The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

International Atomic Energy Agency

Workshop on "Physics for Renewable Energy"
October 17 - 29, 2005

301/1679-16

"Concentration & Innovative Concepts in PV"

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Concentration & Innovative Concepts in PV

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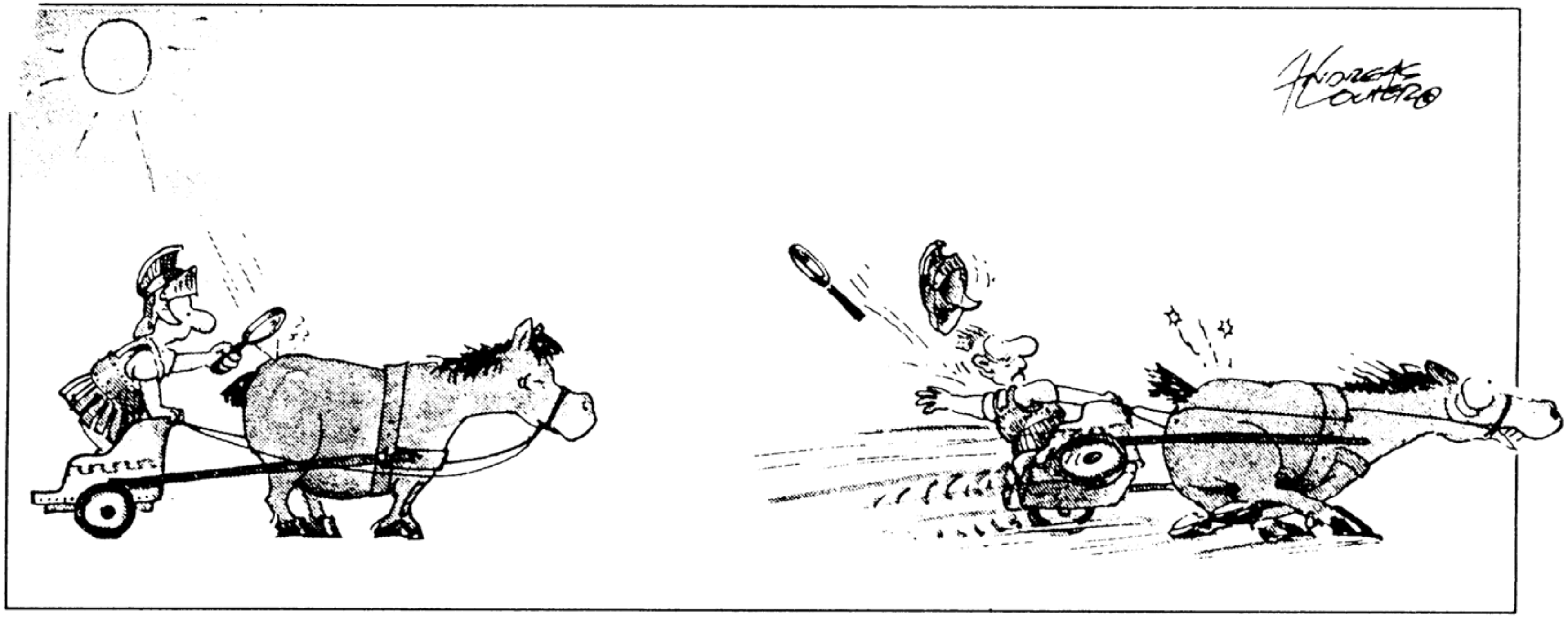
Workshop on "Physics for Renewable Energy“ October 17 - 29, 2005‘ ICTP-Trieste, Italy

Outline

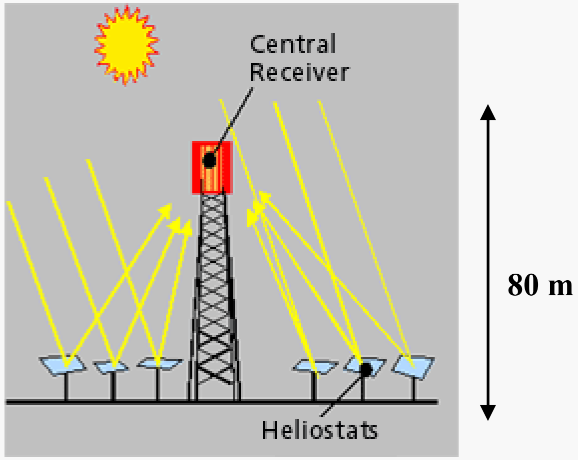
1. Introduction
2. Concentrator PV Systems
3. Solar receiver
4. Optics
5. Traking system
6. Perspective for PV concentrators
7. ENEA Phocus Project

In ~ 700 years BC the Vestal Virgin used in Rome triangular conic vessels made of mirrors to light sacred temple fire.

Other applications?...

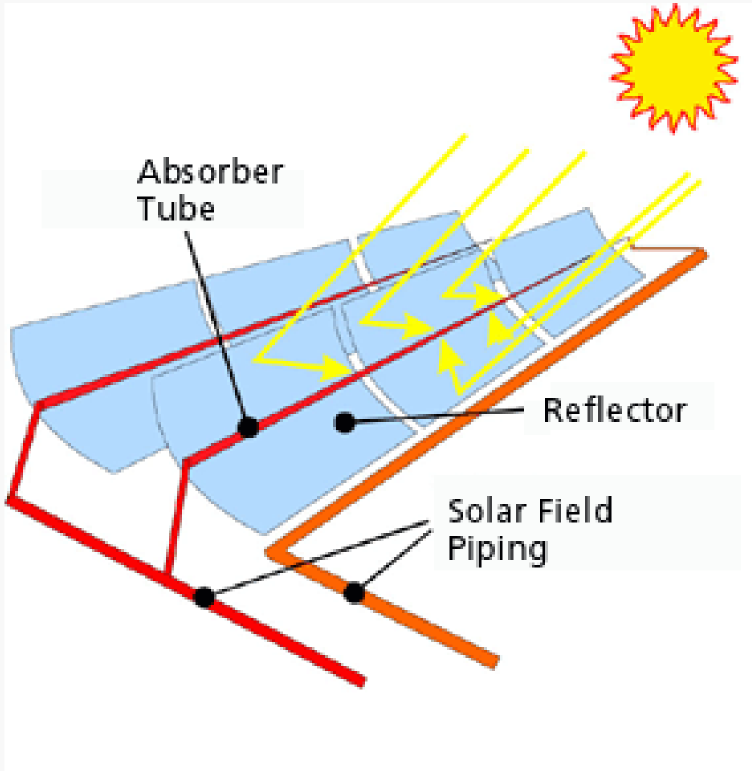


Solar-Thermal applications



Solar Two Plant, 10 MWe (California, USA)

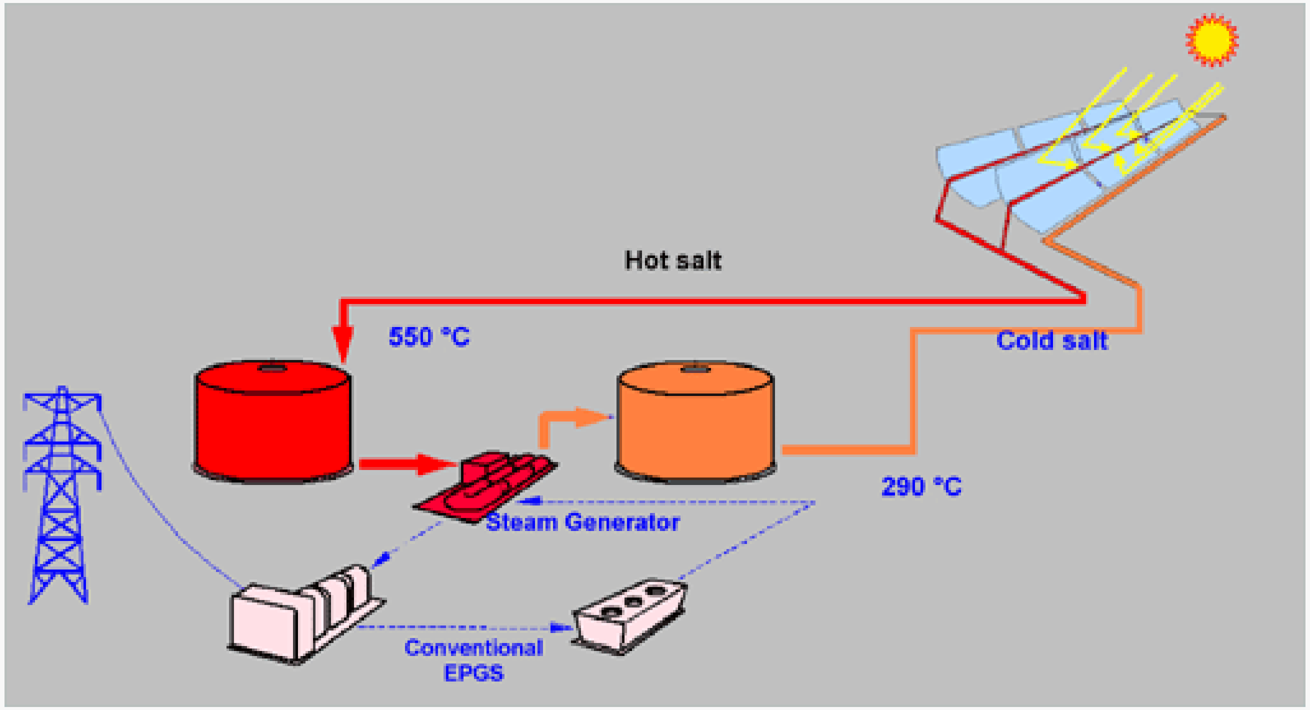
linear parabolic collectors



Linear parabolic collector plant at Kramer Juction (California)

ENEA Archimede concentration solar plant

the generation and *storage of medium temperature fluids (550°C) for the electric power generation; and at higher temperature (> 850°C) for the generation of hydrogen.*



The main innovations of Archimede plant:

- the use of large scale heat storage to provide electric power at a constant rate 24 hours a day, regardless of variations in solar power availability
- The increase in operating temperature (heat carrying fluid and storage) by using a mixture of sodium and potassium salts as heat carrier (other than the synthetic oil) and by a substantial improvement in the optical properties of the coating of the HCE mounted on the collectors to increase heat absorption
- The design of a new cheaper type of concentrator, based on the use of thinner mirrors mounted on a support structur

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Why concentrate light in PV?

- Higher efficiency cell/module
- Reduced amount of toxic and expensive semiconductor material
- Increased collection during the day

Other issues:

- Module/Receiver assembly and traking complexity
- Optical losses
- Needs high volume production
- Difficulties in BIPV applications
- Maintenance (?)

Panel Ramón Areces IES-UPM(1980).

- Point focus Fresnel lens which casts the sunlight onto a circular cell of about 5 cm. in diameter.
- The concentration ratio is in the range of 40X
- Rated power is about 1 kWp

Soleras Plant , Saudi Arabia
(by Martin Marietta).-

350 kW
The modules include Point focus Fresnel lenses

Nevada Power Company-AMONIX

- 168 modules made of 168 Fresnel lenses parquets and 168 receivers.
- Each receiver includes 24 lenses and 24 cells in two parallel strings of twelve. T
- The array size is 13,82 m wide, 11,53 m long and 0,53 m wide.

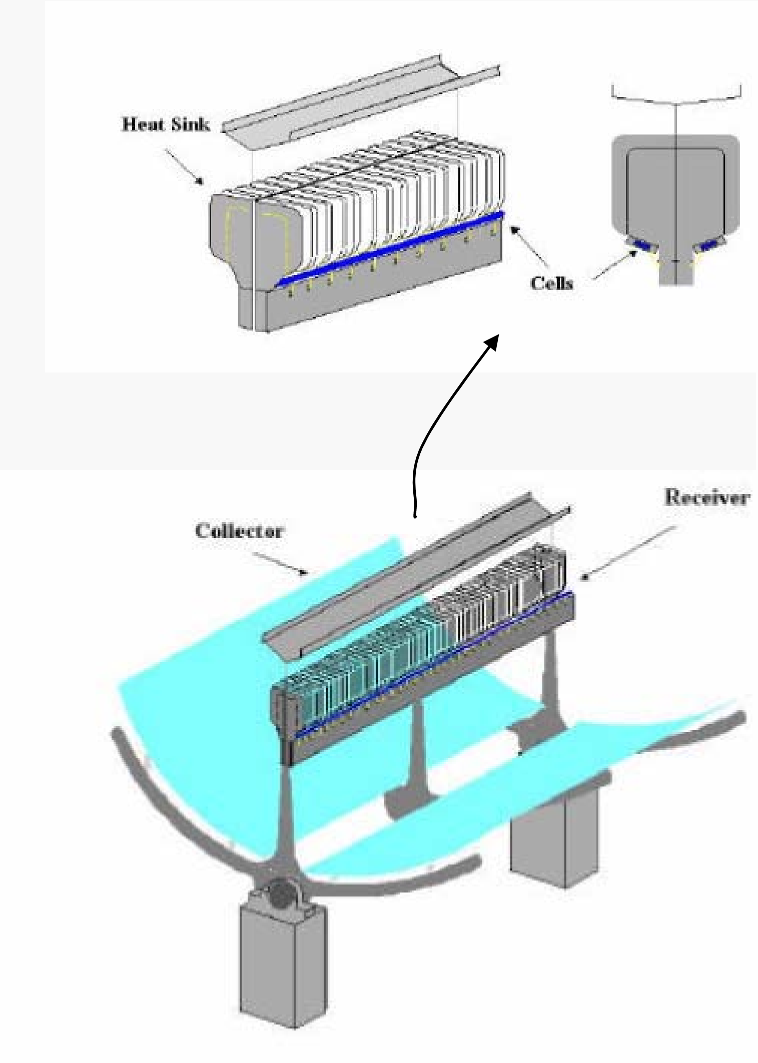
AMONIX-APS, Arizona, USA

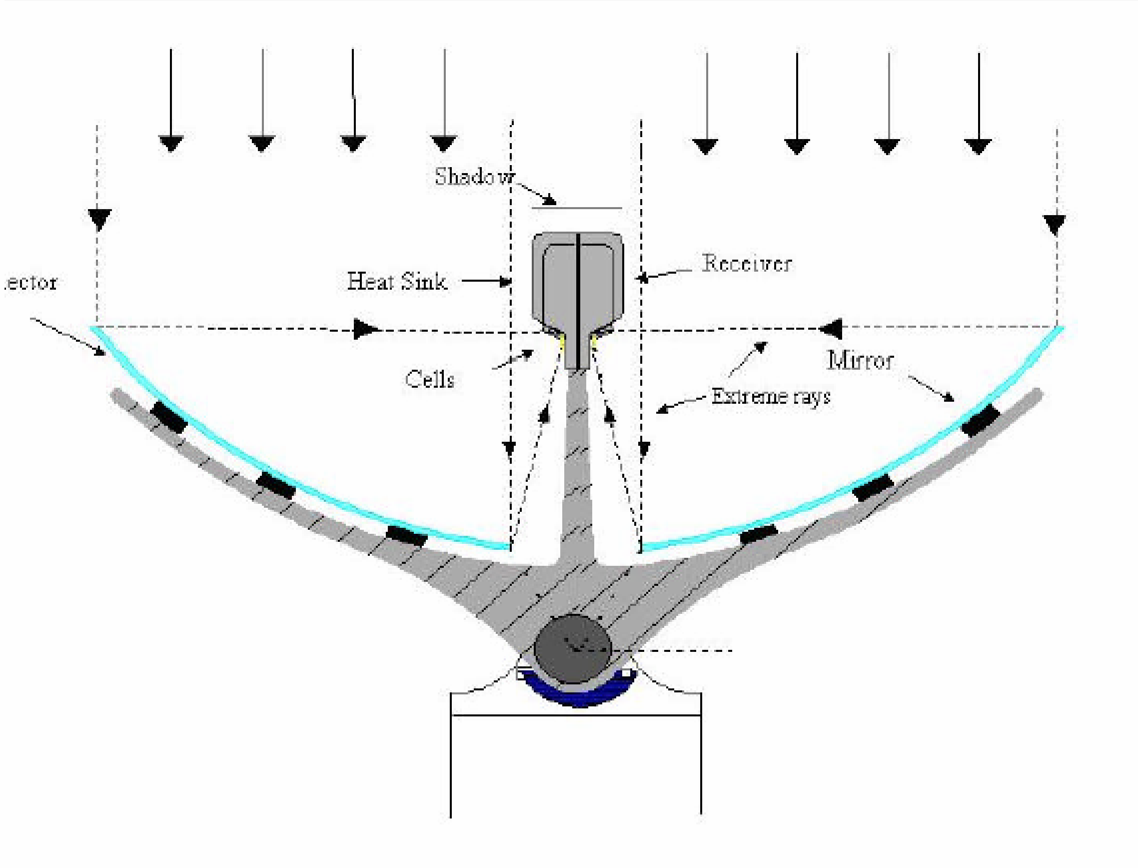
Figure 1: Amonix/APS 100 Kilowatt High-Concentration PV Installation in Arizona, USA

EUCLIDES Concentrator Array (JOULE THERMIE V):

- 140 reflective parabolic trough mirrors casting the light onto 138 linear receivers of 10 cells.
- The length of the array is 84 meters and the overall width is 3.60 m.
- The aperture area is 250 m2,
- Tracking by 1 N/S oriented axis, parallel to the ground.

