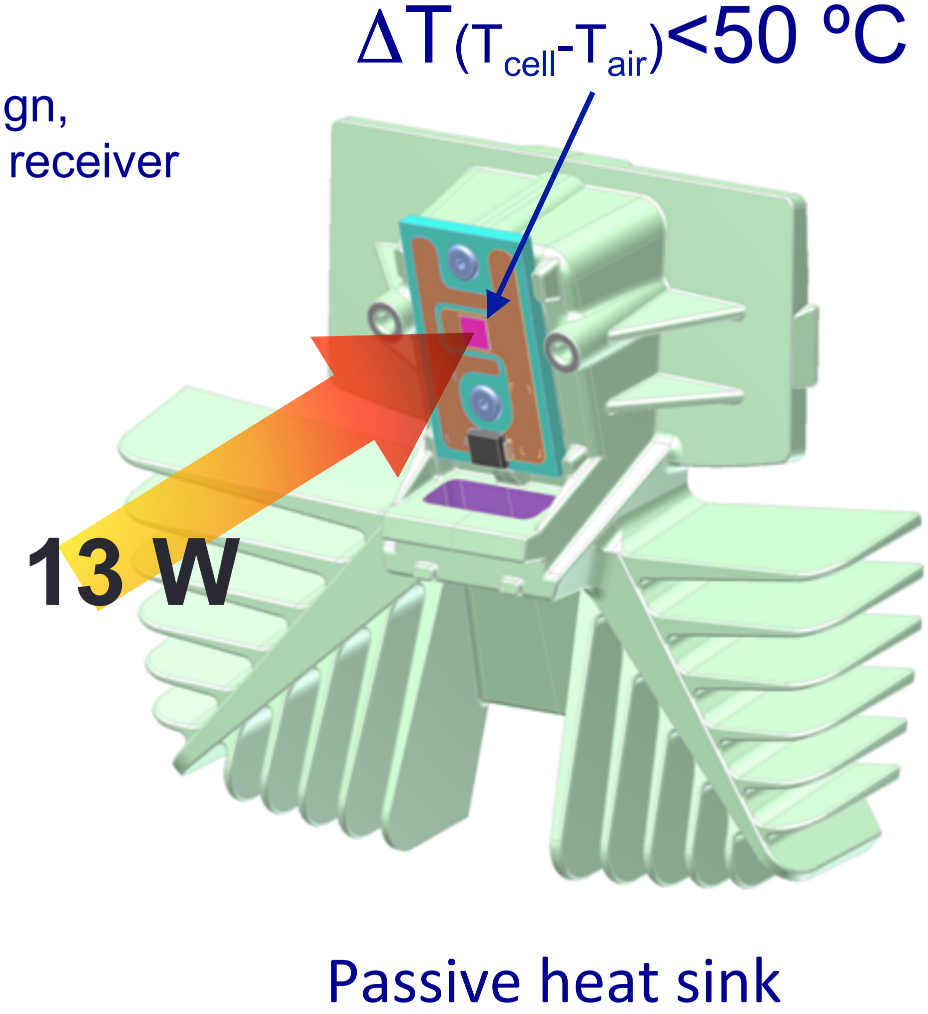
$$V_{oc} = \frac{nkT}{q\log(e)} \cdot \log(X) + V_{oc,X=1}$$

Heat sinking

It is always necessary an in-house design, simulation and measurements on solar receiver

Thermal budget at 600 Suns:
13W on a *5.5x5.5* mm^2, 3J cell.

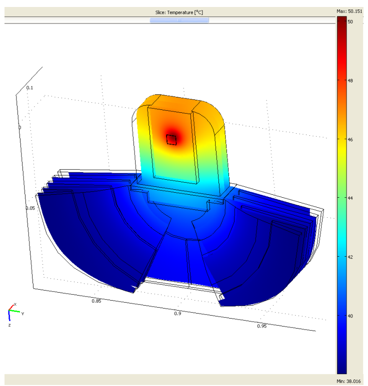


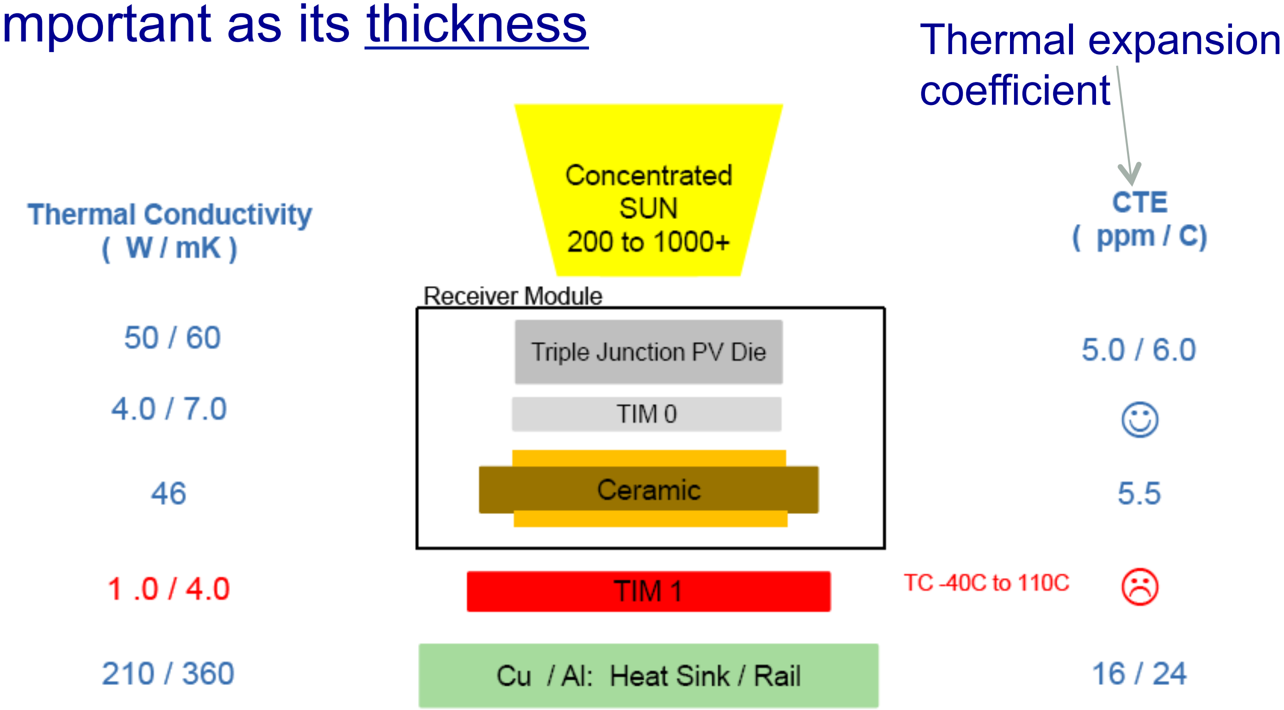


Thermal interface

Typical CPV receiver, thermal view.
Many materials come into play.

Thermal Conductivity (TC) Watt/(meter * Kelvin)
of material is just as important as its thickness



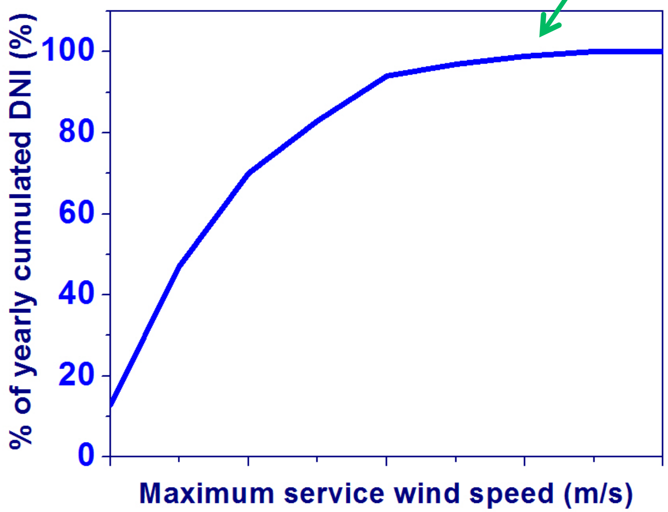


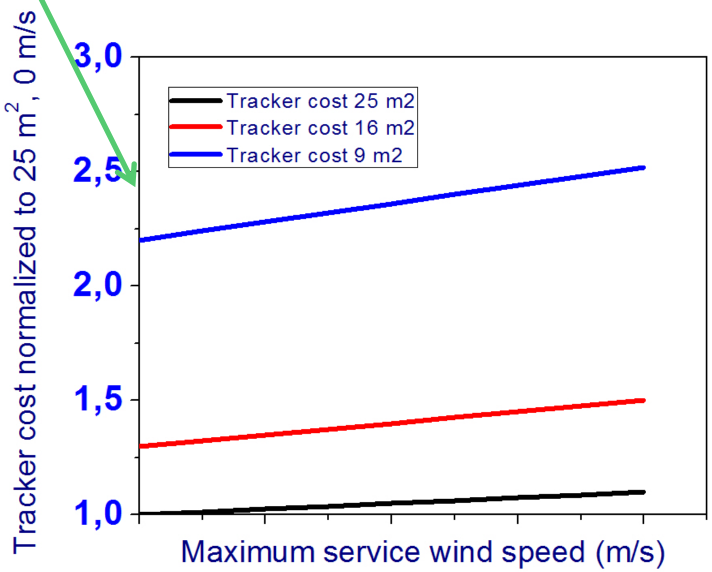
TIM: Thermal Interface Material

Tracking issues

- Mounting: cost!
- Angular range
- Max wind speed

Increasing maximum wind speed at which
the tracker follows the Sun, the energy yield of the system increases.
But it has to be engineered according to the wind profile of the site:
why to have an extremely performant tracker (that costs) if there is not that much wind?

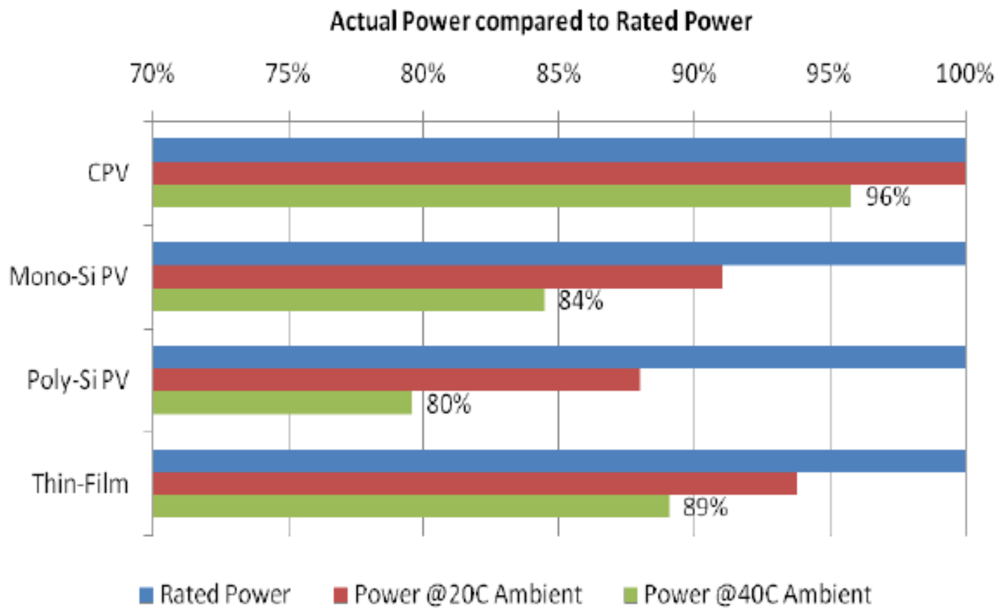




Rated power/real power

Compared to silicon the rated power is more similar to the real power, because rated power for silicon is usually measured in the lab (STC): cells temperature 25°C at conditions that will never met in real world.

