Concentrated PhotoVoltaics (CPV): is it a real opportunity?

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Intro

• CPV «in the back of the envelope» is trivial: take a small solar cell, some concentrating optics (lens or mirror) and a Sun tracker.
• But: how? Why?
• We will see, it is not such easy «how», many technological and economical constrains shape the module.
• «Why» is easier to explain: reduce semiconductor to reduce cost, and efficient use of higher efficiency solar cell to reduce size of power generator.
Motivations [1]

Why «Concentrating»

1. «Traditional» photovoltaics based on silicon solar cells need **large areas** due to its low (~14%) efficiency. CPV with higher efficiency need less area.

2. The very high (~500 – 1500 X) concentration ratio allows substitution of large areas of solar cells with **cheap materials** as moulded plastic.

3. **Silicon solar cells** have large (0,3 %/K) dependence on temperature: a problem in very hot climates.

4. **3J solar cells** have small (-0,04 %/K) dependence on temperature: **an advantage in very hot climates**
Motivations [2]

4. For power plants large areas of land are spoiled, roof top photovoltaics can be limited by area of the rooftop.

5. Possibility of industrialization using reliable technologies (plastic moulding, aluminium, glass), all mature technologies.

6. Dual land usage.
Different layouts

- Point focus
- Linear focus
- Heliostat

Standard technology, passive heat sink possible

Active heat sink necessary: cost!

Low concentration ratio
How it works

- Mirrors or lenses concentrate solar light on very small (<1cm²) solar cells

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

Concentrating optics

- 85% Optical efficiency
- 35% Cell efficiency
- Heat sink

Conventional simple designs

Fresnel lens

Cell

Parabolic mirror
Triple junction Solar Cells [1]

From space application.

**Lower temperature dependence of efficiency:** -0.04%/°C

Important in hot climates and for thermal budget.

-0.4 %/(10°C). From 40% (at 25 °C) to 36% at 125 °C, but cells usually are below 80 °C.

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

Almost the whole solar spectrum converted
Triple junction Solar Cells [2]

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

Typical dimensions of the solar cell: 5.5x5.5 mm²

Road map commercial cells
Efficiency depend on concentration

- The dependency on concentration is a result of physical parameters, as just seen, but also on engineering:

The concentration of the maximum depends basically on 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: **higher losses.**

A compromise must be engineered.
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

Increase efficiency increasing number of junctions:

Silicon
Current mismatch

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

- Current mismatch because of:
  - Spectrum mismatch: the spectrum of the light shining on the cell is not the one for which the cell was optimized;
  - Chromatic aberration: different cell receive different power profiles;
  - Cell is damaged.
Dependence on solar spectrum

Because of current mismatch care must be taken not only of different transmission/reflection, but also time of the day/region in which the power is rated.

Example: a measurement 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. Why? Relative amount of higher energy photons in 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 NIR

DNI: Direct Normal Irradiation

Normalized current (current/DNI) decreases as amount of UV decreases relative to NIR
Differences 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 angle allows less stiff tracker (lower cost)
• High angle allows lower precision in optics (lower cost)
• High angle allows lower precision in assembly (lower cost)
• High angle allows lower precision in field installation (lower cost)
• High angle allows reduced mismatch losses: higher average efficiency
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

Sun’s subtended angle: \( \pm 0.26^\circ \)

Flexure in pedestal and drive

Flexure and torsion in aperture frame

Pointing vector

CPV system 90% power acceptance angle
Technology: an example

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

- Increasing illumination level (that is, concentration ratio) more light shines on the cell and 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.

Nominal Temperature Coefficients at 50 W/cm²

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Absolute, 10°C to 100°C Range</th>
<th>Relative, at 25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>-0.04 absolute %/°C</td>
<td>-1080 PPM/°C</td>
</tr>
<tr>
<td>Vmp</td>
<td>-4.5 milliVolts/°C</td>
<td>-1610 PPM/°C</td>
</tr>
<tr>
<td>Jmp</td>
<td>4.7 milliamps/cm²/°C</td>
<td>570 PPM/°C</td>
</tr>
<tr>
<td>responsivity@Vmp</td>
<td>7.7 X10⁻⁶ Amps/Watt/°C</td>
<td>570 PPM/°C</td>
</tr>
</tbody>
</table>

These coefficients are not constant, see next slide.
Efficiency depends on temperature

- Voltage is linear with temperature, but:
  \[ \text{Power} = \text{Voltage} \times \text{Current}. \]
- Temperature coefficient and voltage depend on concentration \((X)\) and on temperature;

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

\[
V_{oc} = \frac{n k T}{q \log(e)} \cdot \log(X) + V_{oc,X=1}
\]

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

Figure 6. Open-circuit voltage temperature coefficients for multijunction cells. (The voltage decreases with increasing temperature.) Theoretical values using the simple diode
Heat sinking

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

Thermal budget at 600 Suns: 13W

Cell: 5.5x5.5 mm²

Bypass diode

Solar receiver

Passive heat sink

$T_{\text{cell}}$: 85°

($T_{\text{air}}$: 35°C)
Heat sinking [2]

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

**Thermal conductivity:**
Watt/(meter * kelvin)
TC of material is just as important as its thickness
Thermal issues

**Simulation** of temperature profiles of solar cells and heat sinks

- Optimization of shapes and dimensions
- Realization of prototypes
- **Validation** of numerical simulations, both in the lab and under the Sun

- The temperature of the solar cells must be as low as possible to increase:
  - **Efficiency**
  - **Reliability**
Tracking issues

- Mounting: cost!
- Angular range: number of hours
- Max wind speed: number of hours

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?

Must find a compromise
Rated power/real power

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

Since 3J solar cells ave less dependency on temperature, rated power, as measured in field is less dependent on air temperature.

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

But...
How to rate CPV?

- So far, each company chooses its own rating conditions:
  - Irradiance: 850, 900 or 1000 W/m²?
  - Temperature: 25 °C cell or 20 °C ambient?
- IEC committee proposes:
  - Test condition 900 W/m², 25°C cell;
  - Operating condition 900 W/m², 20°C ambient.

- But as we will see: when will be possible to have operating condition? Current/DNI depends on spectrum (current mismatch), so spectrum has to be accurately measured during power measurement: depends on time of the day and season.
- Standards are for AM1.5d, but how to have it exactly the same day in which wind < 1m/2, and T_air=20°C?
- Before or after inverter? AC/DC?
Certification

• IEC 62108 is the standard norm for CPV, necessary for two reasons:
  • Countries that grant a feed-in tariff usually require 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
Where

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

CPV have higher energy yield with the same installed power in hottier and sunnier sites, where DNI (direct normal irradiation) is higher. €/Wp is not a good metric, use lcoe (levelized cost of energy): €/kWh.
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
Levelized 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.

Cost reduction may come from more standardization (lesson learned from Si-PV)

Size of power plant is also important.
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
Conclusions

• Concentrated photovoltaics is a mature technology. Despite the very simple principle, it implies the mastering of very different technological fields: optics, thermal management, fine mechanics, simulation tools, experimental skills, production, science of materials, meteorological science, and many others.

• With a scientific approach it is possible to reach grid parity, and be more economical than other power system, in higher DNI areas.