EUCLIDES Concentrator



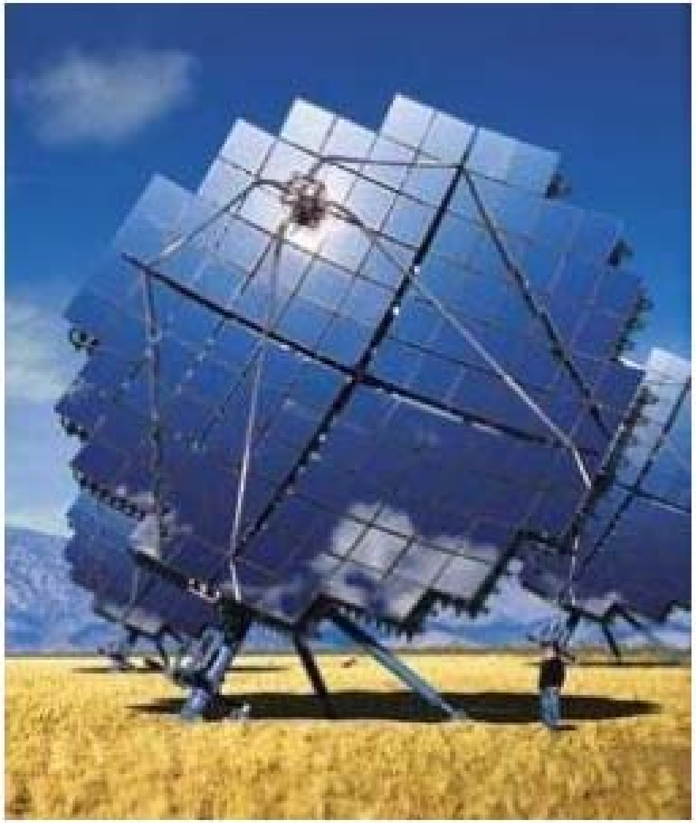


CSW Solar Park in Texas (by ENTECH Inc.)

- *100 kW system. Each of four array comprises 72 Concentrator Modules with 220 s.q.m. total aperture.*

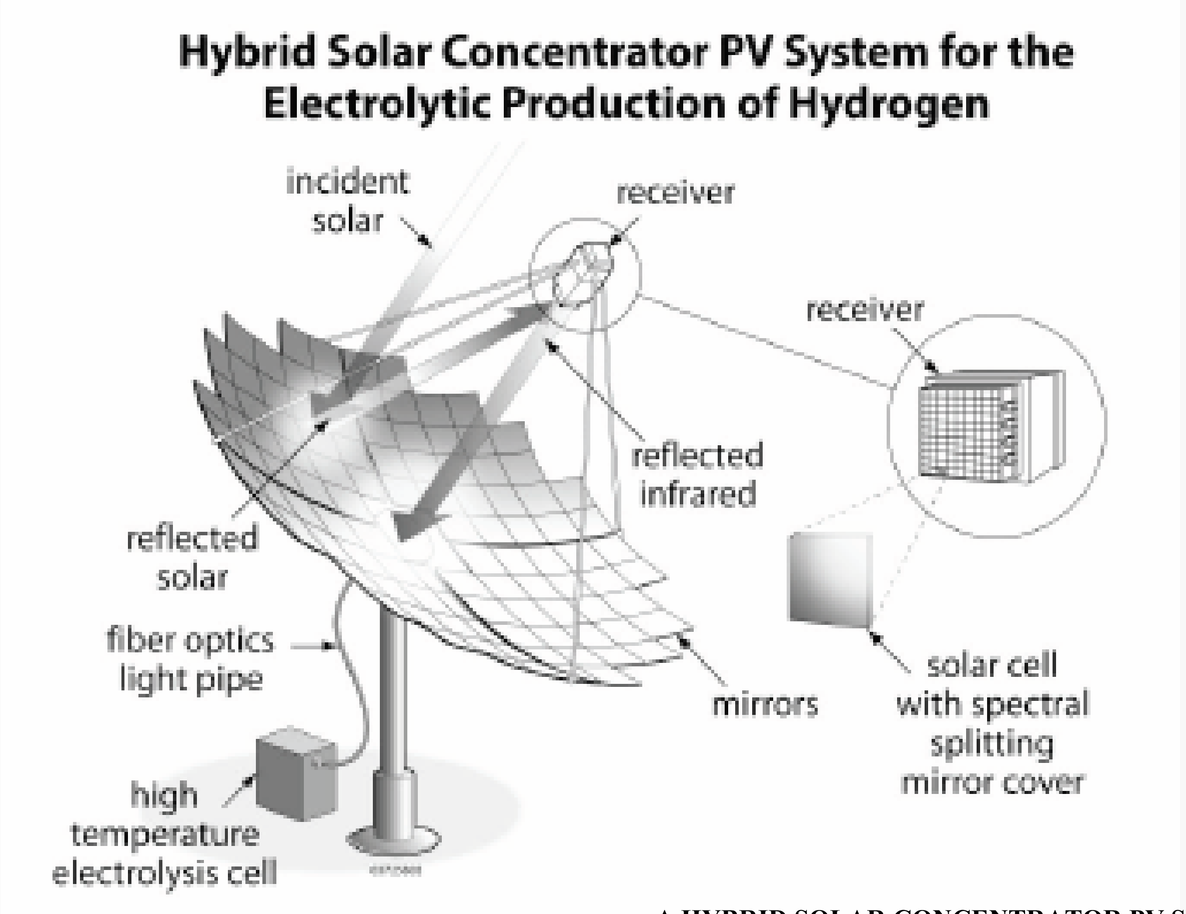
Solar Systems' solar farm, Alice Springs (Australia)

Visitors



Parabolic Dish Australia. Solar Systems Pty concentration ratio of 500X. Each dish is nominally 20KW

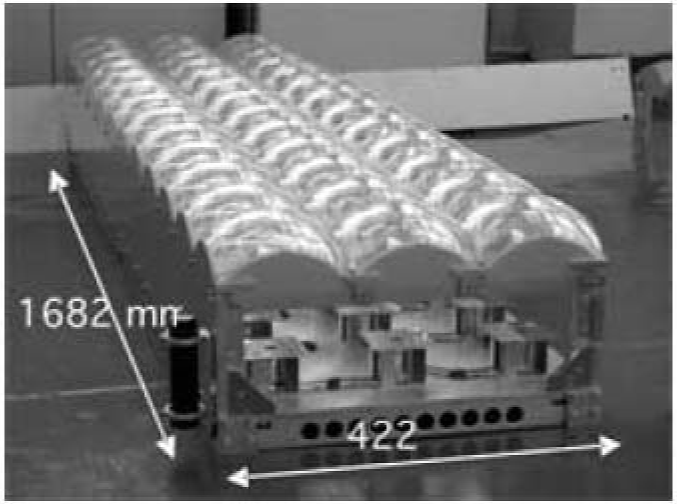
Innovative application: H2 production



Solar Systems P/L.The sunlight is reflected and focused on the receiver, with reflected infrared directed to a fiber-optics waveguide for transport to a high-temperature solid-oxide electrolysis cell. Solar electricity is sent to the same electrolysis cell that uses both heat and electricity to split water.

A HYBRID SOLAR CONCENTRATOR PV SYSTEM FOR THE ELECTROLYTIC PRODUCTION OF HYDROGEN; R.D. McConnell, J.B. Lasich, and C. Elam; 20th EPVSEC 1CO.6.6

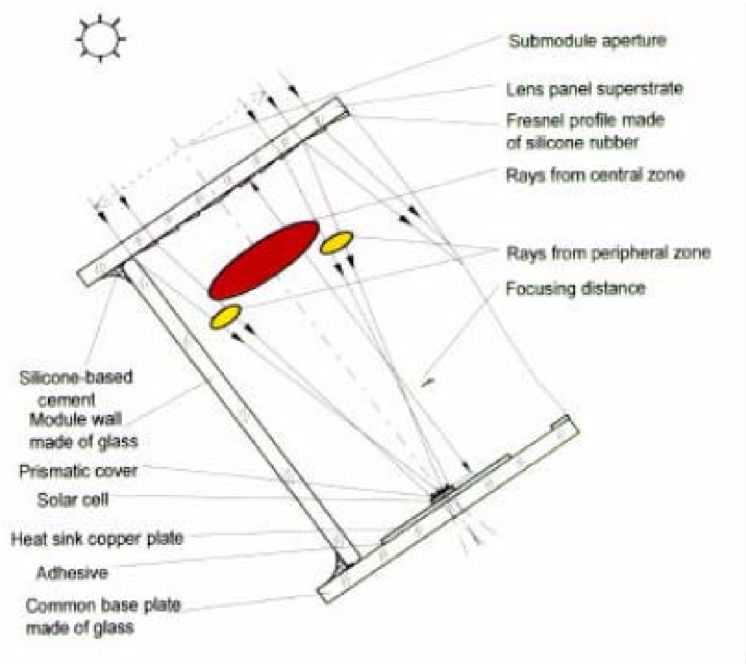
Toyota Dome-Shaped Fresnel lens



- 550X Concentrator System with Dome-Shaped Fresnel realized by TUAT through injection molding;
- 4*10 cells/ module - rating: 300W - weight: 25 Kg → 0,08 Kg/W;
- triple junction η>37 % at C=500X;
- SOE glass rod kaleidoscope homogenizer;
- Module efficiency 28,9%

The prototype of the static concentrator (UPM-Universidad Politécnica de Madrid) with bifacial cells.

FISE /Ioffe-Institute



- Water resistant all-glass concentrator module designed by FISE and the Ioffe-institute
- Test module based on an all glass design with an area of 64 cm2,
- Geometric concentration ratio of 123 and 2 cells in series and 2 strings in parallel.

Flatcon Module ®

Compact PV Concentrator systems

Whitfield Solar PV concentrators

Whitfield Solar PV Concentrators

Materials
-PMMA Fresnel lens parquet
-Stainless Steel base frame
-Extruded aluminium troughs
Aluminium top frame

Configuration (1 unit)
-24 X 1 troughs per unit in series
-Footprint 4,10 x 0,98 m
-Concentration 40X Geometric
-End stops N/S + E/W

Tracking
-Intelligent 2 Axis Tracking to 0,1 degrees
-Individual Controllers for each unit
-Power saving sleep function
-Multi-speed movement
-Logarithmic response

Electrical Performance
- 160 Voc; 140 Vpp; 2A Isc; 250 Wp

Gira-Sol System; Spain

Number of sub-modules	5
Cells per sub-module	10
Total solar aperture	0,72 m2
Cell efficiency	35%
Module efficiency	28%
Voc	150V
Isc	1,5A
FF	85%
Wp at 1kW/m2 DNI	192
Dimensions (mm)	1200 x 1250 x 200
Weight	25 Kg

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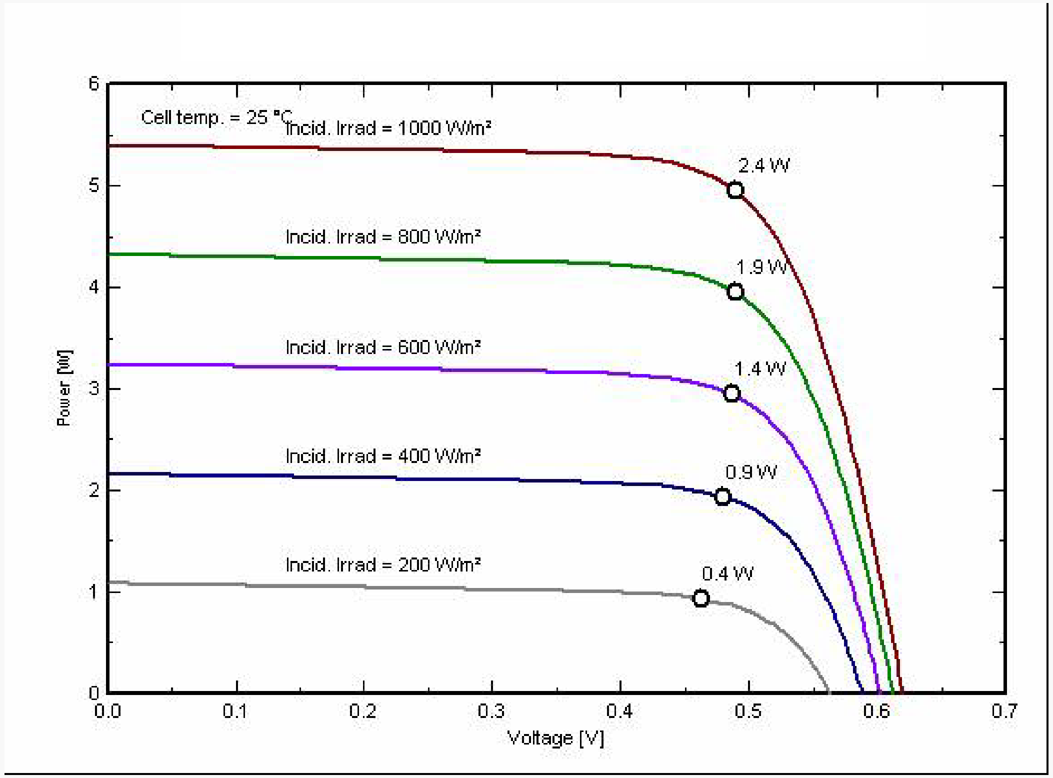
Effect of changing light intensity