Since 3J solar cells have less dependency on temperature: rated power measured in field is less dependent on air temperature.



Best performance at high temperature: best for MENA region and high DNI in general

TwinFocus®

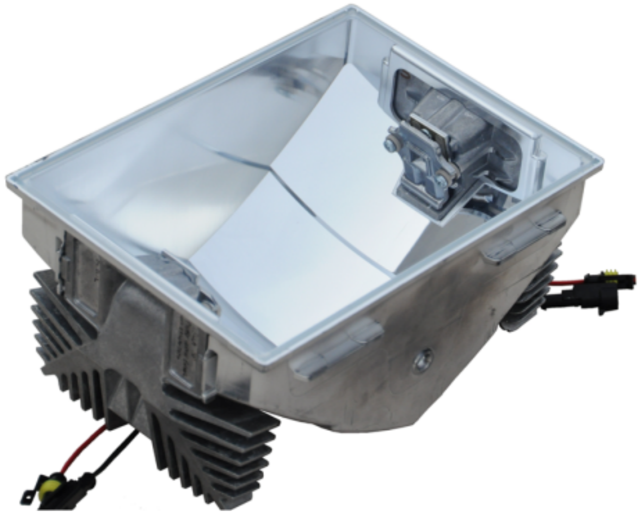
Limitations

The general layout of the TwinFocus (head-light)$^{-1}$ prototypes had shown two major limitations:

-unit size too small, that requires a **complex mechanical support structure;**

-consequently also the **wiring of the units is bulky;**

-moreover cells cast **shadow** onto mirrors.



TwinFocus ®

Evolution

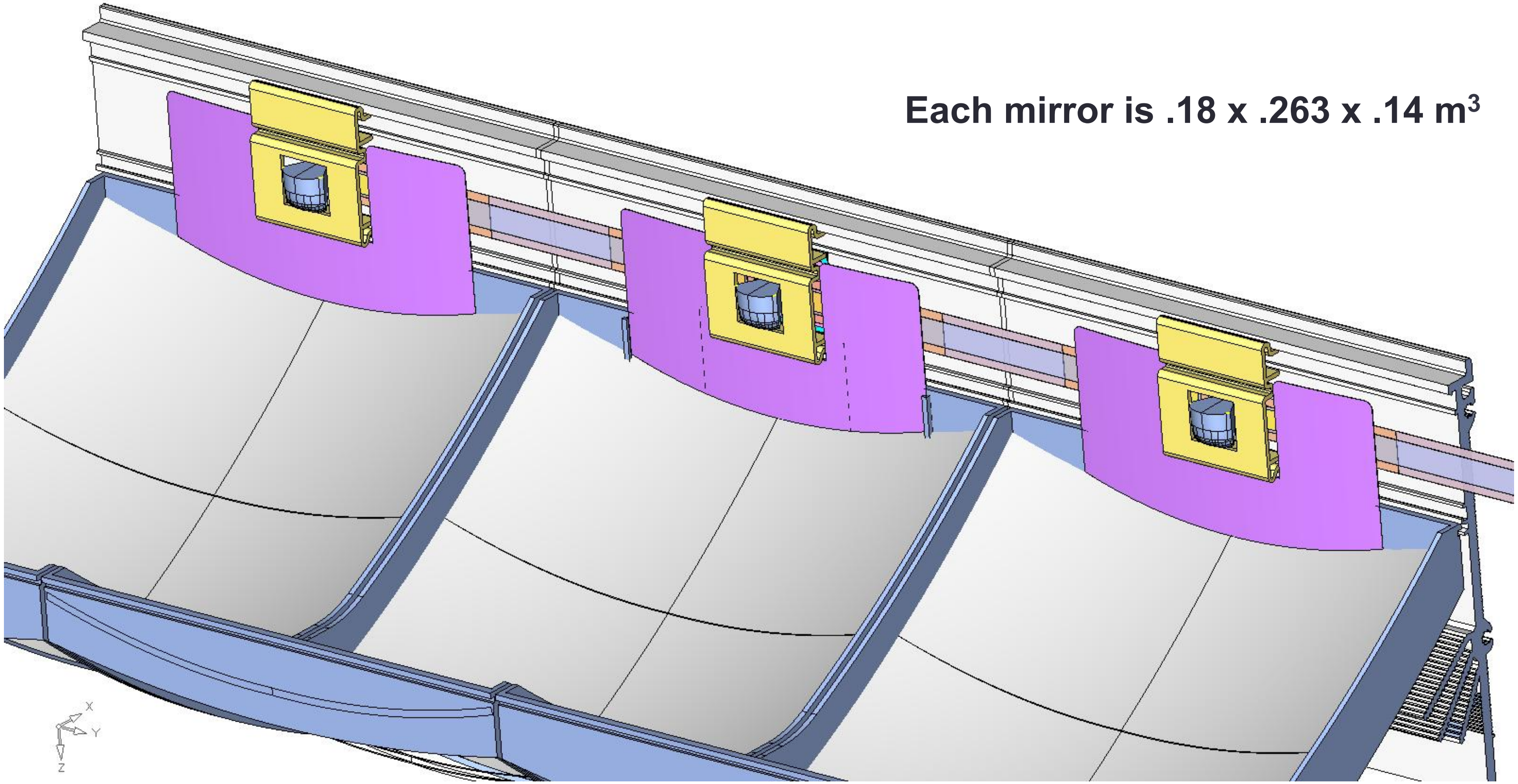
-Make larger units **integrating mechanical supports and heat sinks**;

-Increase **concentration avoiding shadows** onto mirrors;

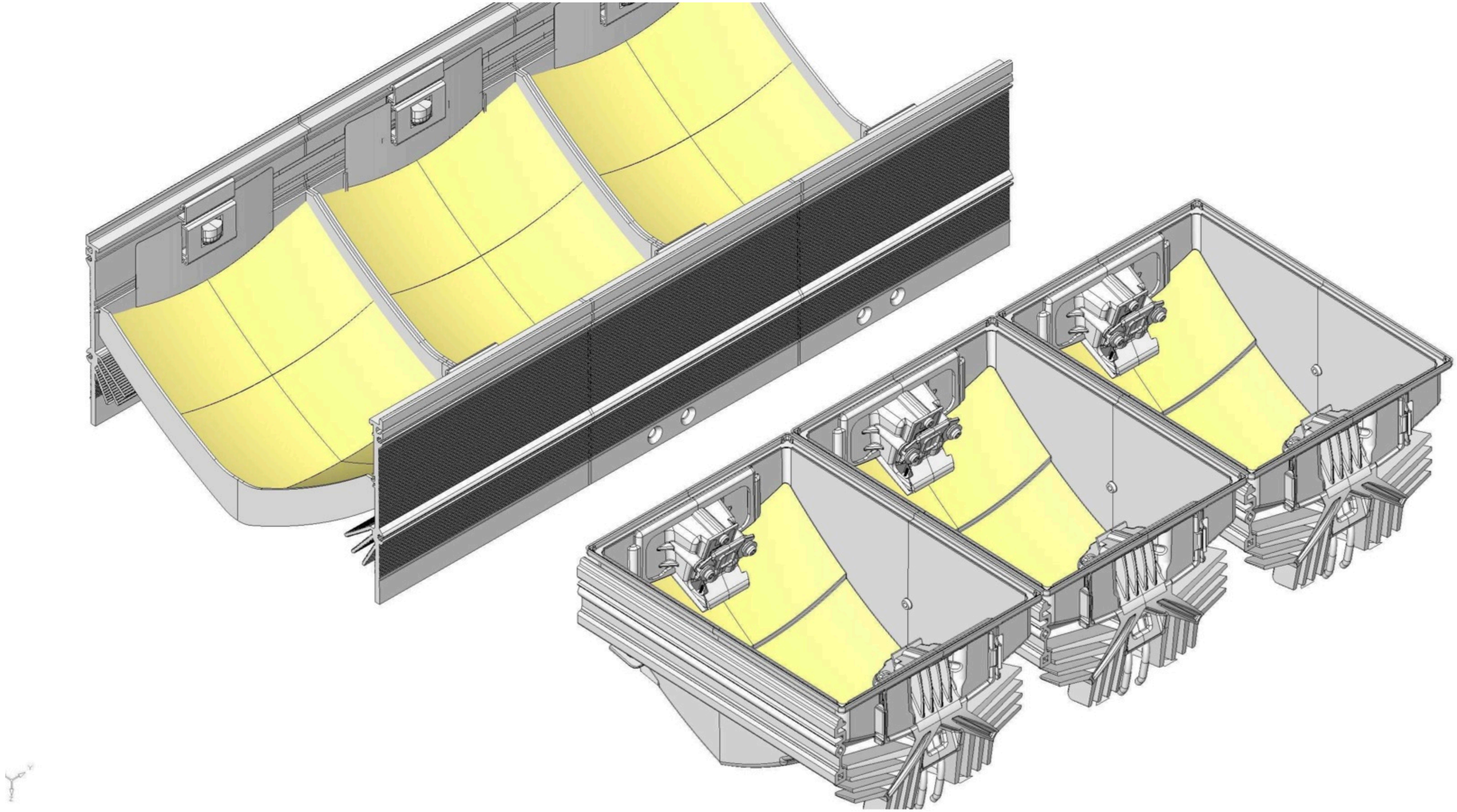
-Simplify the **electrical connections**;

-Use of **dovetail techniques** to fix components avoiding use of screws.

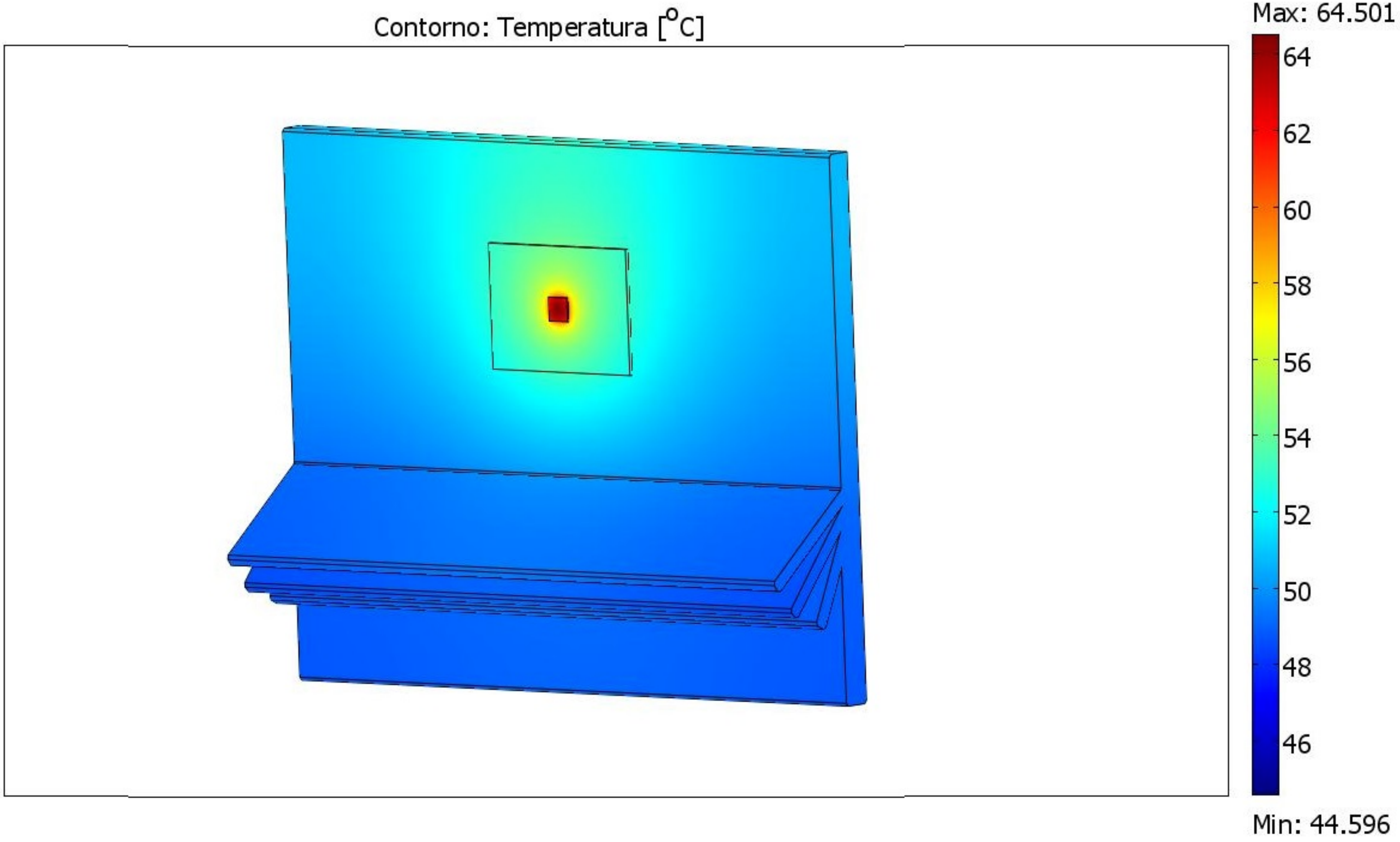
In the **NEW version Two aluminum proprietary extruded profiles** hold TWELVE mirrors, support TWETYFOUR cells and provide **efficient thermal sink**. Daisy chain connections of the cell is **internal** and uses standard wiring techniques. Module is about **2.3 x .29 x.14 m^3** with a **concentration >800 x. New optical design** allows to keep **cells vertical: no shadows.** Module **extremely thin (14 cm)** compared to concentration factor!



Each mirror is .18 x .263 x .14 m^3

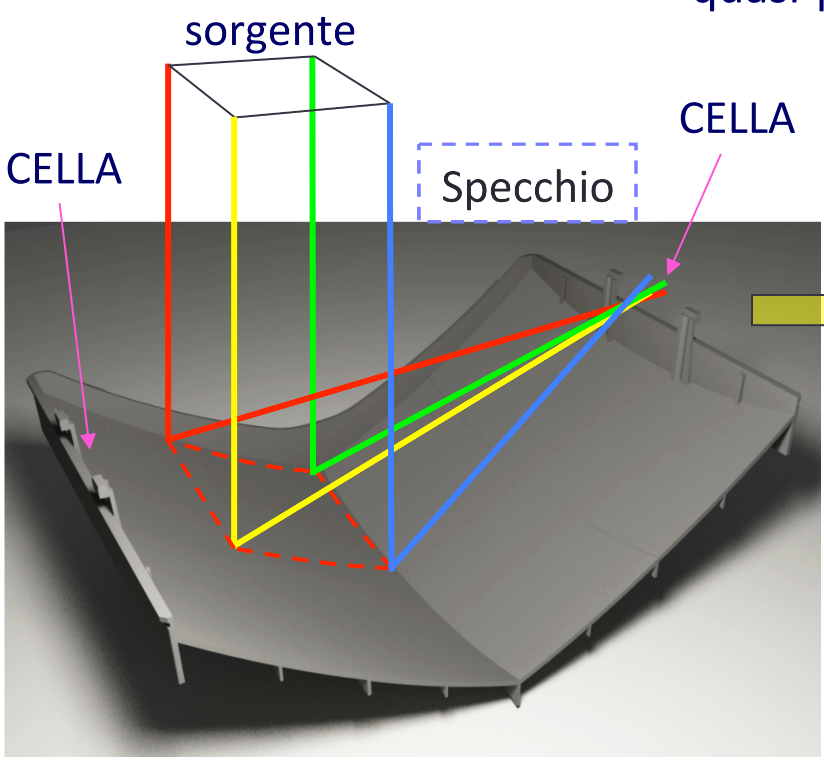


Simulation of thermal profiles at 25 ºC ambient.

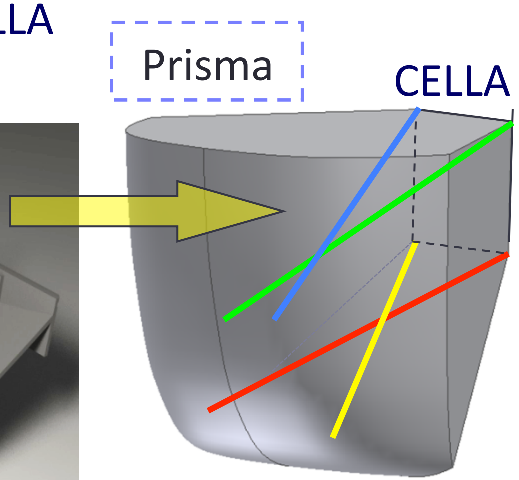


Improved optical design

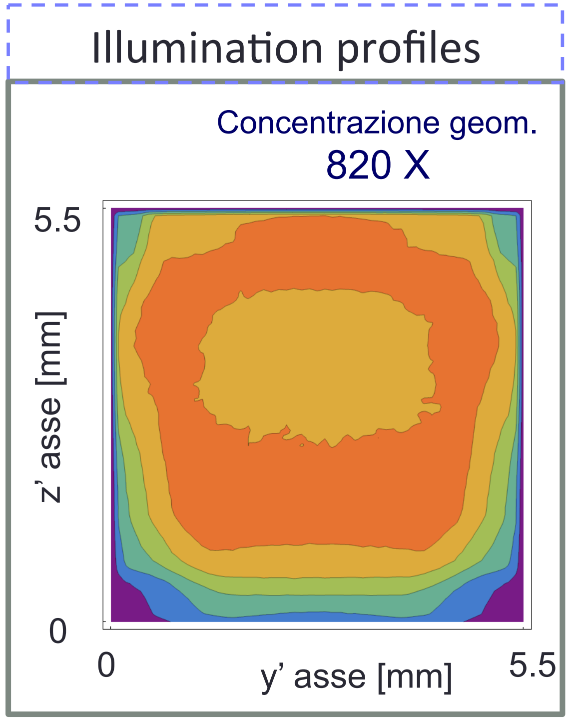
Each concentrator consists of 4 sections of off-axis quasi-parabolic mirror



Discretization of the problem: each reflective sector completely fills the cell 3J



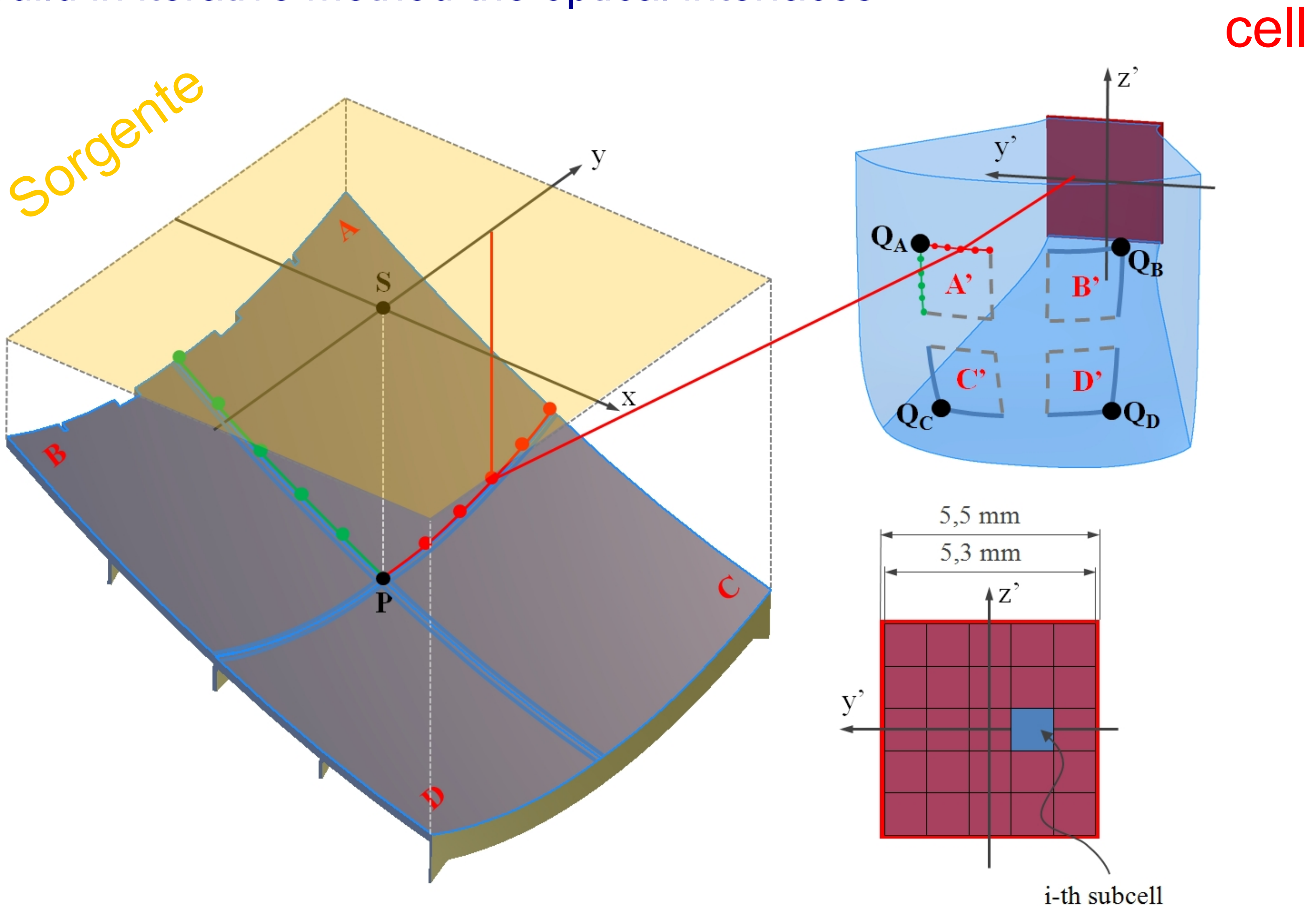
The cell is placed after the focus of each reflective sector