$$V_{OC} \approx \frac{kT}{q} \ln \frac{I_{SC}}{I_{o1}}$$

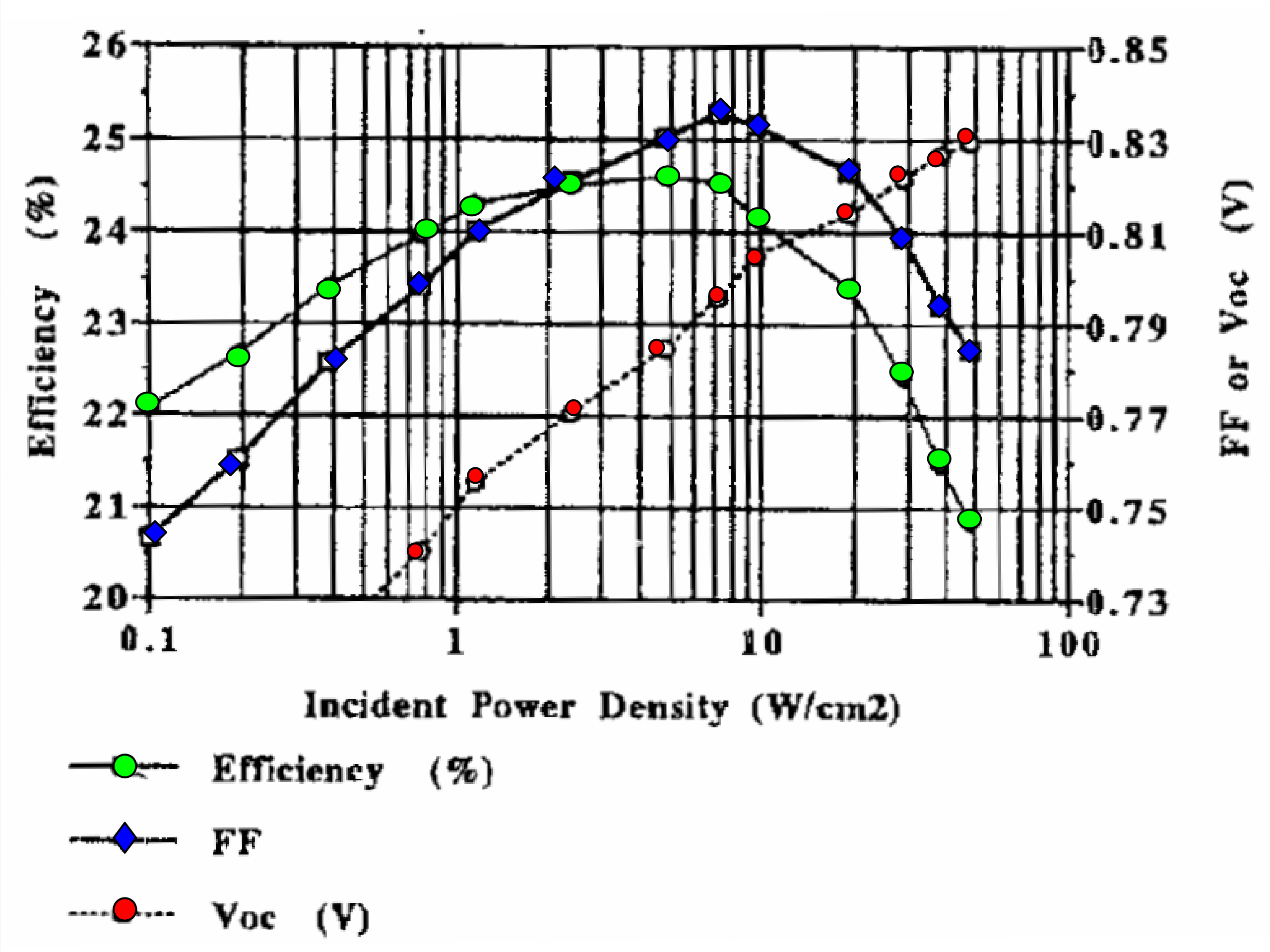
Isc $\propto$ Inc.Irrad

FF initially remain almost unchanged

⇩

Efficiency initially increase with intensity of the light but Fill factor drops to higher incident radiation due series resistence losses at high current

Efficiency of Silicon Solar cells for concentration – vs- Incident power density



Reducing Series Resistance

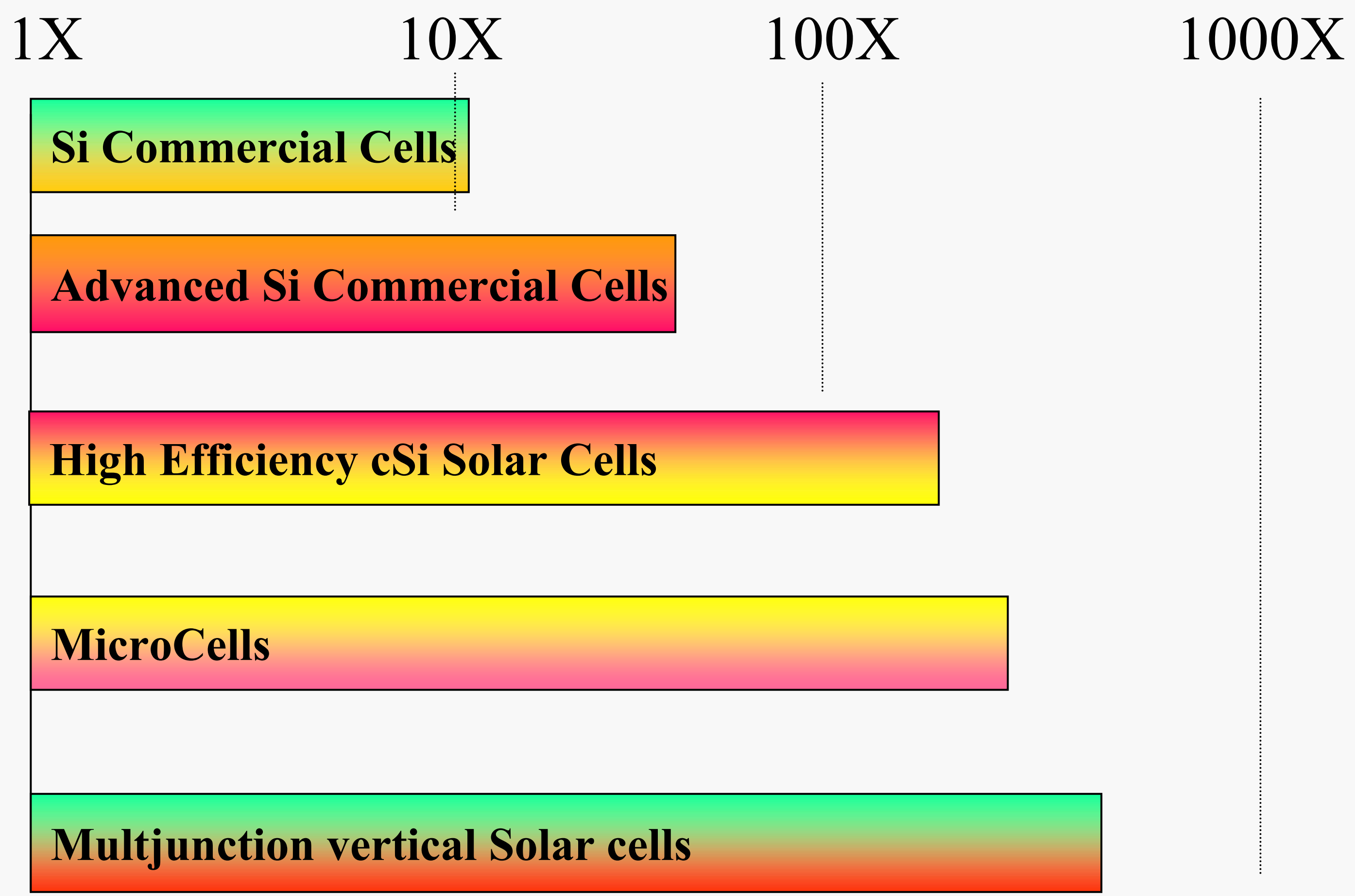
- Metal finger resistence
  - by using low resistivity metals (i.d. Ag) and thick fingersMetal finger resistence
- Metal/Semiconductor contact resistence
  - Heavy diffusion below metal contacts
- Diffused emitter resistence
  - Relatively thick, and higher diffused emitter are attractive
- Base region
  - Optimized contact point spacing

⇩

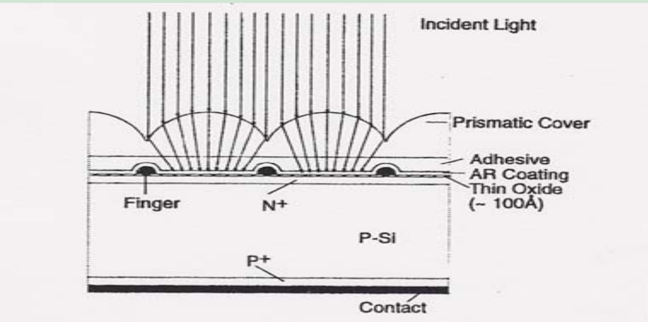
A trade-off exist between proposed actions and

- Contact Shading
- Emitter ricombination

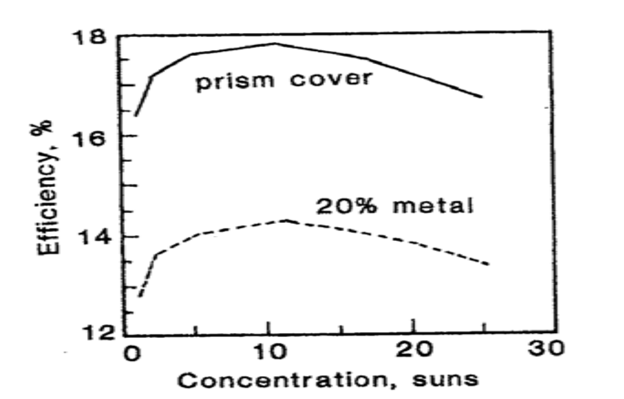
Si Solar cells for the PV concentration



Si commercial Solar cells for Concentration

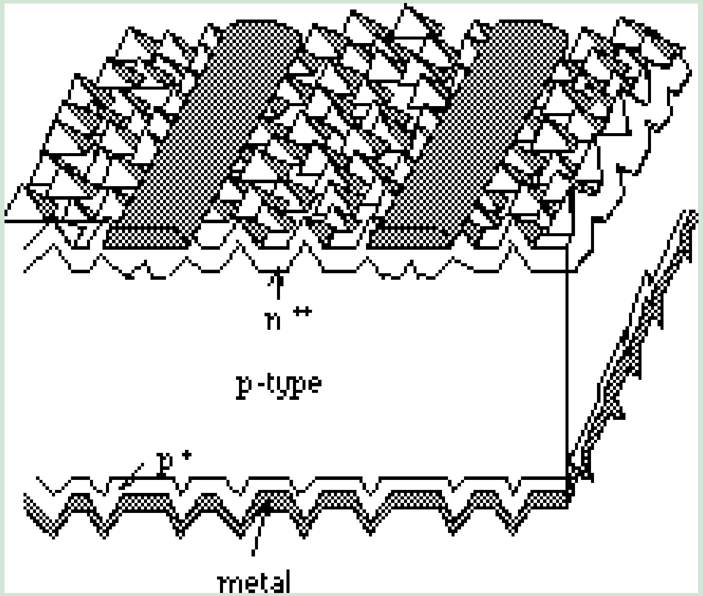


Secondary prismatic concentrator



Entech 300kW$_p$, EFF 15%

20X



Solar cells having printed contacts
A=100 cm^2

Advanced Commercial Si Solar cells
BURIED CONTACT CELLS

40X

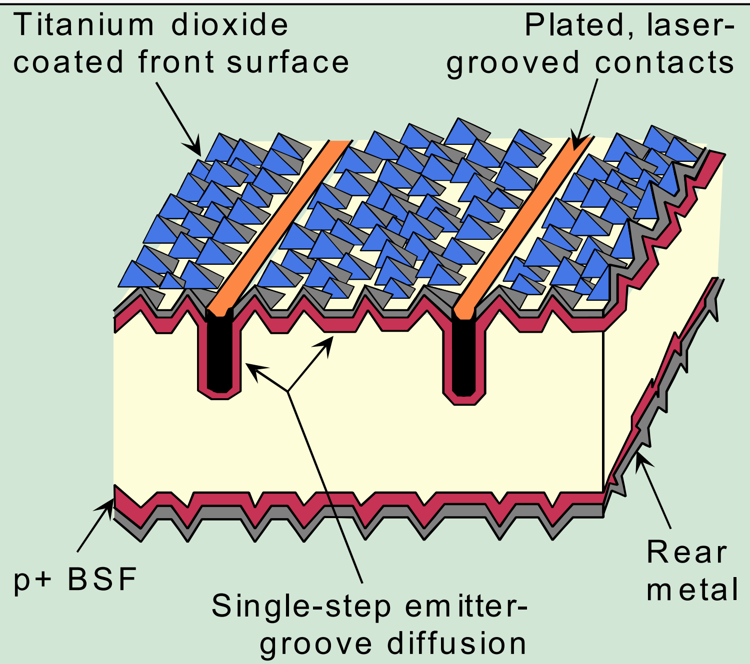
EFF 17-18% Cell

16% Module

13% System

Tenerife Plant

480kW$_p$ 20cents/kWh

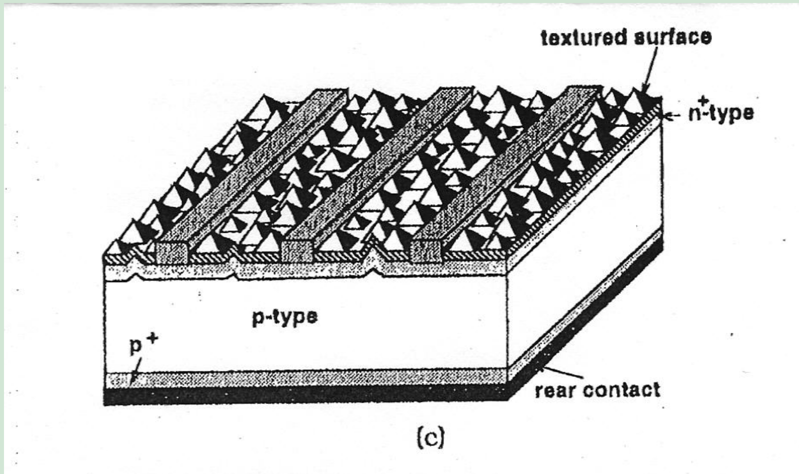


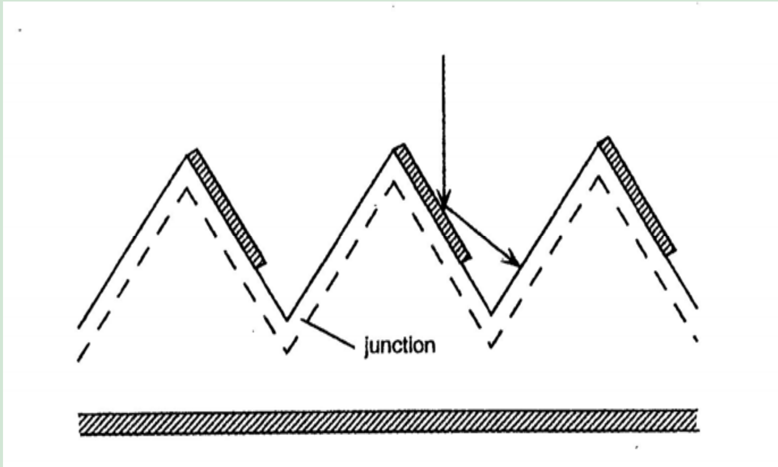
Laser Grooved Buried Grid solar cells

(BP Solar) A = 46 cm^2

Conventional high Efficiency Solar cells

30X-100X





20 cm^2 cells on Fz wafers
one non aligned photolithography step
Cell eff 22% under 30 suns
20 KW_p prototype in Perth
(Australian National University)

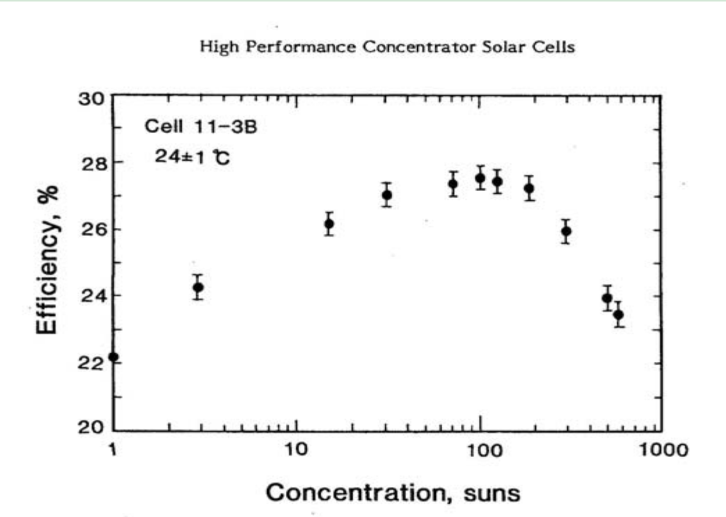
V-groove solar cell
All Light Specularly Reflected from the Top Contact Metal Strikes the Opposite Face of the Grooved Surface