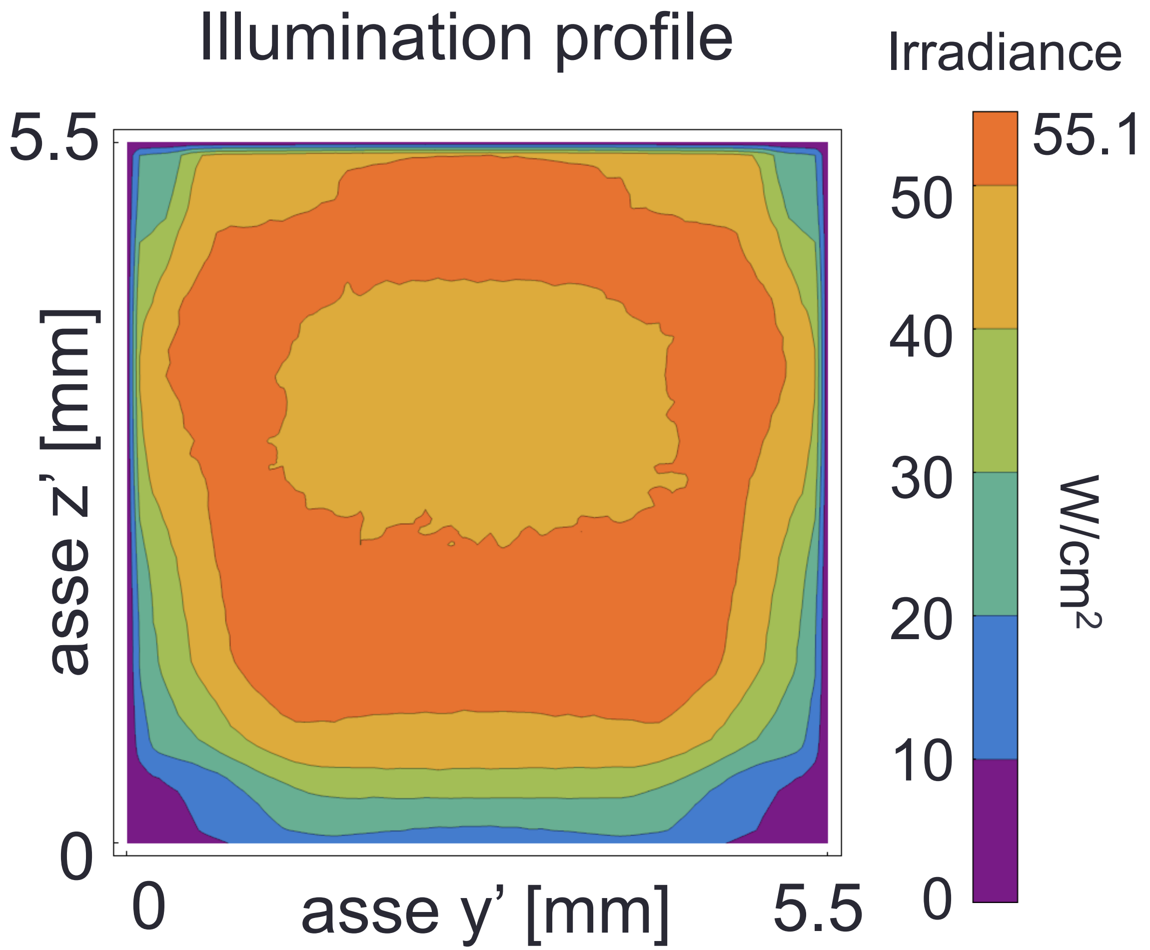
Optimizing primary and secondary optics→ illumination profile

Project technique

A map is created between the source and the cell in order to build in iterative method the optical interfaces



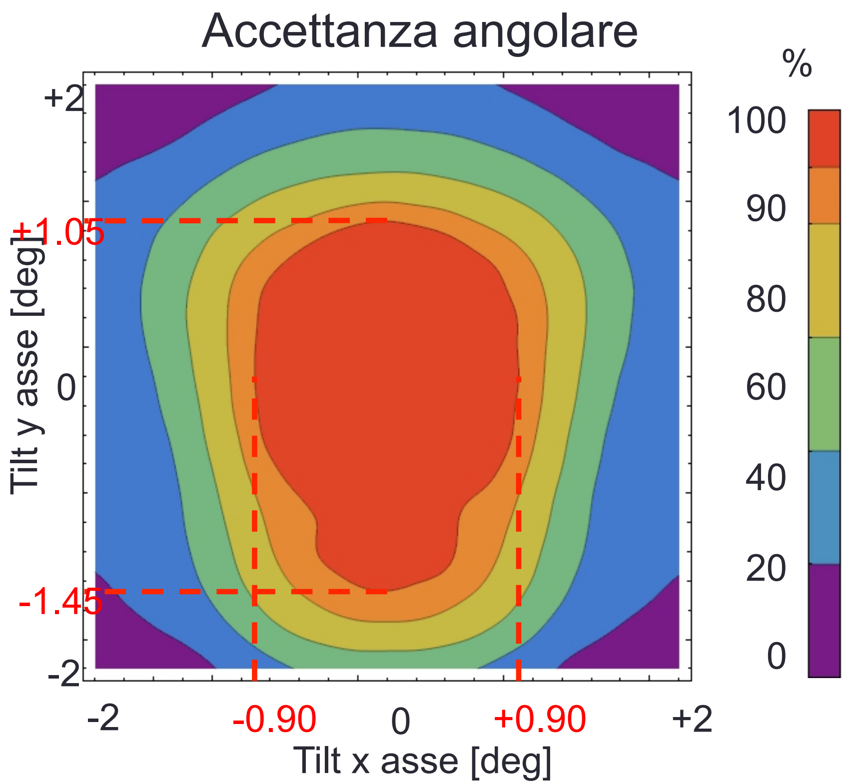
Simulation results

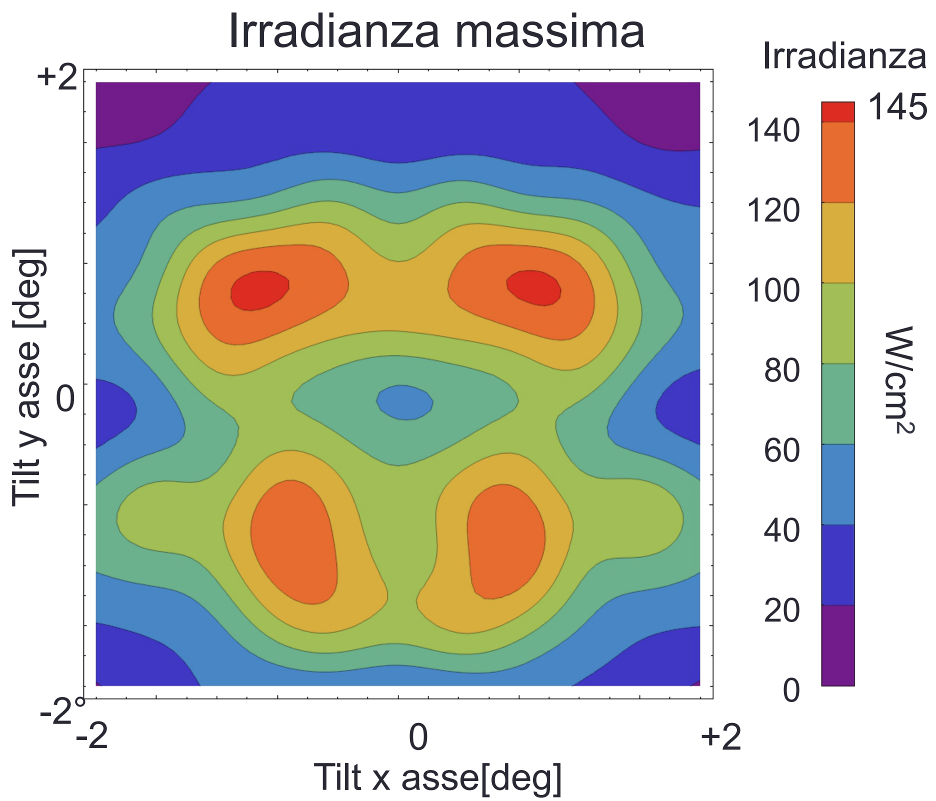


Area cella: 5.5x5.5 mm^2
Area cella effettiva: 5.3x5.3 mm^2
Geom. conc. factor: 820X

Potenza incidente: 13.2 W
Irradianza massima: 53.6 W/cm^2
Peak/mean ratio: 1.40

Optical design compliance

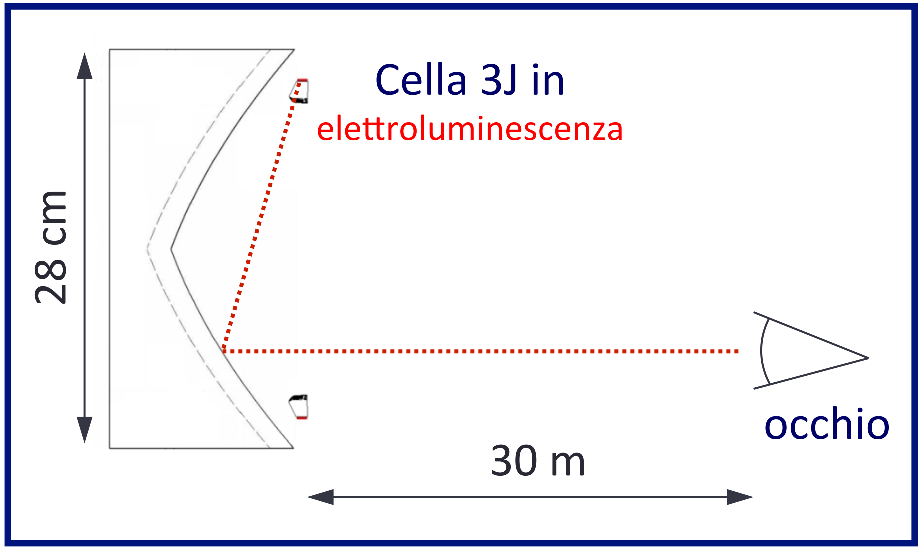




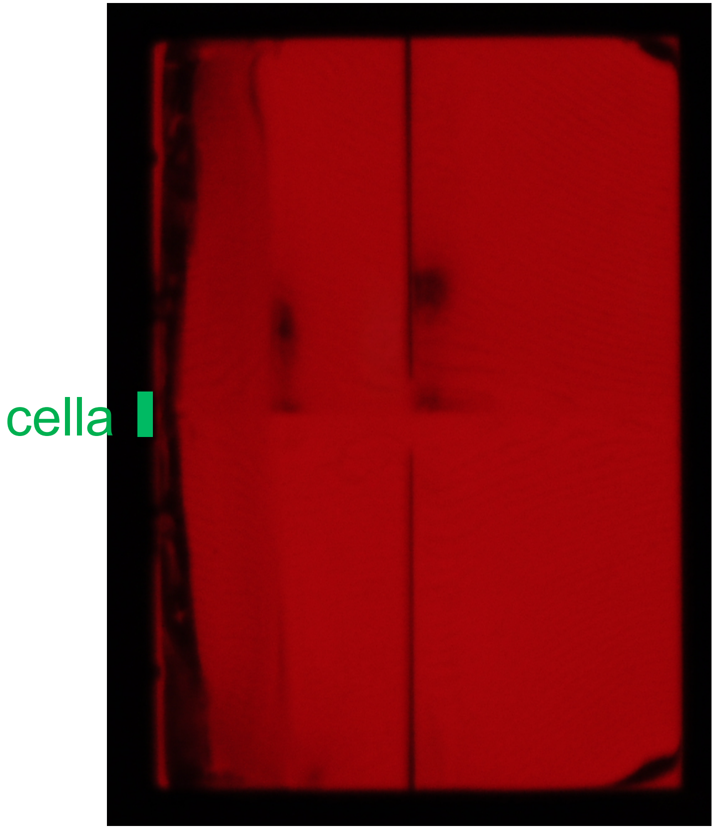
The objective of obtaining a value of angular acceptance of ± 1.0 ° was well achieved for the y axis, while the x axis would have required a prism of excessive size.

The maximum irradiance ('hot spot') in certain conditions of misalignment is 145W/cm2, corresponding to about 1600 suns (1 sun = 0.09 W/cm2). Acceptable in accordance with the datasheet of the 3J cell.

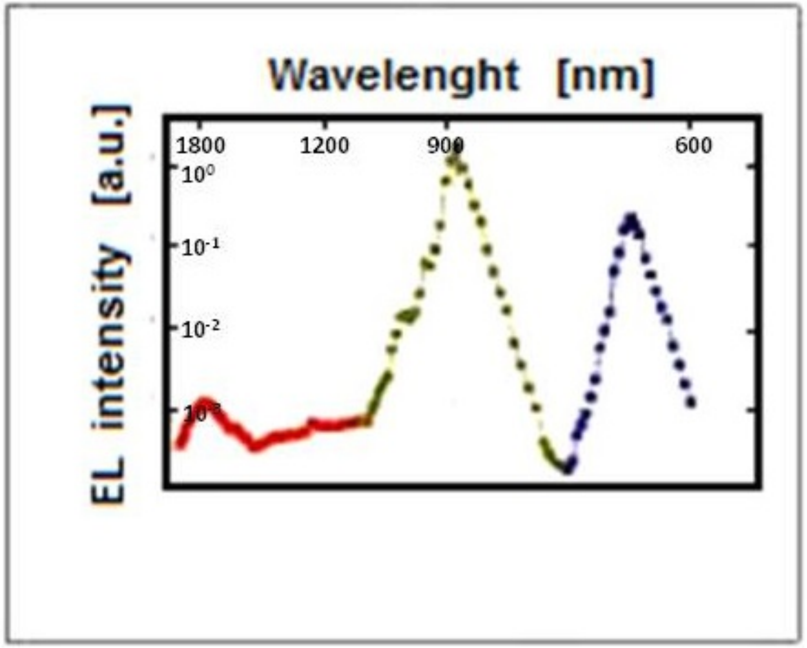
Electtroluminesce test



Optimization of molding parameters, and the position of the cell and the prism.