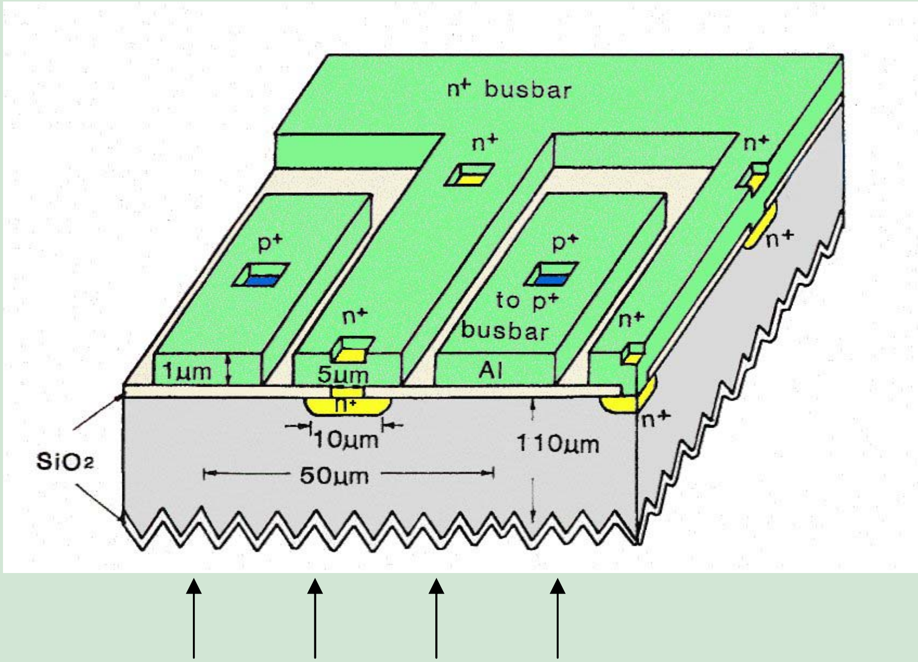
High Efficiency Si solar cells

POINT CONTACT SOLAR CELL

100X- 300X

EFF 27.5% 100X





Arizona Plant 100kW$_p$, 250X,

EFF 20% sistema

Back Sided Point Contact Solar Cell
(Stanford University)

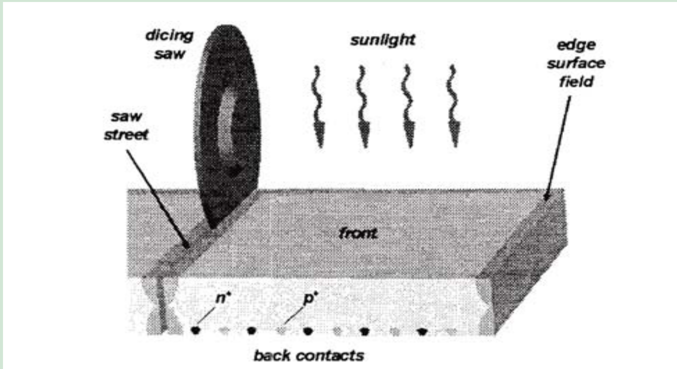
Micro Solar cells

SunPower concentrating photovoltaic (CPV) module

300X

"chip-size" silicon solar cells

(-0.05 cm^2) Eff 24%



Module efficiency projected to be about 18%

all-back point- contact silicon solar cell technology

$ 2.20 per watt (proiected)

Series connected 5x6 array

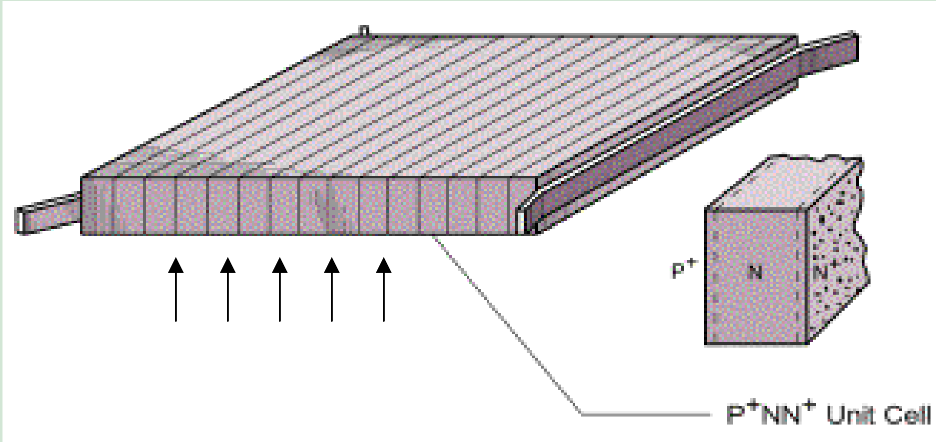
1300 cells on a single 100 mm diam wafer

Vertical Si Multi-junction Solar Cells

PhotoVolt Inc.

Technical feasibility under the Department of Energy (DOE) Inventions and Innovation Program

Target: 20 percent efficiency at 33.2 watts/cm ^{2}



High Intensity Silicon Vertical Multijunction

(VMJ)

Vertical Si Multi-junction solar cells

PhotoVolt's VMJ

- ✓higher voltage and lower current operation
- ✓ lower costs through high efficiency at high intensity
- ✓No photolithography processes
- ✓Less silicon than conventional solar cells
- ✓Simple design results in lower manufacturing costs
- ✓One-wafer design for all intensities, wide range of cell sizes
- ✓Low series resistance at high intensities

Record Efficiency concentrator solar cells (single Junction)

Classification	Eff. %	Area (cm^2)	Intensity (suns)	Test Centre (date)	Description
GaAs	27.6 ± 1.0	0.126	255	Sandia (5/91)	Spire
GaInAsP	27.5 ± 1.4	0.075	171	NREL (2/91)	NREL, Entech cover
Si	26.8 ± 0.8	1.60	96	FhG-ISE (10/95)	SunPower, back contact
InP	24.3 ± 1.2	0.075	99	NREL(2/91)	NREL, Entech cover
CIGS (thin Film)	21.5 ± 1.5	0.102	14	NREL (2/01)	NREL

Multi-junction for higher efficiency

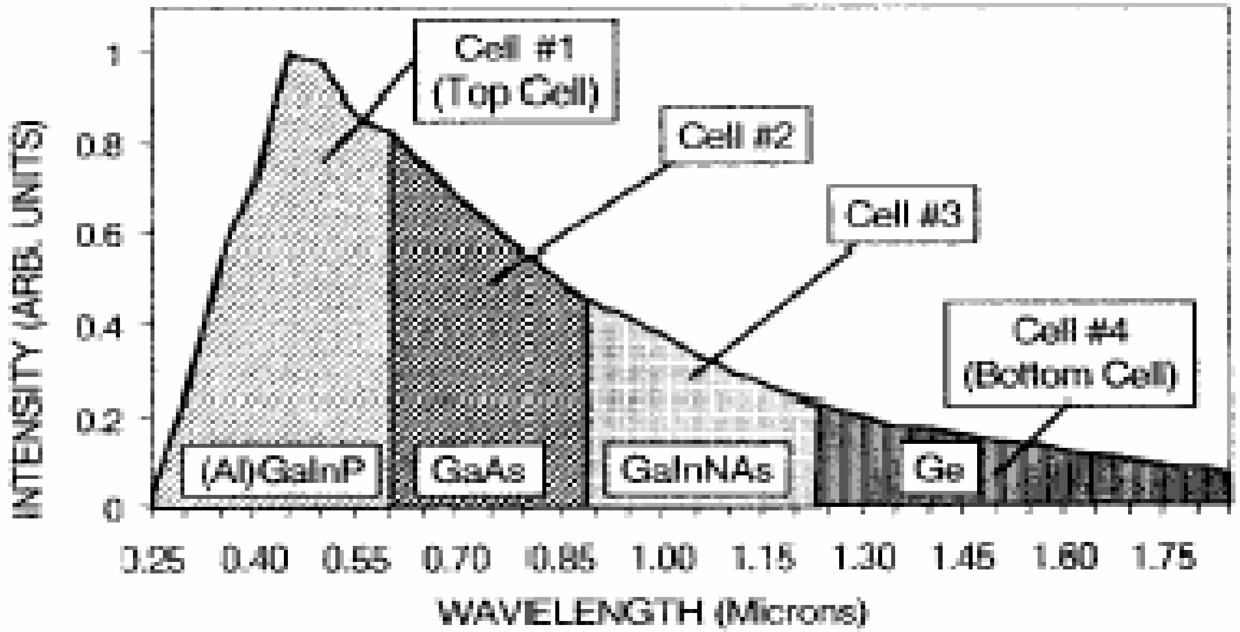
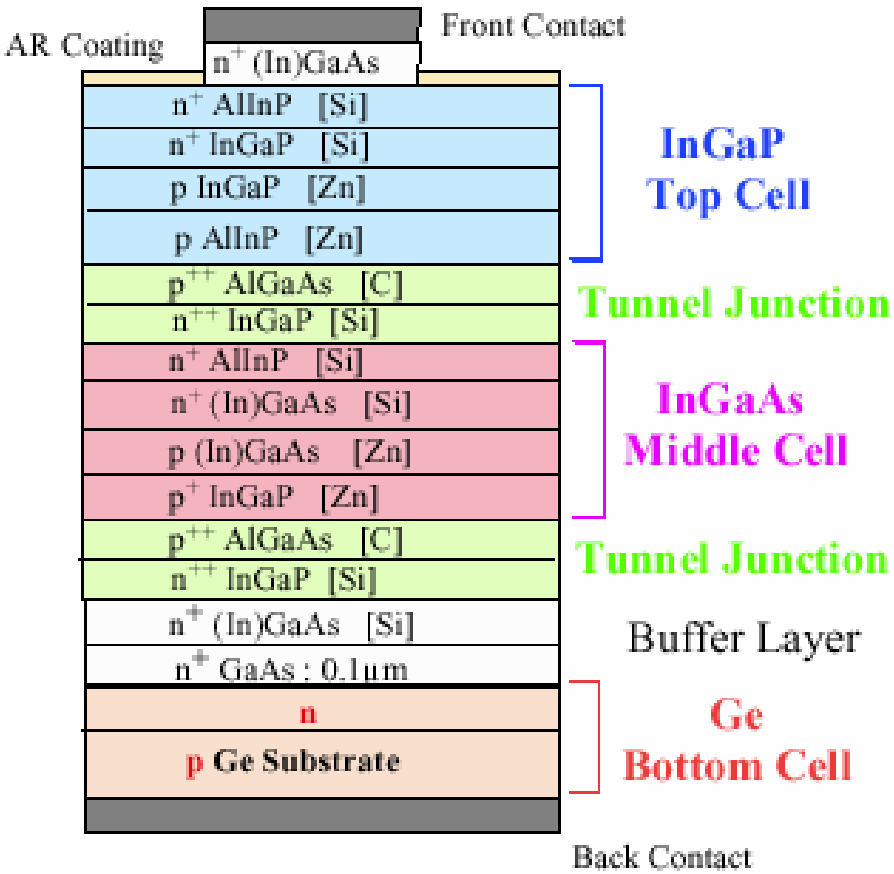
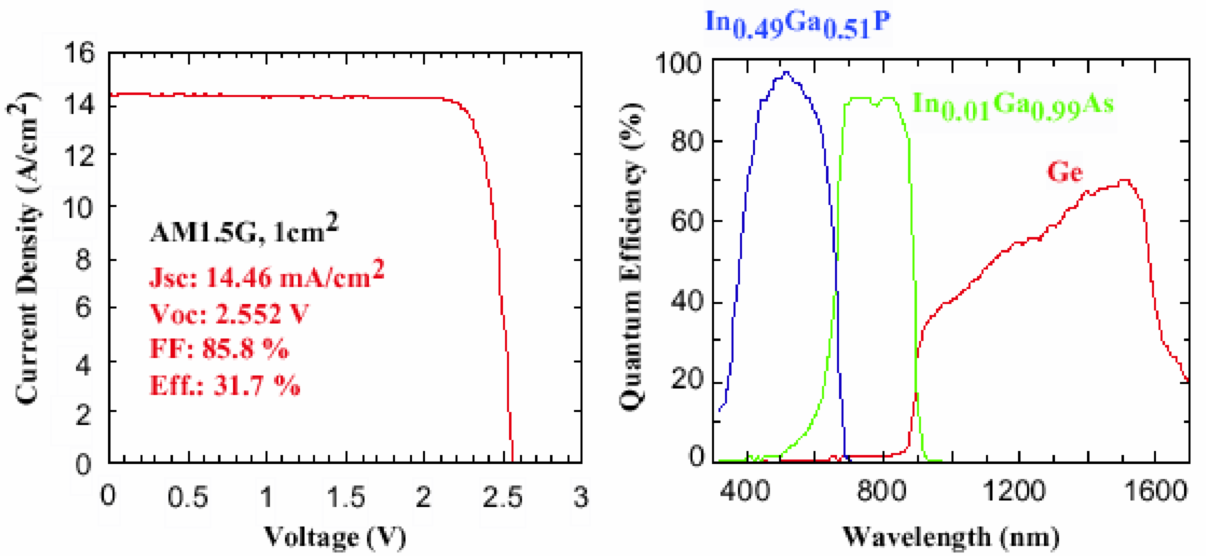


Fig. 9. Division of the AM0 spectrum in a 4-junction AlGaInP/GaAs/GaInNAs/Ge solar cell.