Using the cell as a LED and observing the concentrator by a sufficiently large distance (about 30m) is possible to obtain information on positioning errors of the cell and of the prism: the ideal case requires that the four areas are illuminated evenly. Black areas indicate errors mirror profile, gluing or cell centering prism.

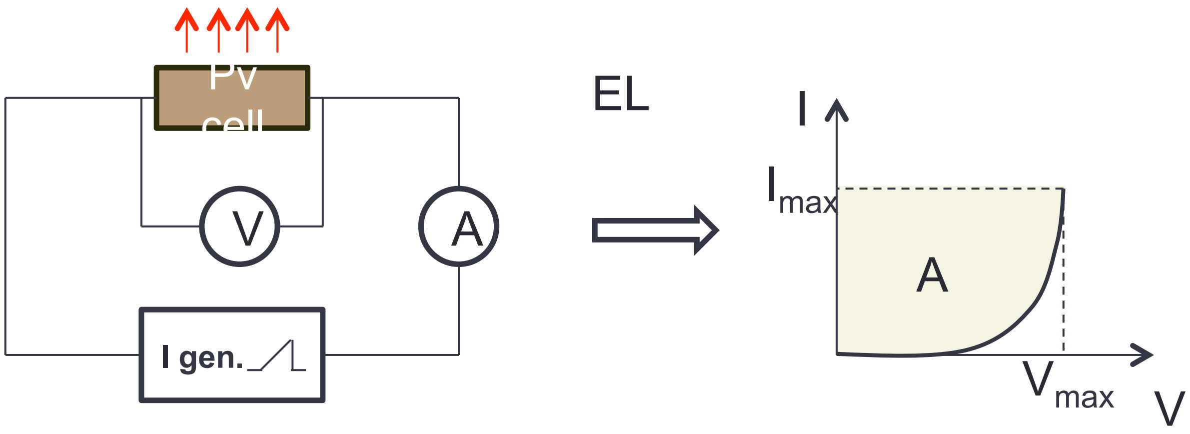


The relationship between the emission spectrum and the potential differences of the sub-junctions is the same that leagues the spectrum of the incident radiation to the tension produced on the photovoltaic cell and is called *reciprocal relationship* (RR):

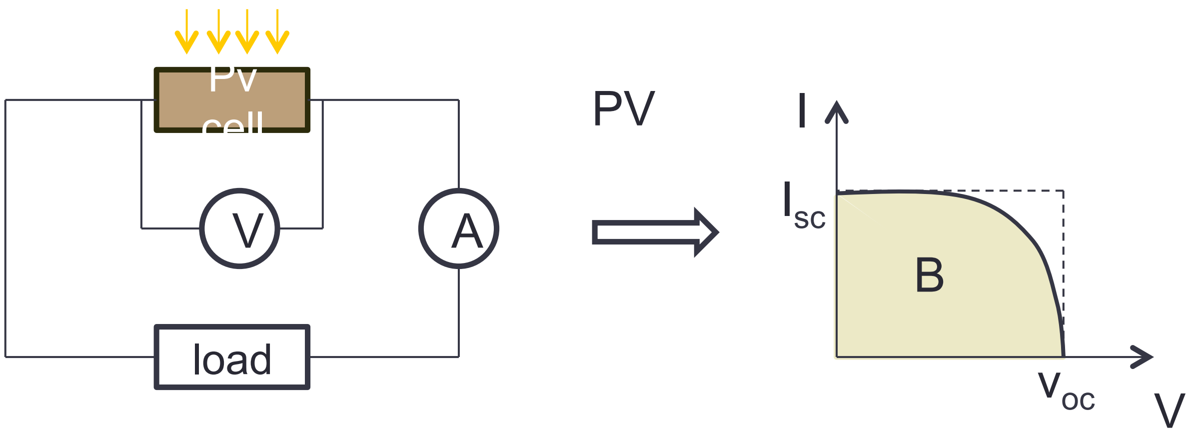
$$\varphi_{PV/EL} = EQE(E) \cdot \varphi_{BB}(E) \cdot \exp((V/V_T)-1)$$

where $\varphi_{PV/EL}$ is the radiation flux emitted/absorbed, EQE(E) is the quantum efficiency, $\varphi_{BB}(E)$ is the Black Body radiation, V is the junction voltage and V_T is the thermal potential.

Using the relationship RR, from the IV curve in EL we can determine the curve IV in photovoltaic mode. The efficiency of the cell, which is proportional to the parameter **Fill Factor** (FF) of the IV curves, can then be determined by measurements in EL.