Structure of Triple-Junction (3J) Cell

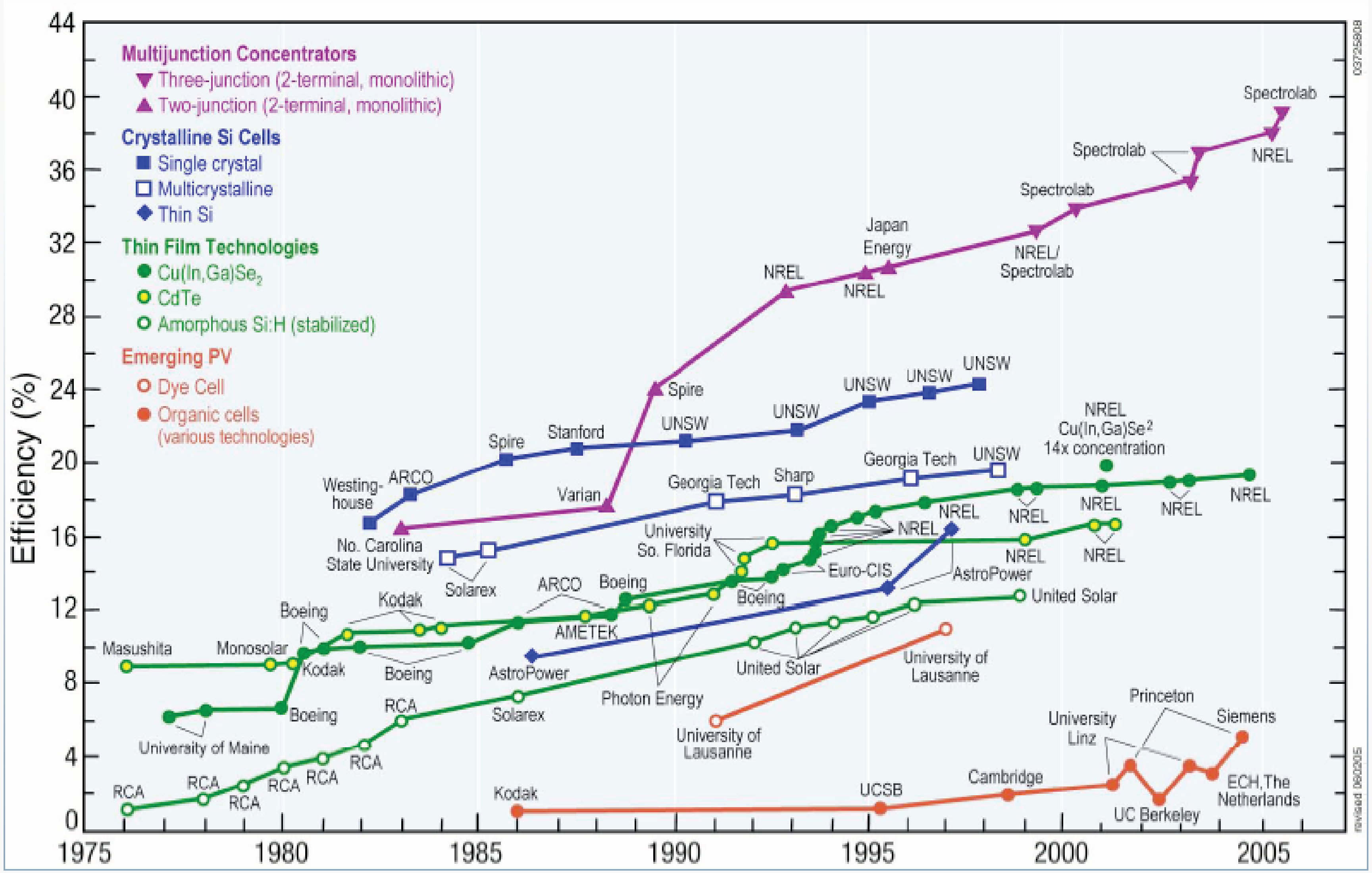


Characteristics of 3J Cell (x=0.01)



A structure, I-V curve and spectral response of a high efficiency InGaP/GaAs/Ge 3-junction cell fabricated on a Ge substrate.

Best Research-Cell Efficiencies



Record Concentrator III-V Cell efficiency

Material	Eff. %	Area (cm^2)	Intensity (suns)	Test Centre (date)	Description
GaInP/GaAs/Ge (two-terminal)	35.2	0.266	66.3	NREL (2/03)	Spectolab
GaInP/GaInAs (two-terminal)	32.0	0.13	280	Fh-ISE (02)	Fh-Ise, AM 1.5 g spectrum (bandgap 1.67/1.18 eV)
GaInP/GaInAs/GaSb (tmechanical stack)	33.5	0.13	300	FhG-ISE (02)	Fh-Ise, AM 1.5 g spectrum (bandgap 1.88/1.18-0.72eV)
InGaP/InGaAs/Ge	37.4	0.49	200	Not Official	Sharp Corp., Japan
Modules					
GaInP/GaInAs	24.8	64	123	Fh-ISE (02)	Fh-Ise, outdoors, monolithic
GaAs/GaSb	25.1	41.4	57	Sandia (3/93)	Boeing- Three Mechanical Stack
GaInP/GaAs/Ge	27.0	34	10	NREL (5/00)	Entech
GaAs	20.1	248	160	Fh-Ise (02)	Fh-Ise, outdoors
InGaP/InGaAs/Ge	28.1	7056	400	Sharp (03)	Daido Metal/Sharp, Japan

Measured under direct beam AM 1.5 spectrum at the cell temperature of 25°C

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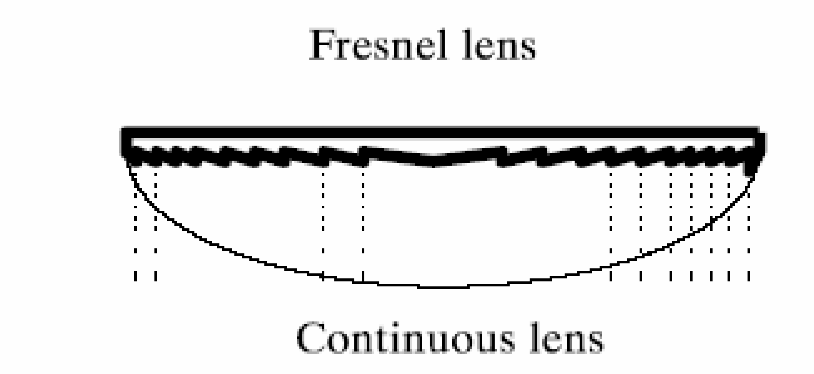
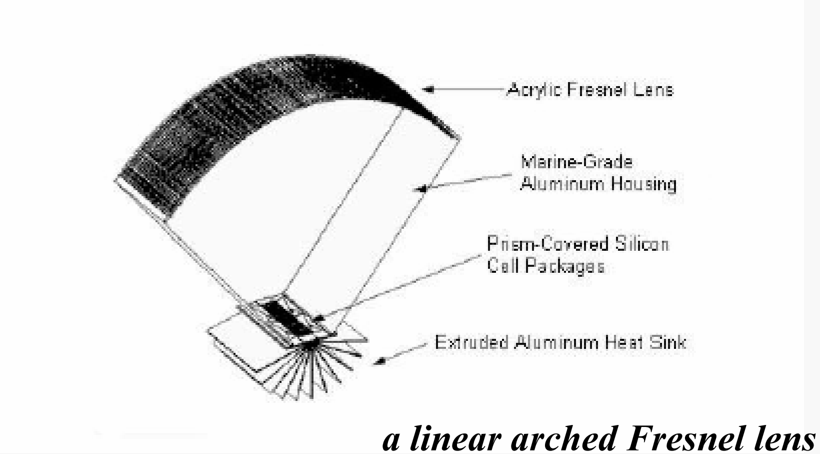
Refractive Concentrators



Fresnel lenses are made by projecting the lens surfaces onto a plane or curved sheet in such a way that the rays encounter the same slopes as in a conventional lens,

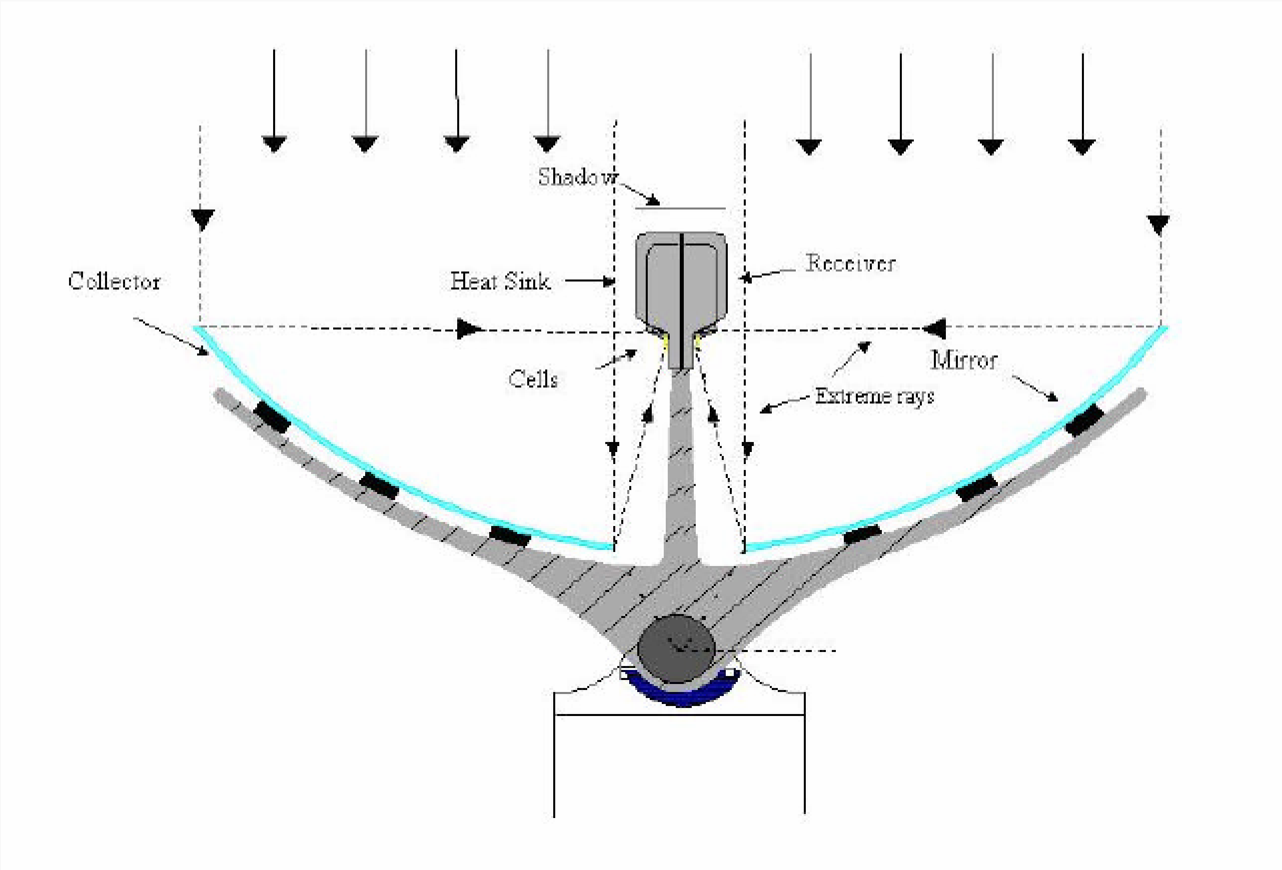
↓

less weight and cost advantages compared with conventional lenses, but less optical efficiency

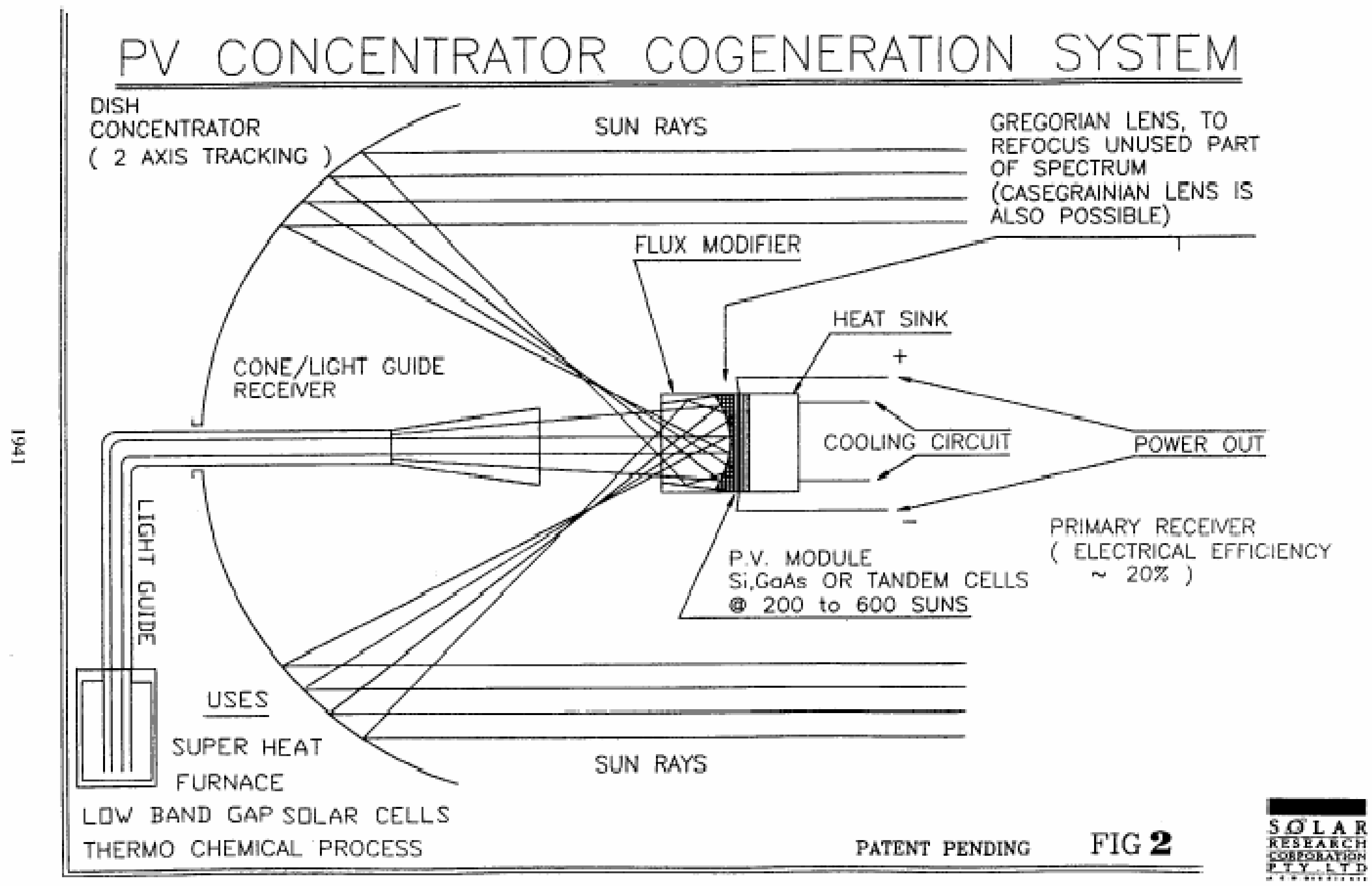


a linear arched Fresnel lens made by Entech

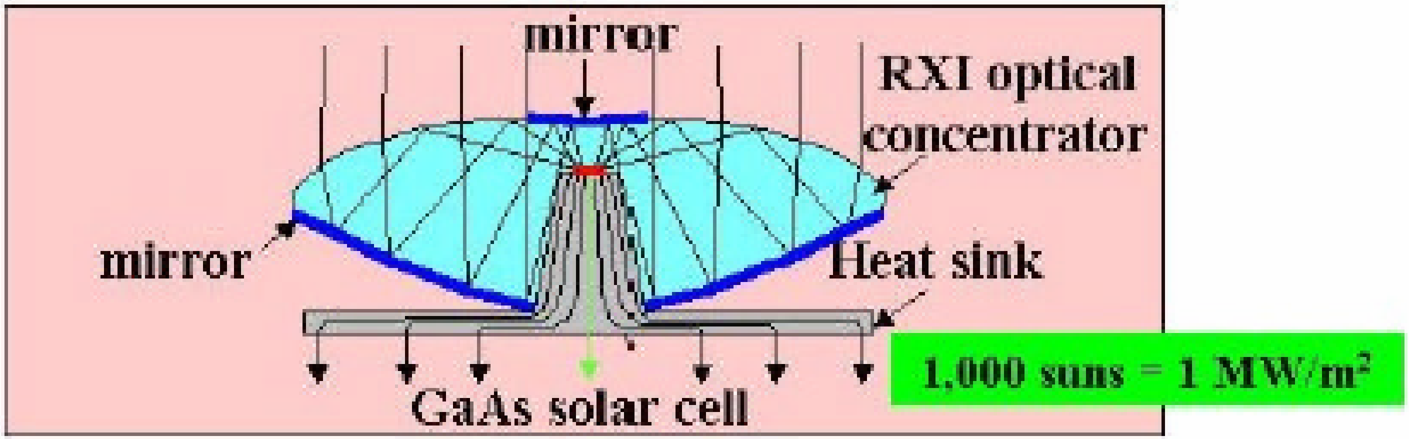
Reflective concentrators



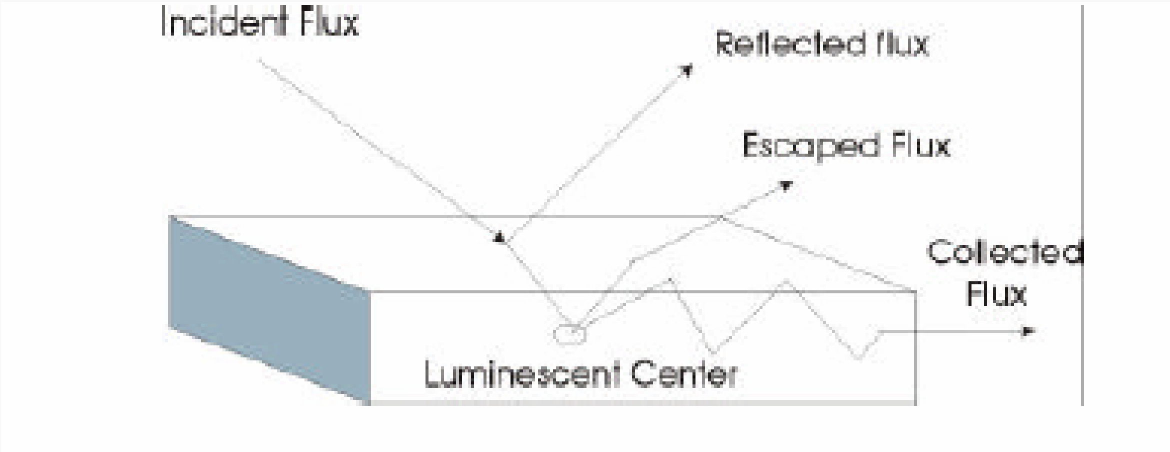
DISH CONCENTRATOR



RXI device (Refractive & Reflexive &Internal Reflection)

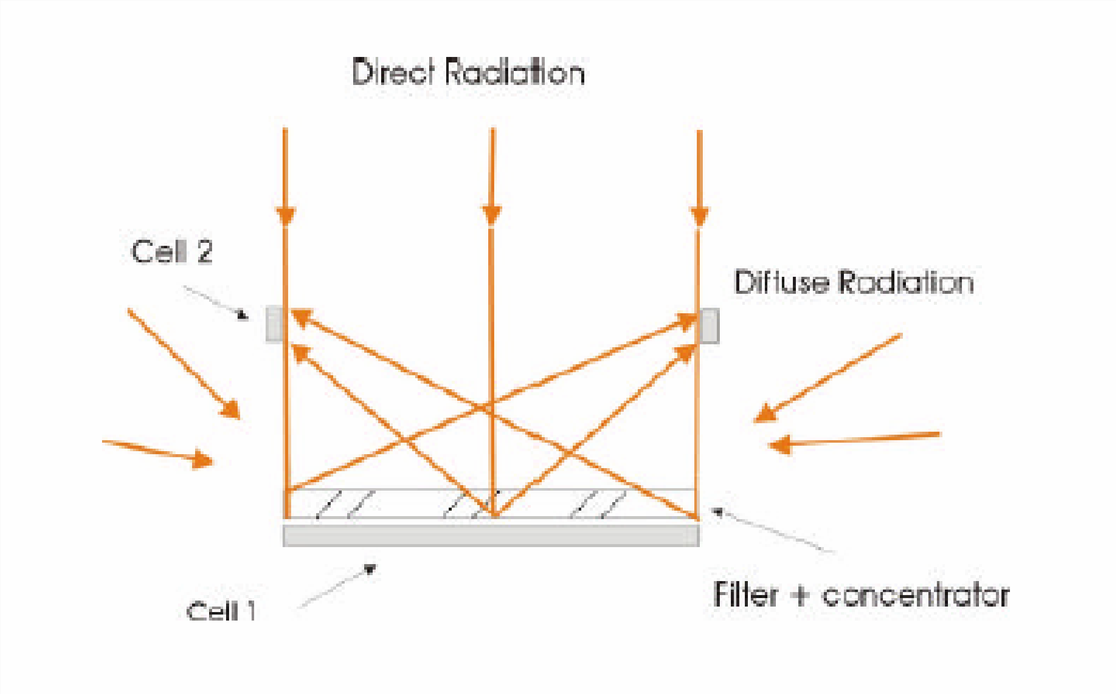


LUMINESCENT CONCENTRATORS (LC)



non-imaging optical device for collecting and concentrating light energy formed by a planar optical matrix embedded with a luminescent dye reflective on one side. Photons incident on the LC are absorbed by the dye at molecular level. These luminescent centers may then emit new photons, a large fraction of which are trapped within the LC and guided to its edges by total internal reflection

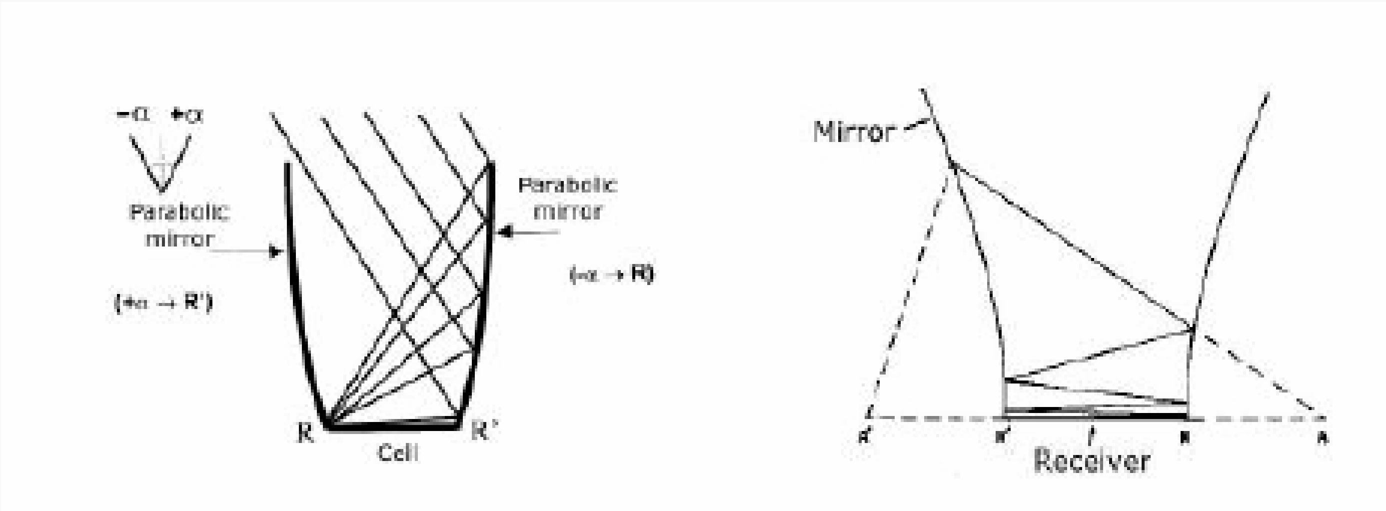
Holographic concentrator



- spectral beam splitting by means of light diffraction effects

- Utilization of solar cells optimized for each specific area of light spectra

2D Concentrators



Compound parabolic concentrator (CPC) with angular acceptance ±α

Compound hyperbolic Concentrator (CHC) or trumpet concentrator

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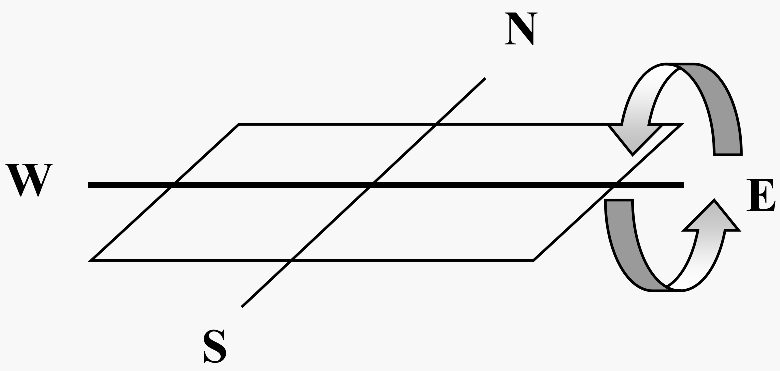
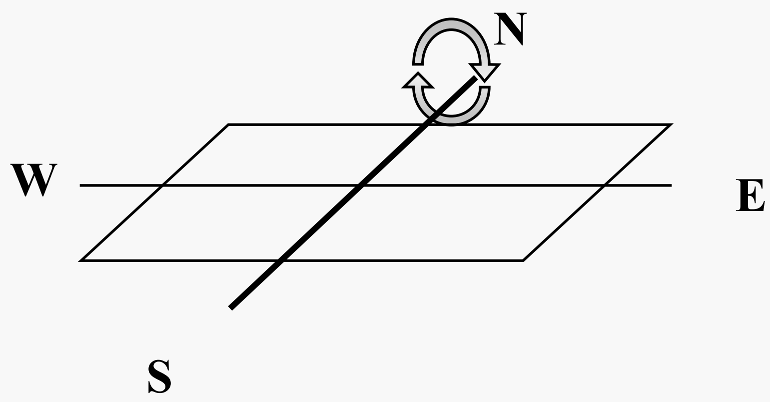
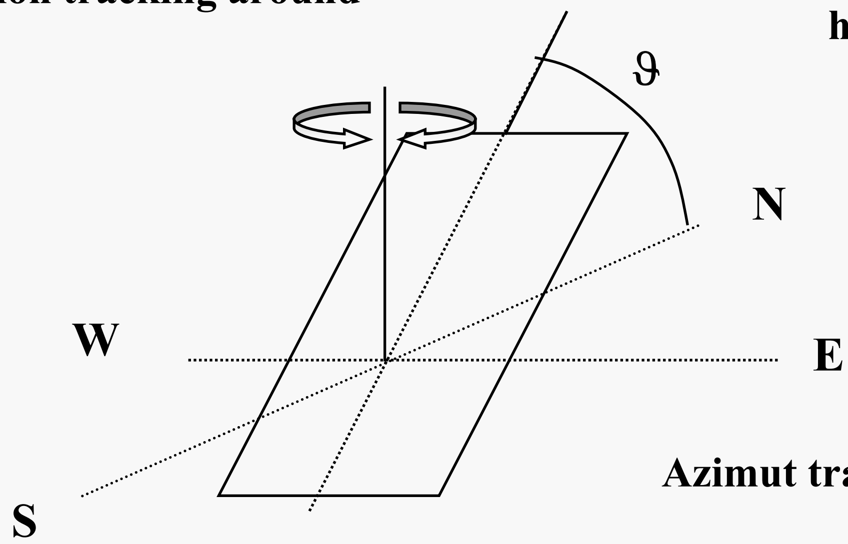
Semplified tracking schemes



Yearly elevation tracking around an E-W axis;

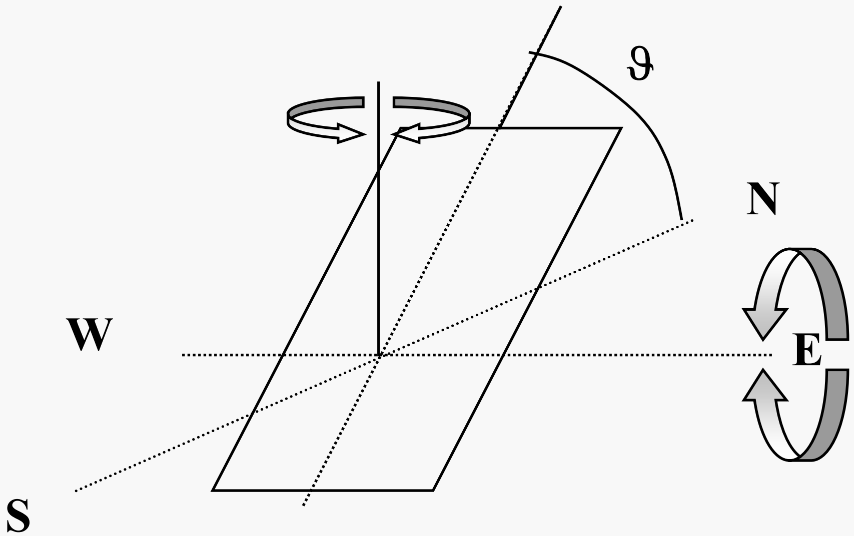


Hour angle tracking around an horizontal N-S axis;

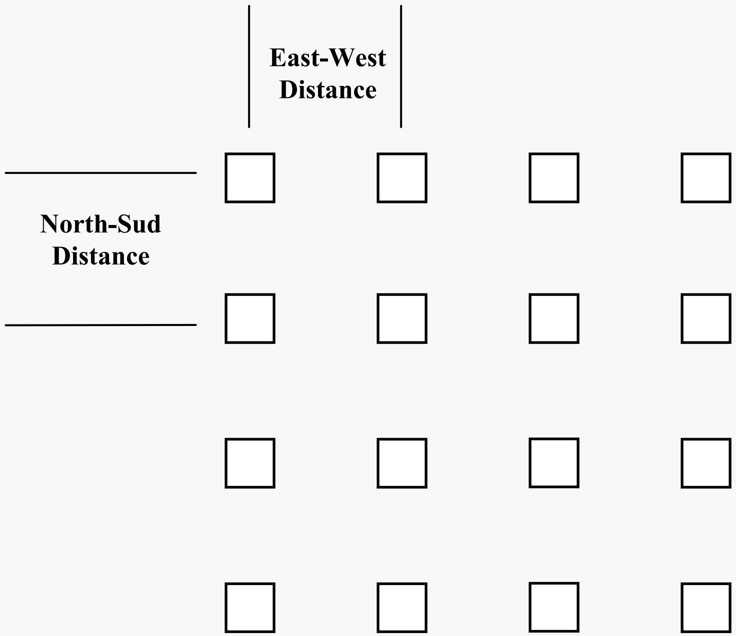


Azimut tracking around a Vertical axis

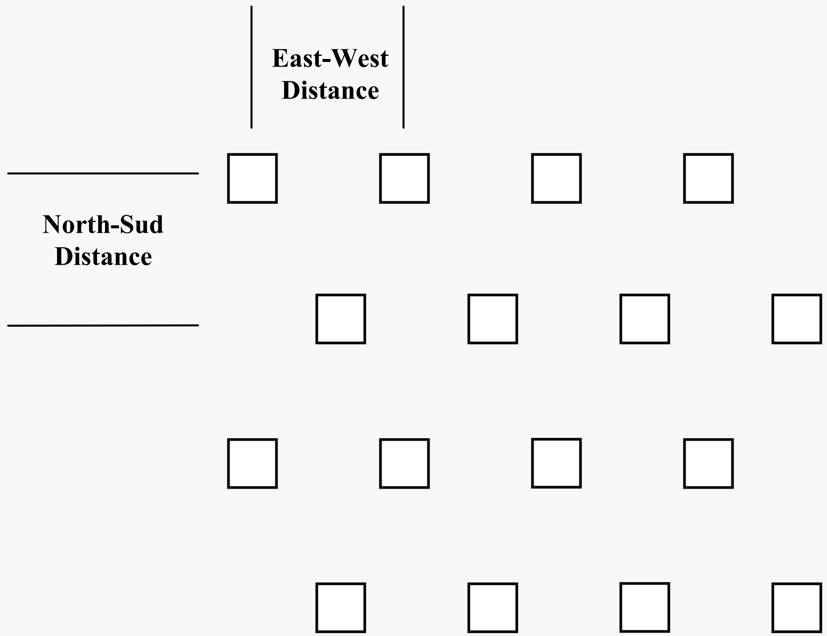
Two axis tracking around horizontal and vertical axis



Layout of PV array



Schematic of part of square field layout of pv arrays (for two-axis trackers)



Schematic of part of exagonal field layout of pv arrays (for two-axis trackers)