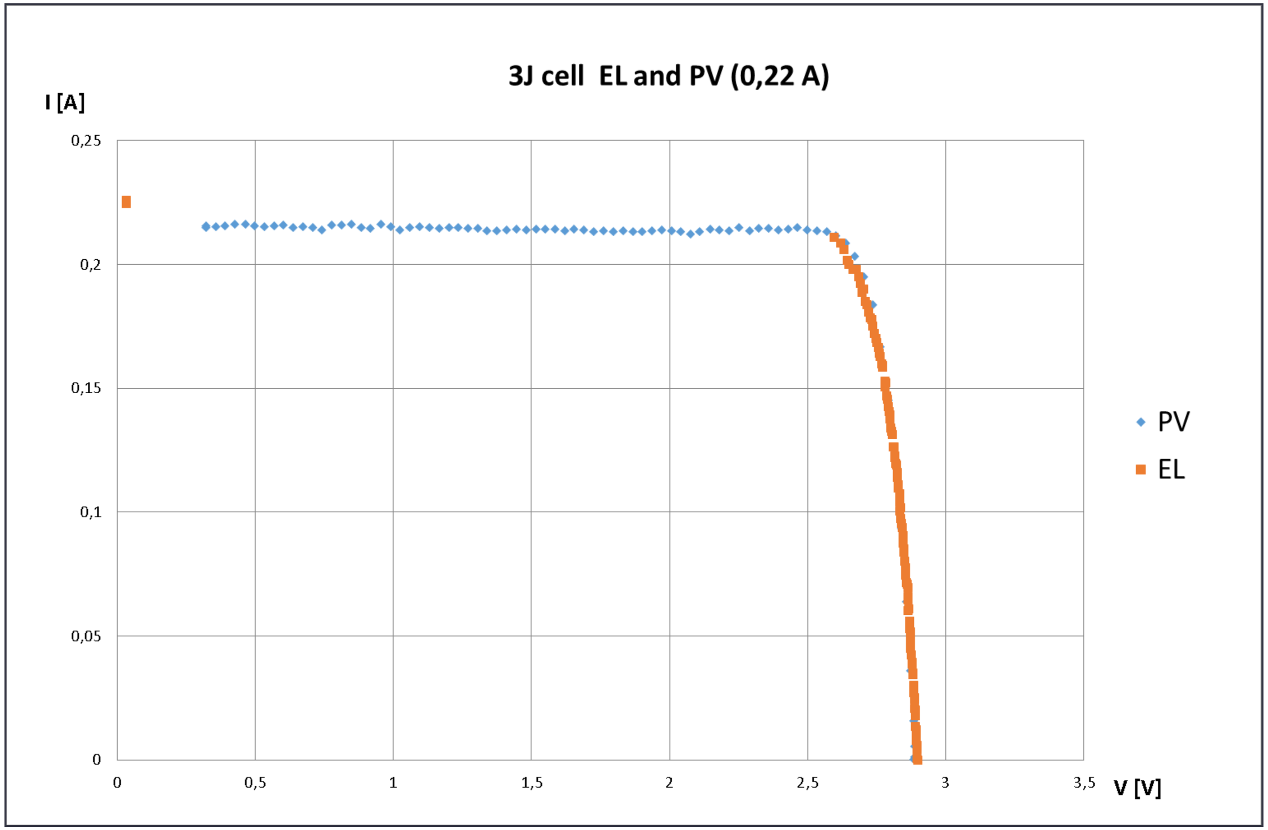


$$FF_{EL} = A/(I_{MAX} \cdot V_{MAX})$$



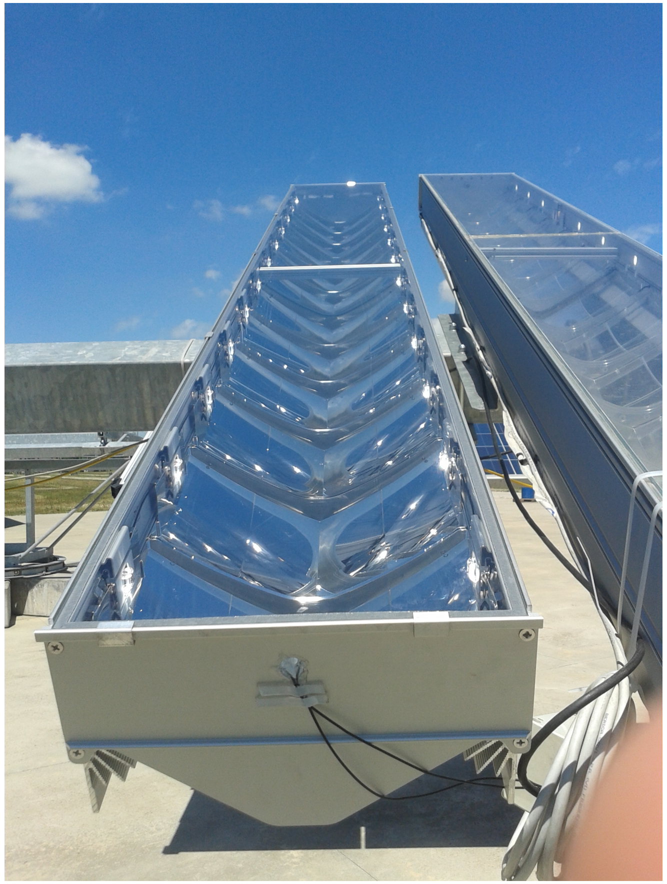
$$FF_{PV} = B/(I_{sc} \cdot V_{oc})$$

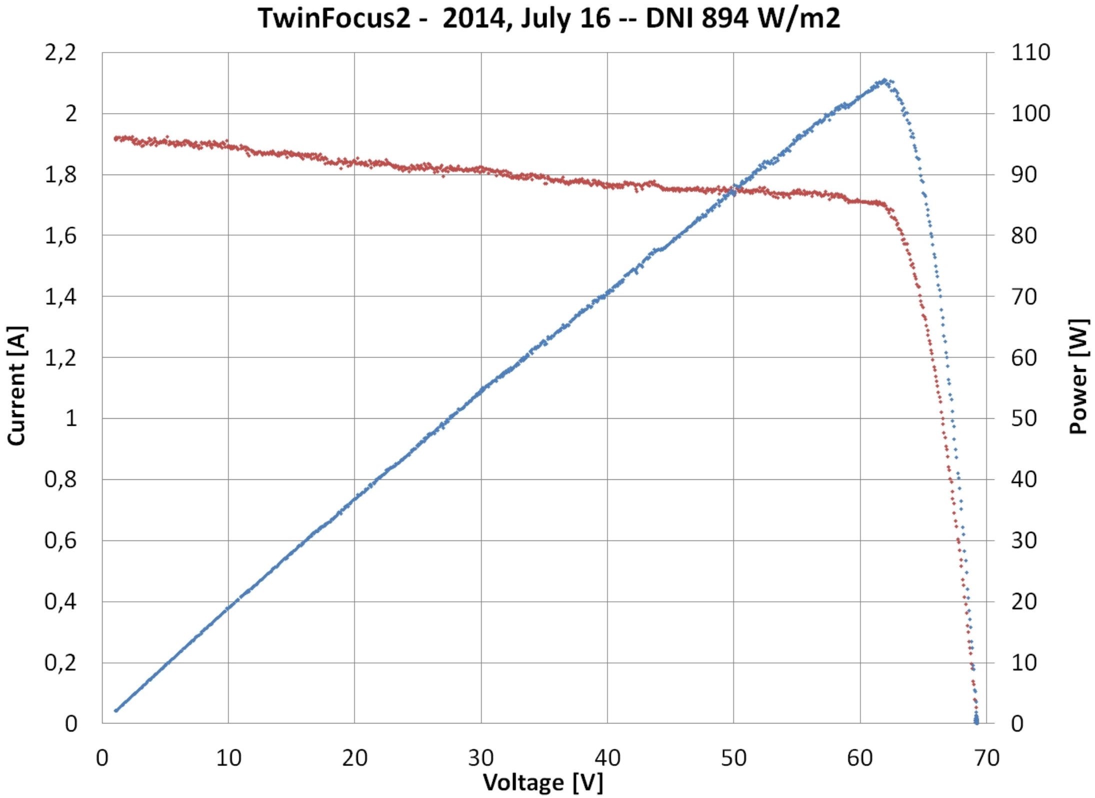
$$FF_{EL} = FF_{PV}$$



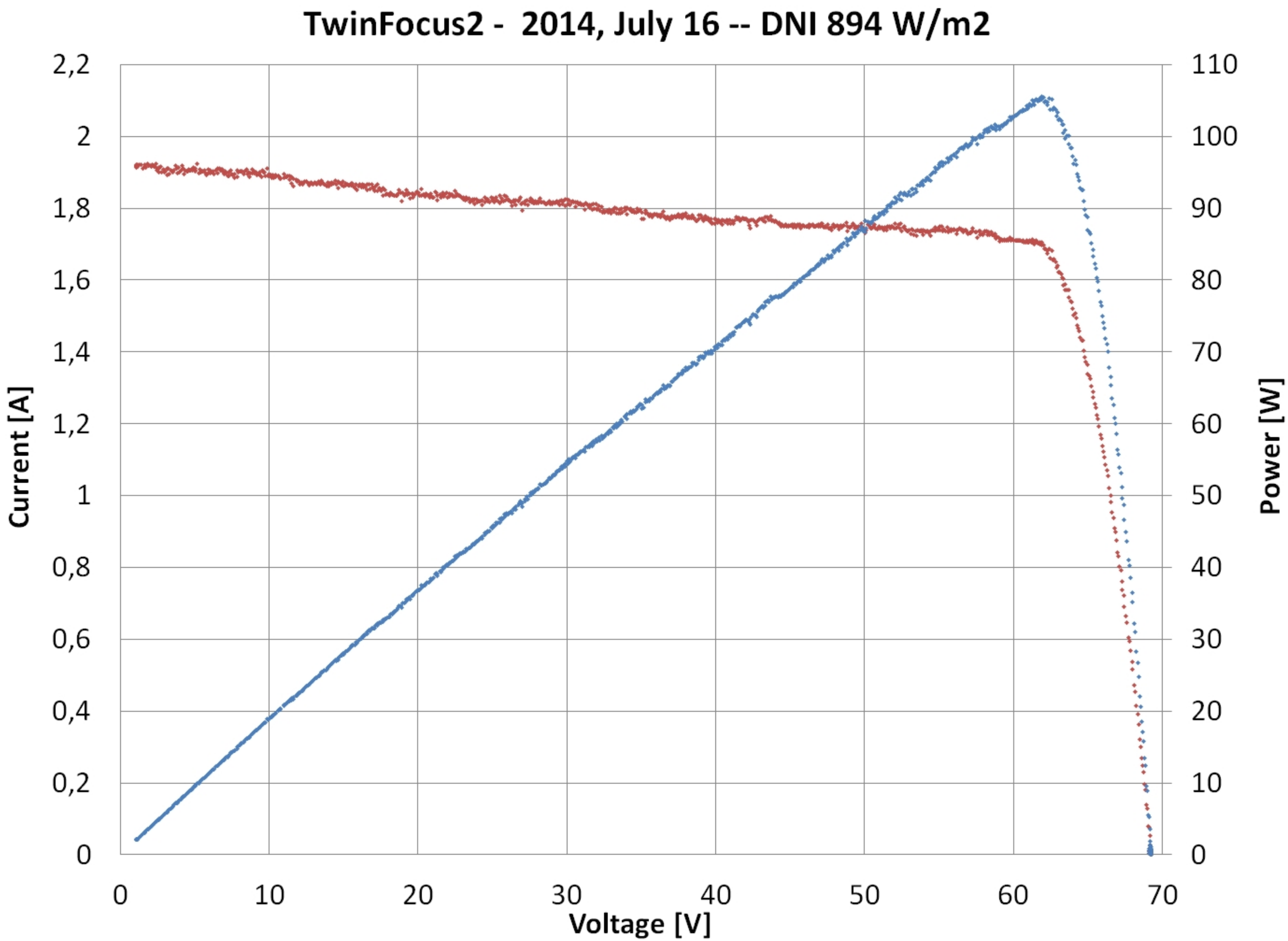
I versus V curve of a cell through **active load** interfaced with a PC

First prototype in field tests





Test with active load of a complete module.
Two times 4 crews on the caps keep the elements together.

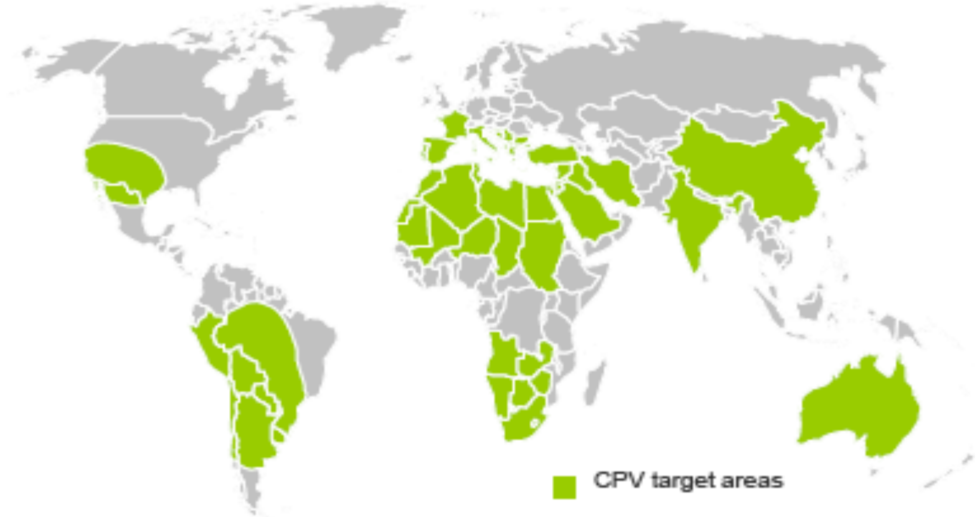


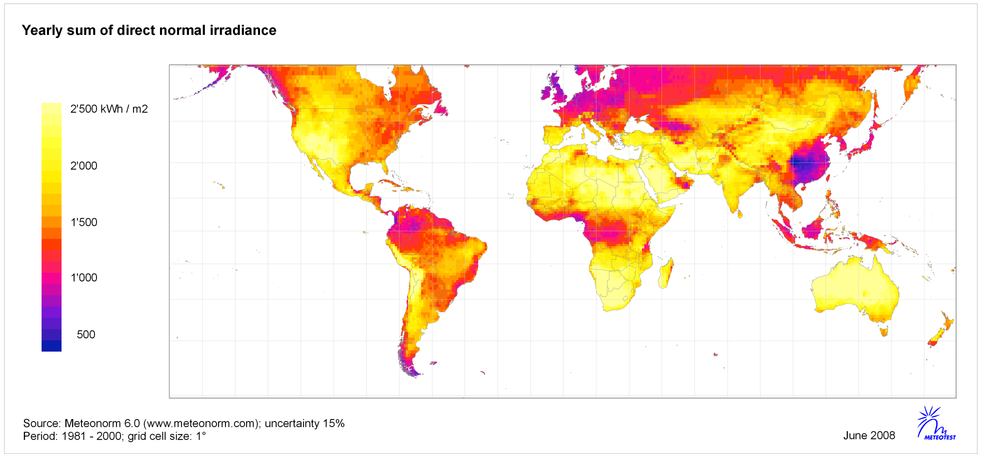
TwinFocus2 - 2014, July 16 -- DNI 894 W/m2
Current [A]
2,2
2
1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
Power [W]
110
100
90
80
70
60
50
40
30
20
10
0
Voltage [V]
0
10
20
30
40
50
60
70

Where CPV is favored

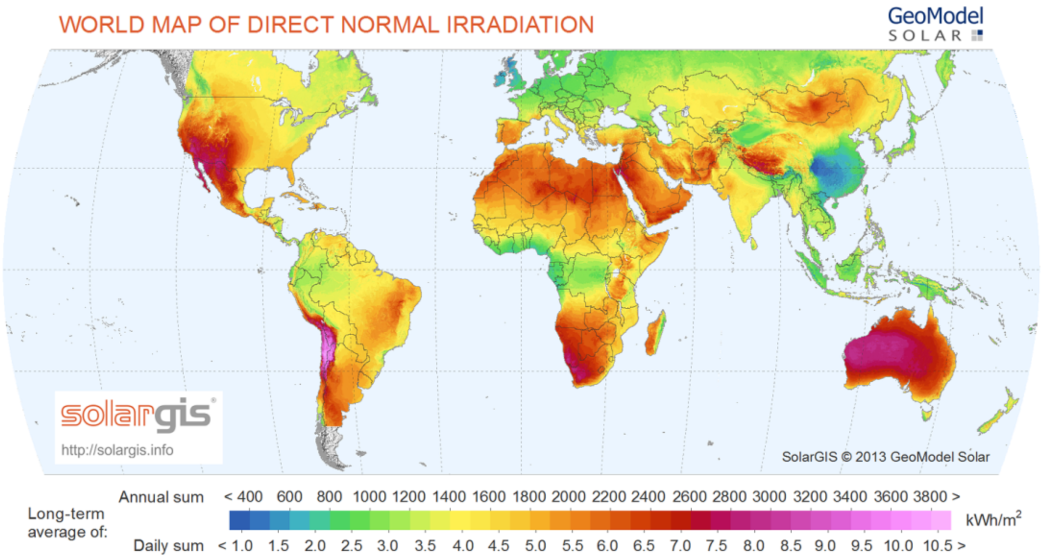
So far, due to very low cost of solar grade silicon (unexpected in 2008), CPV has higher cost (€/Wp). However it is not power, but **energy** that matters.

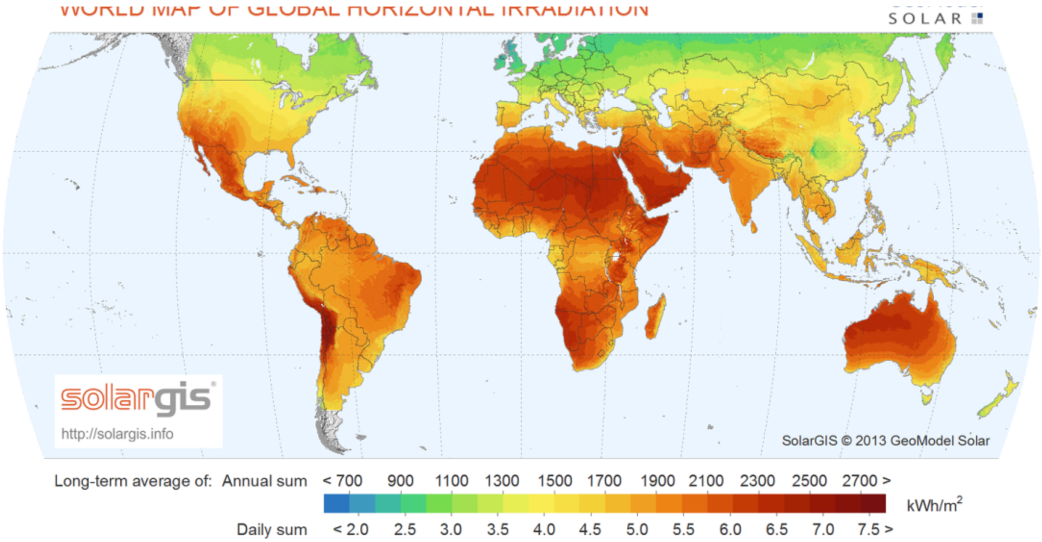
CPV have much higher energy yield with the same installed power where DNI (Direct Normal Irradiation) is higher.





DNI & GHI world maps





Location	TwinFocus 15 kWp ($73 m^2$)	Silicon PV 9.4 kWp ($73\ m^2$) § (same area)	Silicon PV 15 kWp ($116\ m^2$) § (same installed power)
North. Italy (DNI = 1300 kWh/m^2)	19 MWh/year	12 MWh/year	19 MWh/year
Central Italy (DNI = 1600 kWh/m^2)	24 MWh/year	14 MWh/year	22.4 MWh/year
Sicily (DNI = 1800 kWh/m^2)	27 MWh/year	15 MWh/year	24 MWh/year
MENA*(DNI = 2800 kWh/m^2)	42 MWh/year	16 MWh/year	25.6 MWh/year

Data: PVGIS calculator (http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php)

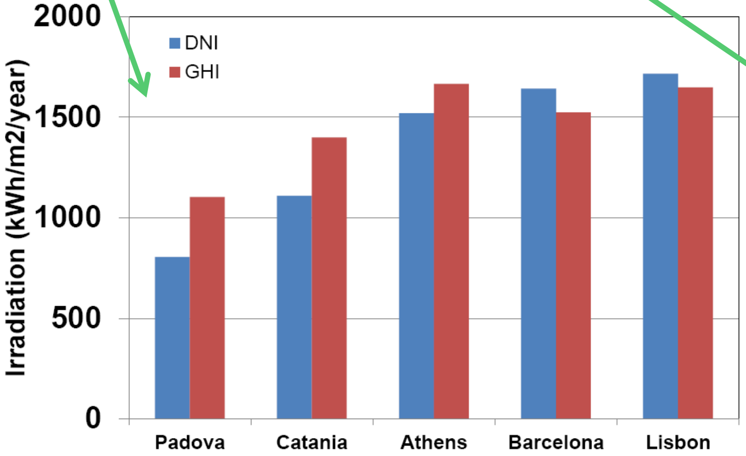
§ Modules: 255 Wp

*MENA: Middle East+North Africa

Thank you!

DNI resources

- The DNI resource is not known so exactly as GNI is.
  Some software give DNI: Eosweb, epw, Meteonorm,
- In general are **calculated**.



As calculated by epw, some locations have even more DNI than global irradiation:
not a paradox

SSE Homepage | Find A Different Location | Accuracy | Methodology | Parameters (Units & Definition)

ATMOSPHERIC SCIENCE DATA CENTER

NASA Surface meteorology and Solar Energy - Available Tables

Latitude 38.017 / Longitude 12.517 was chosen.

Geometry Information

Elevation: 41 meters taken from the NASA GEOS-4 model elevation

Northern boundary 39

Western boundary 12

Center Latitude 38.5 Longitude 12.5

Eastern boundary 13

Southern boundary 38

Show A Location Map

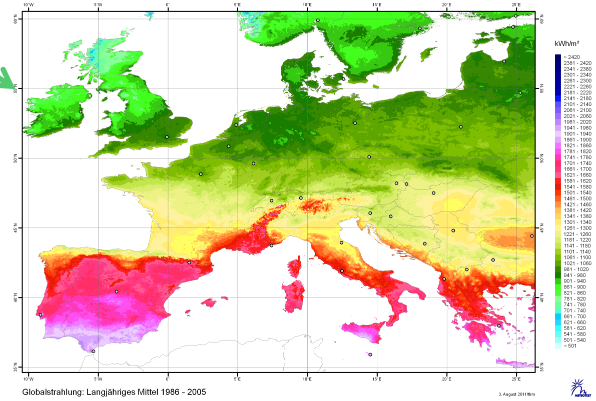
Parameters for Sizing and Pointing of Solar Panels and for Solar Thermal Applications:

Monthly Averaged Insolation Incident On A Horizontal Surface (kWh/m²/day)

Lat 38.017 Lon 12.517	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
22-year Average	2.34	3.33	4.76	6.01	7.14	7.88	7.95	7.03	5.41	3.89	2.50	2.00	5.03

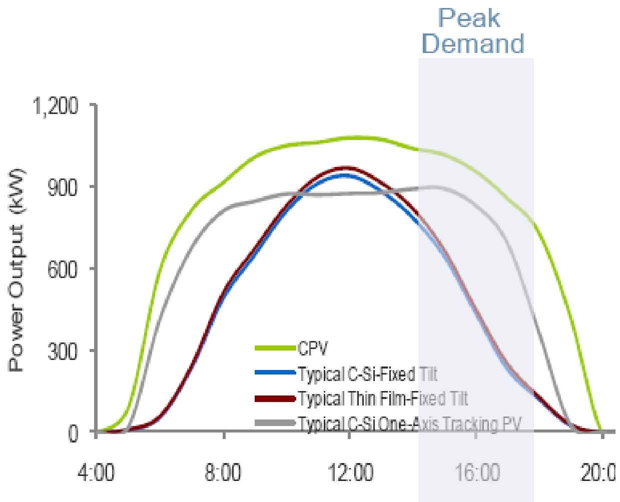
Monthly Averaged Direct Normal Radiation (kWh/m²/day)

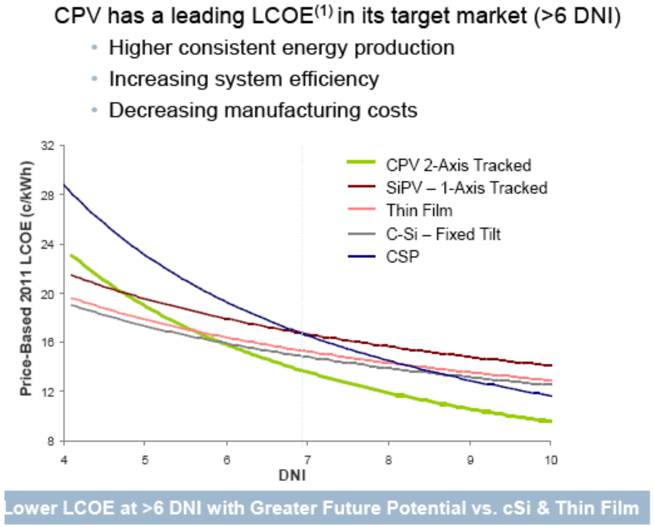
Lat 38.017 Lon 12.517	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
22-year Average	4.09	5.05	6.33	7.02	8.10	9.17	9.63	8.78	7.06	5.79	4.11	3.59	6.57



LCOE

Leveled Cost Of Energy is the most important parameter when choosing a power system.
Basically: (yearly energy yield)/(cost of system).
A CPV system may be more lucrative than a fixed silicon system of lower installation cost (€/Wp) because the energy yield is higher:
This may happen in higher DNI end/or temperature areas. The DNI level that defines the break-even point depends on many factors, not last the cost of the systems.





Conclusions

- CPV despite the very **simple principle**, it implies the mastering of **very different technological fields**: optics, thermal management, fine mechanics, simulation tools, science of materials, meteorological science, and many others.

- Taking advantage of **mature technologies developed in other fields**, especially automotive, it is possible to reach grid parity, and be more economical than other power system, in higher DNI areas.

CPV activities at Physics Dept., Univ. of Padova (Italy) are funded by:

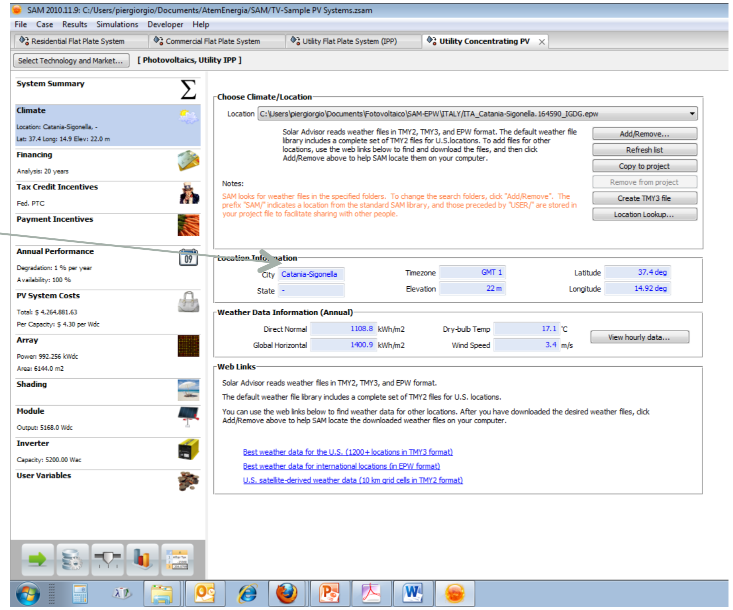
CENTRO FERMI
Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

pfv
polo fotovoltaico
veneto

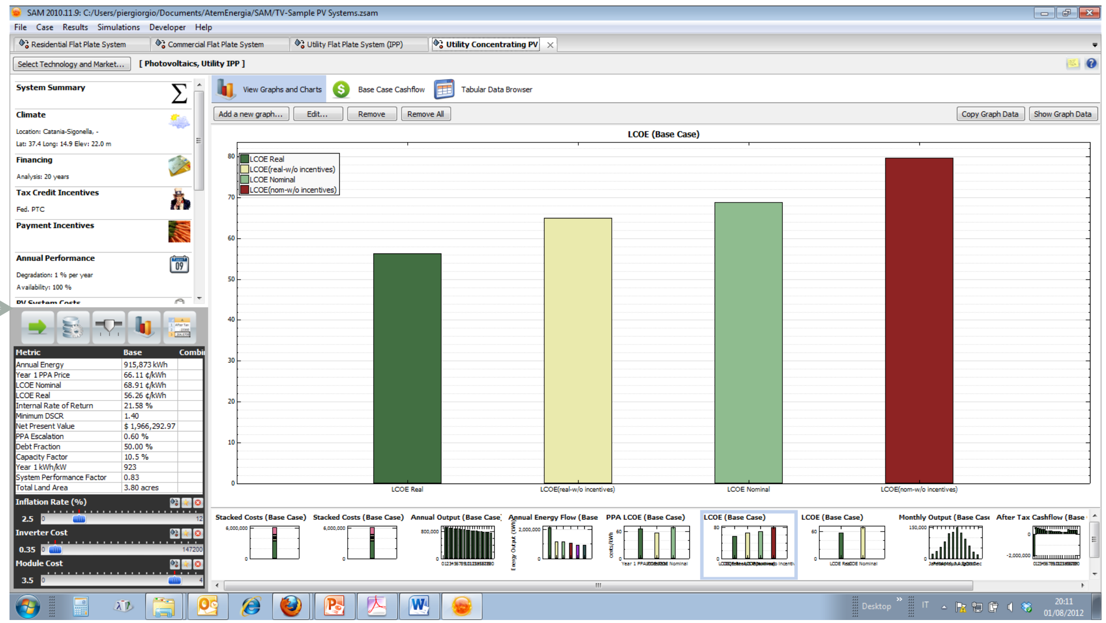
SAM

Softwares help to decide the right renewable to use: Example:
SAM (System Advisory Model)