Shading losses

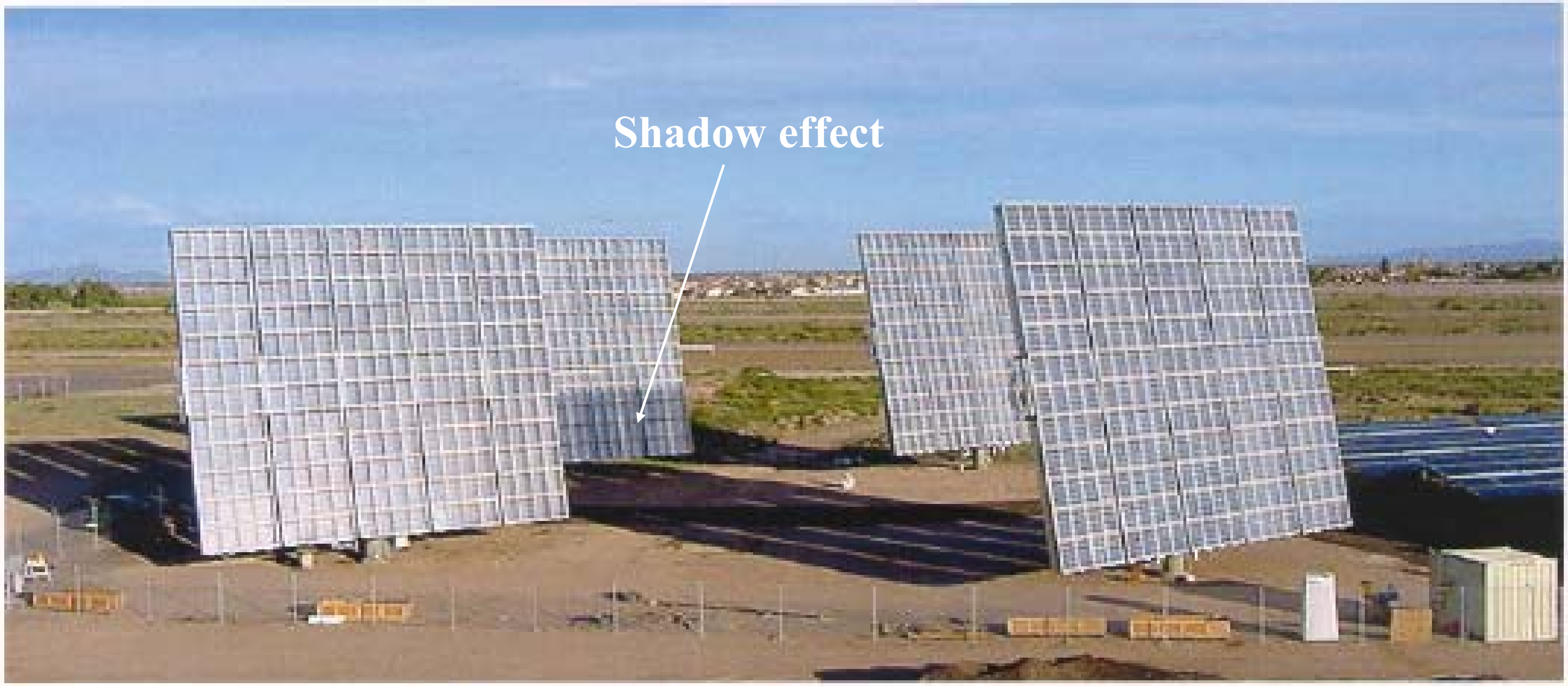
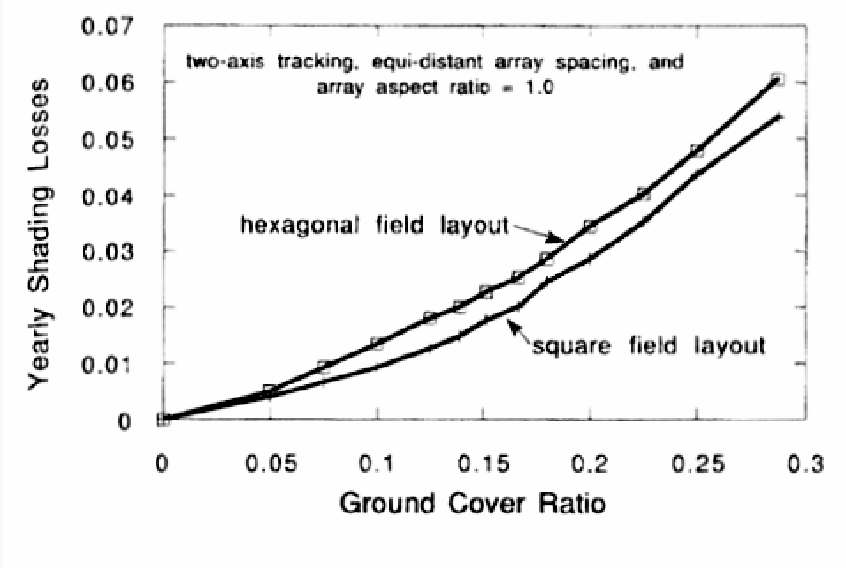
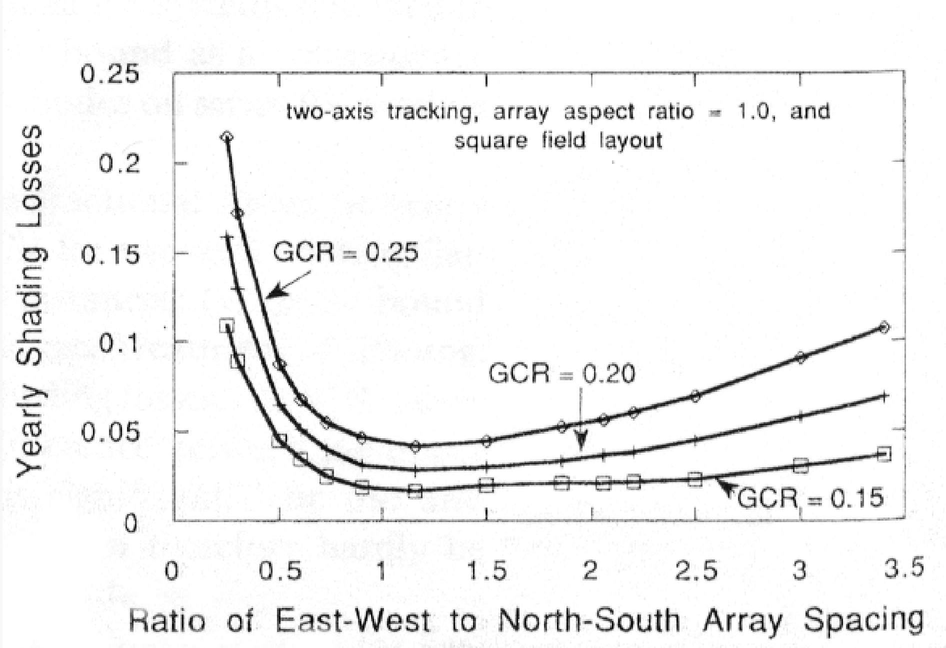
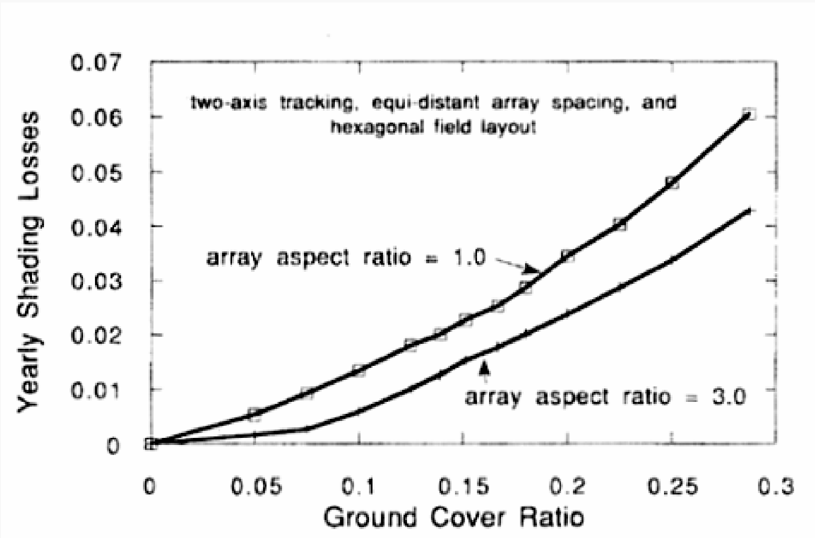


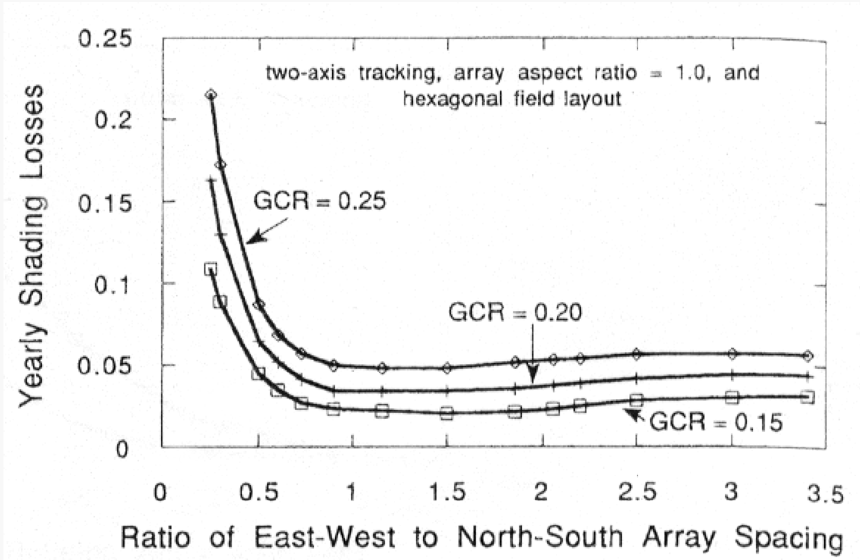
Figure 1: Amonix/APS 100 Kilowatt High-Concentration PV Installation in Arizona, USA

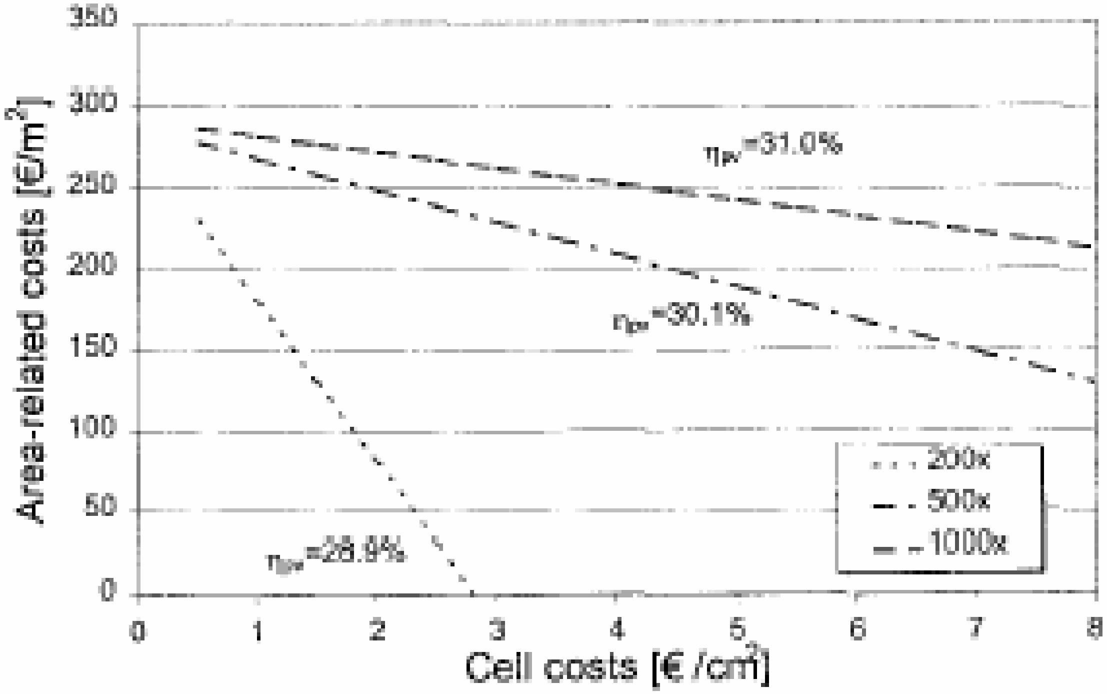
Yearly shading losses











Estimation of area-related system costs versus cell costs depending on the concentration level of the system. The given PV-cell efficiencies are the values which would be measured in the laboratory under a certain concentration

Outline

1. Introduction
2. Concentrator PV Systems
3. Solar receiver
4. Optics
5. Traking system
6. Perspective for PV concentrators
7. ENEA Phocus Project

Objectives

Short-Middle term Target

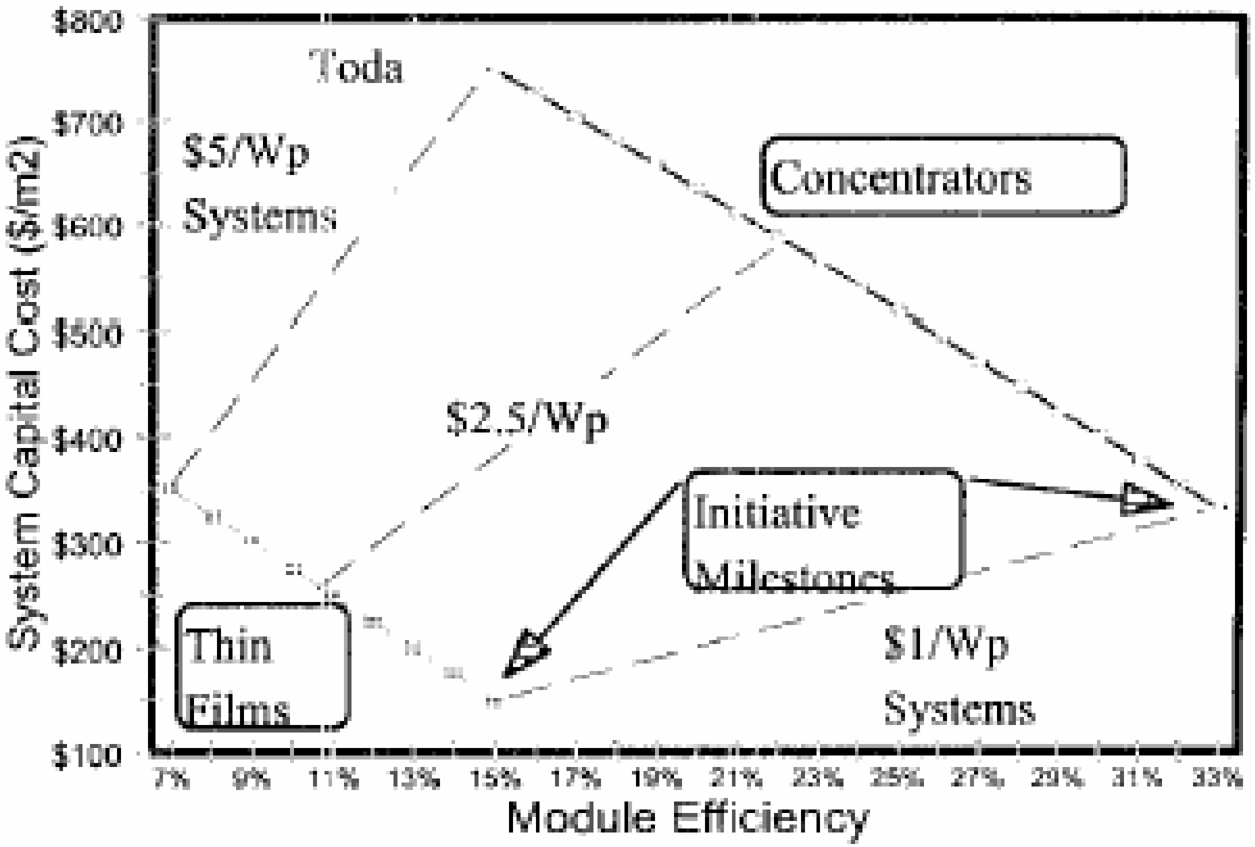
- Accelerate the development of PV to meet economic andenvironmental needs
- Double sunlight-to-electricity conversion efficiency of cost-competitive PV technologies