Decide location



Input system parameters,
As efficiency, financing, cost…
and compare lcoe



Different layouts

- Point focus
- Linear focus
- Heliostat

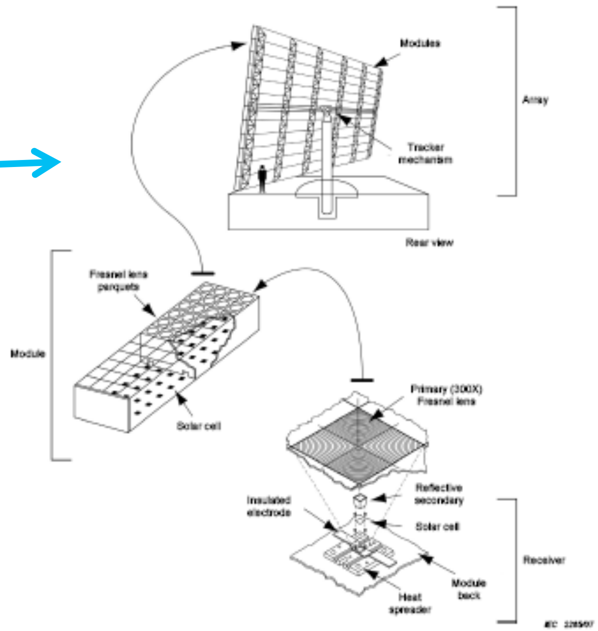


Figure 3 – Schematic of point-focus Fresnel lens PV concentrator

Standard technology, passive heat sink possible

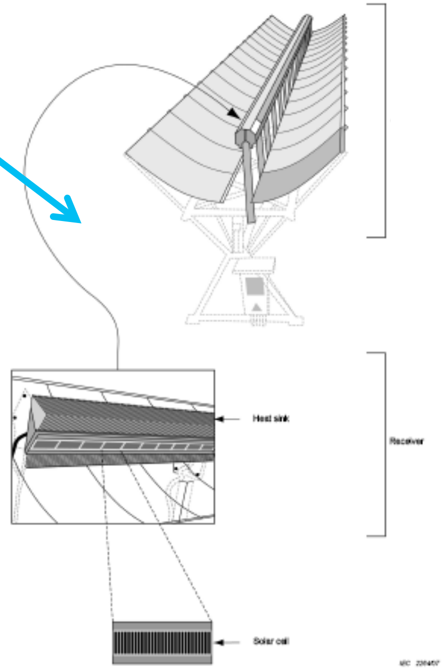


Figure 2 – Schematic of linear-focus trough PV concentrator

Low concentration ratio

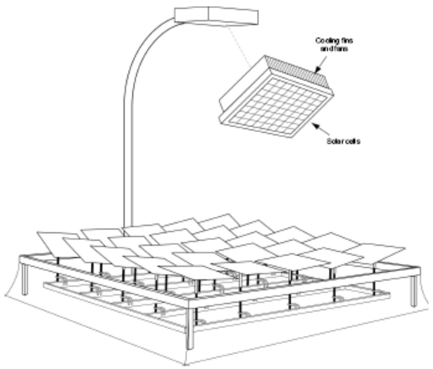
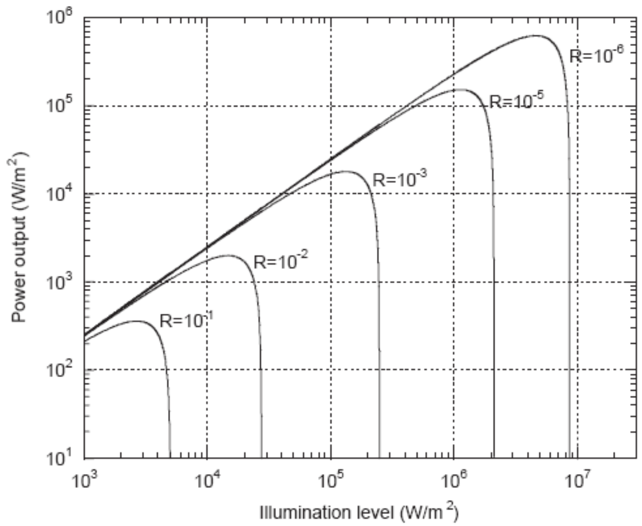


Figure 5 – Schematic of a heliostat CPV

Active heat sink necessary: cost!

Heat sinking

- Increasing illumination level on the cell the electrical output increases up to a limit:
- The limit is given by the amount of heat that the cooling system can dissipate: over a limit the cell's temperature increases lowering the efficiency of the system: more light is useless

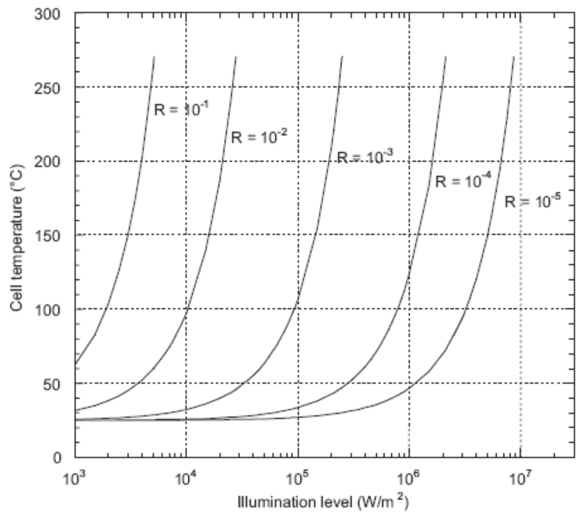


Electrical power output versus illumination level for various values of R_{cool} (K m^2/W).

Nominal Temperature Coefficients at 50 W/cm^2

Parameter	Absolute, 10°C to 100°C Range		Relative, at 25°C	
Efficiency	-0.04	absolute %/°C	-1080	PPM/°C
Vmp	-4.5	milliVolts/°C	-1610	PPM/°C
Jmp	4.7	milliamps/cm^2/°C	570	PPM/°C
responsivity@Vmp	7.7	X10^{-5} Amps/Watt/°C	570	PPM/°C

These coefficients are not constant, see next slide



Cell temperature versus illumination level for various values of R_{cool} (K m^2/W).

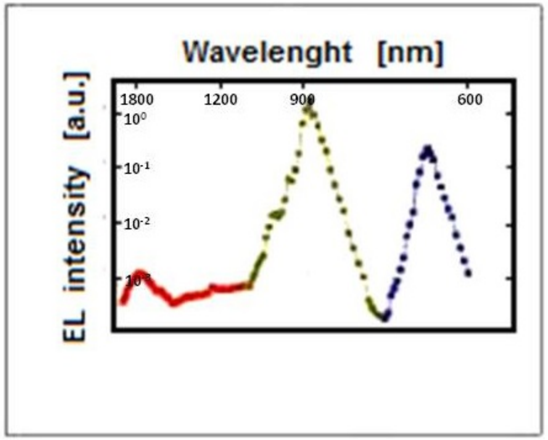
Certification

- IEC 62108 is the standard norm for CPV, necessary for two reasons:
  - Countries that grant a feed-in tarinf usually requires that modules have passed 62108;
  - Buyers/investors/banks see it as a guarantee of «due diligence» and reliability.

- Many **tests**:
  - Electrical performance
  - Ground path continuity
  - Electrical insulation
  - Wet insulation
  - Thermal cycling
  - Damp heat
  - Humidity freeze
  - Hail impact
  - Water spray
  - Diodes
  - Robustness of connectors
  - Mechanical load
  - Off-axis beam
  - Ultraviolet conditioning
  - Outdoor exposure

Bankability

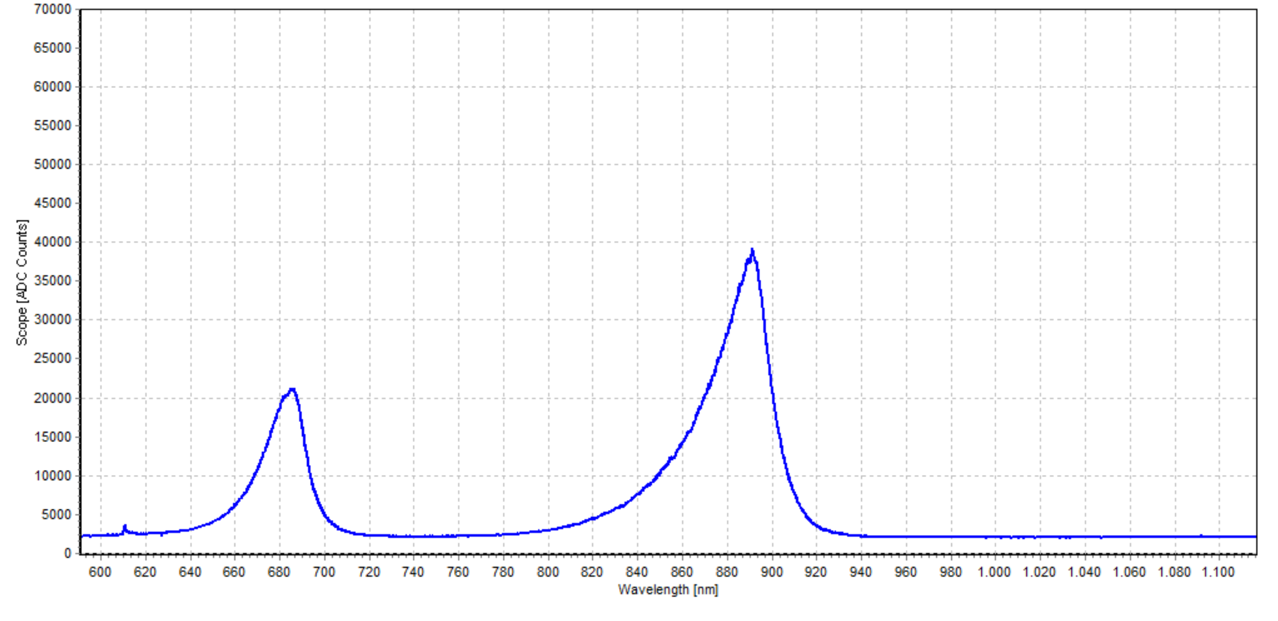
Una cella fotovoltaica a giunzione singola o multipla, alimentata da una corrente diretta I_{inj} ,emette radiazione, detta di elettroluminescenza (EL), similmente ad un LED.
Nello spettro di emissione ogni sub-giunzione determina un picco di emissione alla frequenza corrispondente all'energia della sua band-gap.



La relazione che lega lo spettro di emissione alle differenze di potenziale delle sub-giunzioni è la stessa che lega lo spettro della radiazione incidente alla tensione fotovoltaica prodotta sulla cella ed è detta *relazione di reciprocità* (RR):

$$\varphi_{PV/EL} = EQE(E) \cdot \varphi_{BB}(E) \cdot \exp((V/V_T)-1)$$

dove $\varphi_{PV/EL}$ è il flusso di radiazione assorbita/emessa, EQE(E) è l'efficienza quantica esterna, $\varphi_{BB}(E)$ è la radiazione di corpo nero, V la tensione di ogni giunzione e V_T è il potenziale termico.



La figura mostra uno spettro di EL di una cella a tripla giunzione 3J misurato in laboratorio (LUXOR) dove sono evidenti i picchi di emissione delle sub-giunzioni top e middle.
Il range dello spettrometro non consente di vedere il picco della giunzione bottom.

Dallo spettro di EL, tramite la RR, si possono calcolare le tensioni interne della cella multi-giunzione.
La tensione della giunzione bottom è il complemento delle tensioni top e middle alla tensione esterna della cella.