Long-Term Target

- Higher efficiencies are expected since theoretical efficiencies are still so high. Researchers are seriously designing approaches for fabricating solar cells with over 50% efficiency,

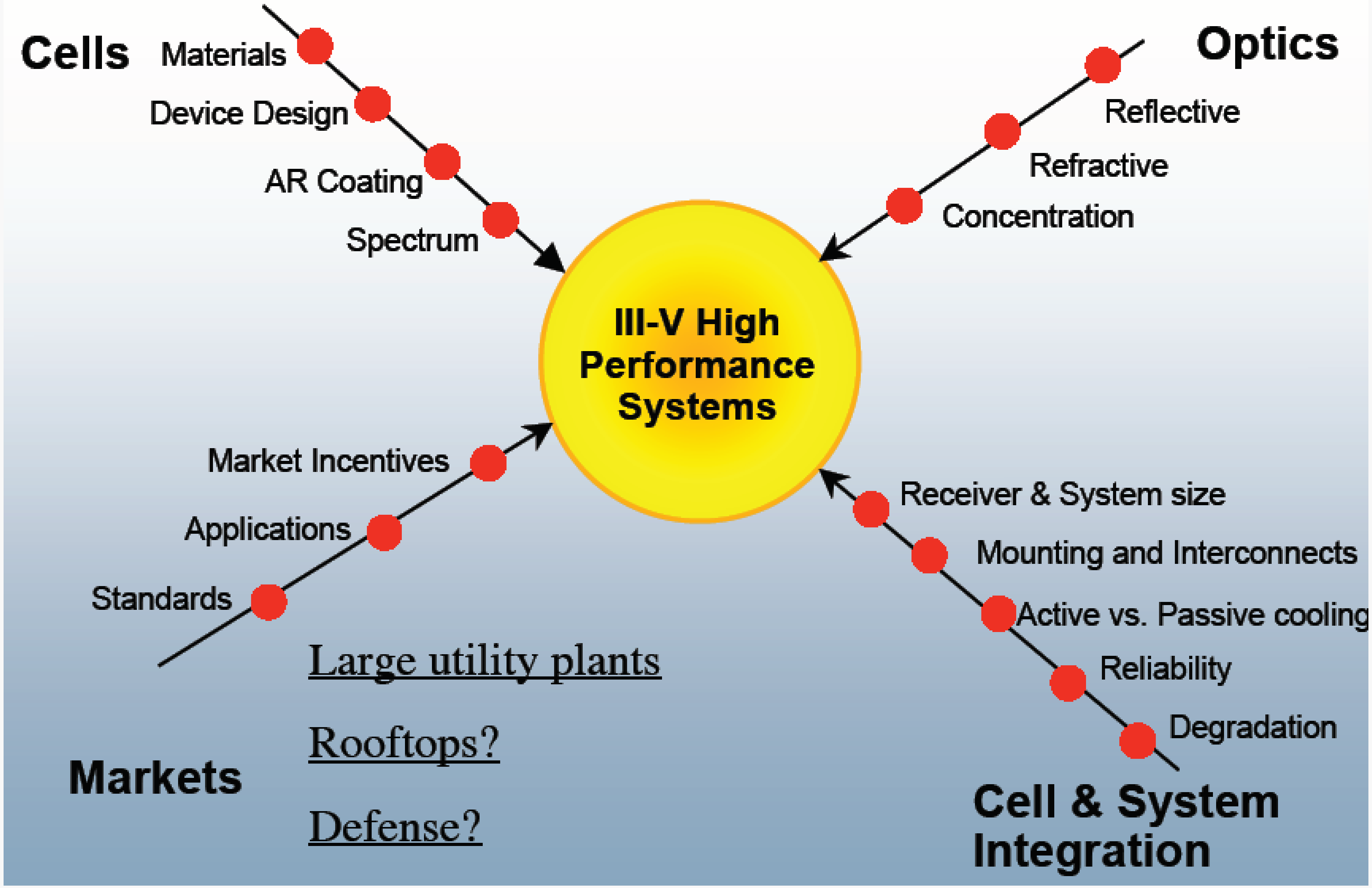
⇩

the elevate ratio (cost for unit area)/efficiency imposes concentration


$800
$700
$600
$500
$400
$300
$200
$100
System Capital Cost ($/m2)
Toda
$5/Wp
Systems
Concentrators
$2.5/Wp
Initiative
Milestones
Thin
Films
$1/Wp
Systems
7%
9%
11%
13%
15%
17%
19%
21%
23%
25%
27%
29%
31%
33%
Module Efficiency

Exploring and Accelerating Ultimate Pathways

20th EPVSEC.-1AP.1.5.5 McConnell, NREL, USA



Outline

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ENEA PV PhoCUS project main purposes

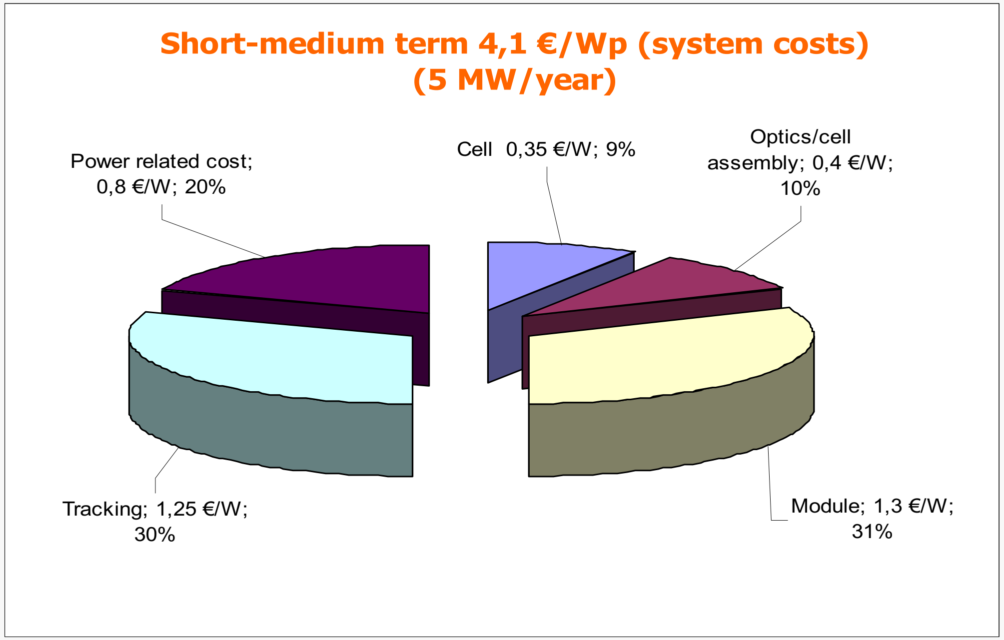
- Development of a technology for Photovoltaic Concentrators to demonstrate the technical feasibility and its potential to accelerate reduction cost of PV technology

  - Cost-Effective solutions coming from consumer products (automotive, diffused electro-mechanical components,etc)

  - Industrialization

PhoCUS - Road-map and target

- Solar cell technology: high efficiency c-Si
- Concentrating type: refractive optics able to be integrated into module (no SOE) point focus/ 200 X
- Peak power: 5 kWp (diffuse generation and utility scale)
- Two axis heliostat (32 m^2). High tracking accuracy (+/-0.2°)



The *PhoCUS-5* Standard Unit (5kWp)

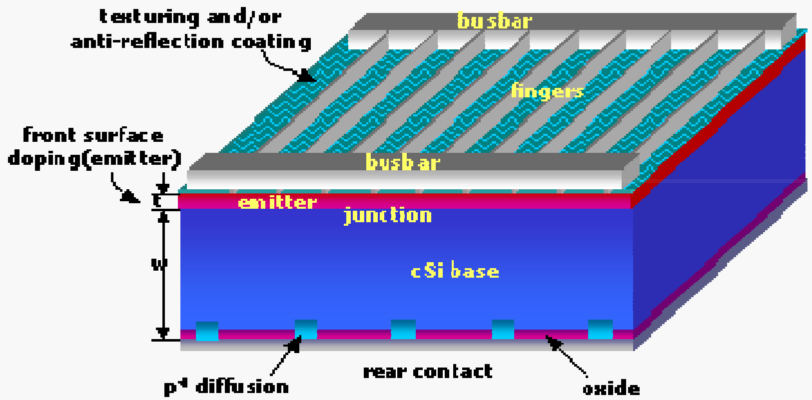
- Solar receiver
- Optical concentrator
- Photovoltaic module
- System engineering
  - 2-axis tracking structure
  - Power Conditioning Unit

R&D activities on Solar Cells

At present: Optimization of conventional cell structure (based on frontal emitter and contacts) to get low cost-high efficiency c-Si solar cells for concentration application

↓

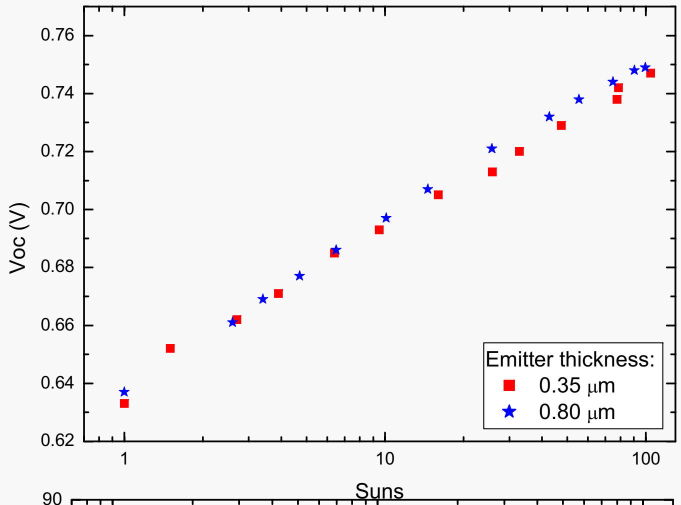
For long-term: high efficiency-low cost solar cell

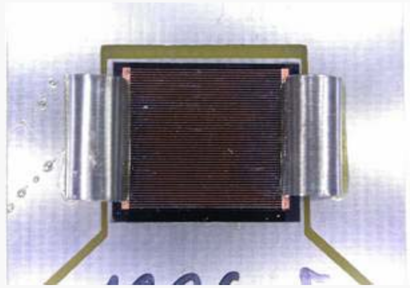


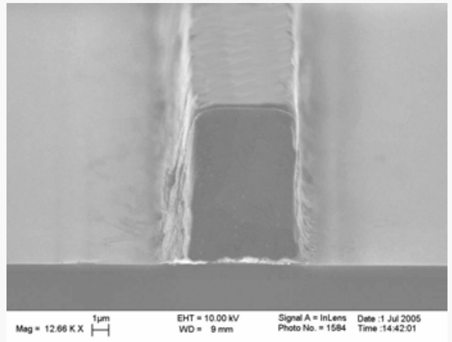
crystalline base	p-type FZ 0.3 Ωcm, cSi, 250 μm thickness
Active area (~8% fingers shadowing included)	11 x 11 mm^2
Emitter	n-type 40-80 Ω/□, depth<1 μm,
Emitter passivation	SiO_x, 16-18 nm
Back contact	2 μm Al
ARC	MgF_2/ZnS, $R_{eff}\approx 7.5$ %
Finger (height/width/distance)	10 μm/12 μm/285 μm
Two busbars outside active area (height/length/width)	10 μm/11 mm/0,5 mm

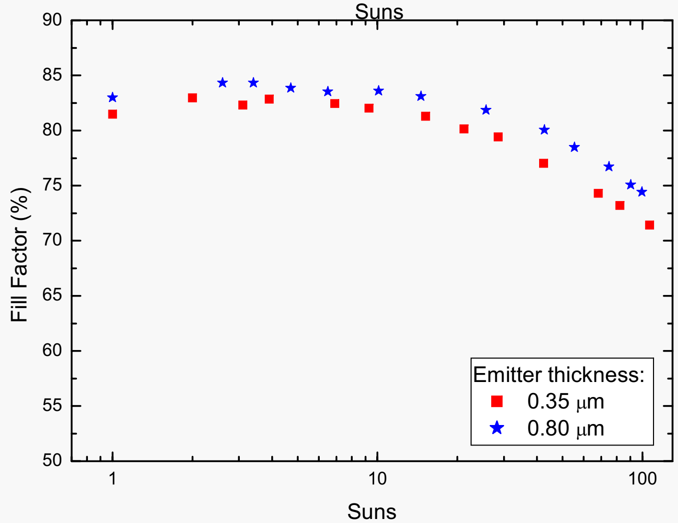
ENEA solar receiver : first results

(a)

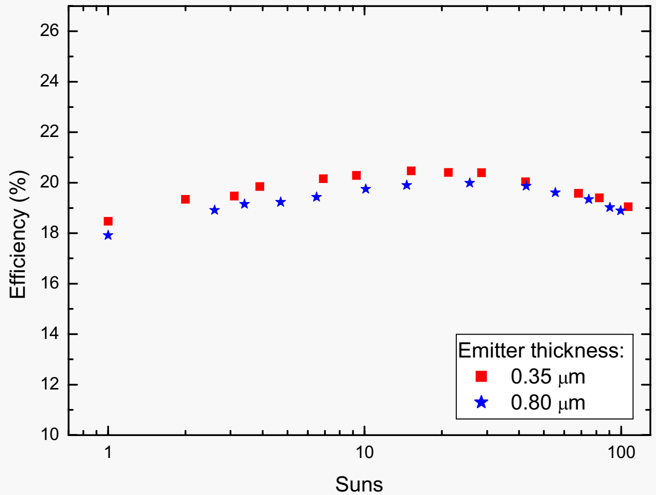






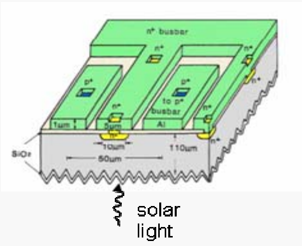


(b)

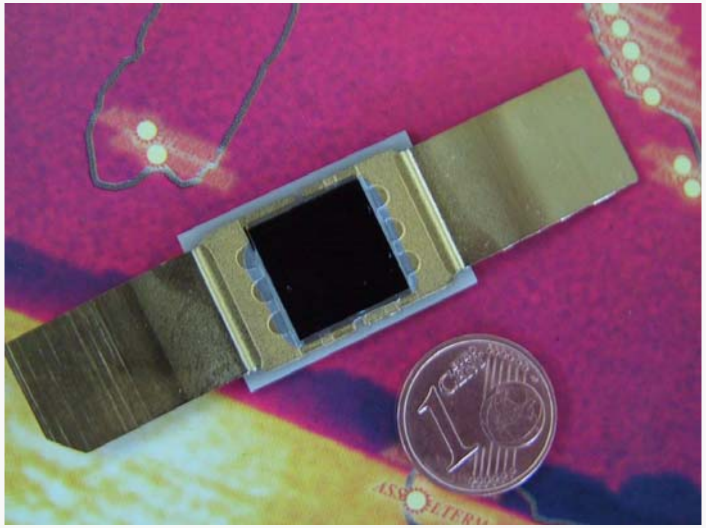


(Pasan Sun Simulator III) with a pulsed xenon lamp (AM 1.5 spectral distribution, 1000 W/m2 irradiance, 10ms). Light has been concentrated using a Fresnel lens.

Phocus-5Kwp units (n.6)

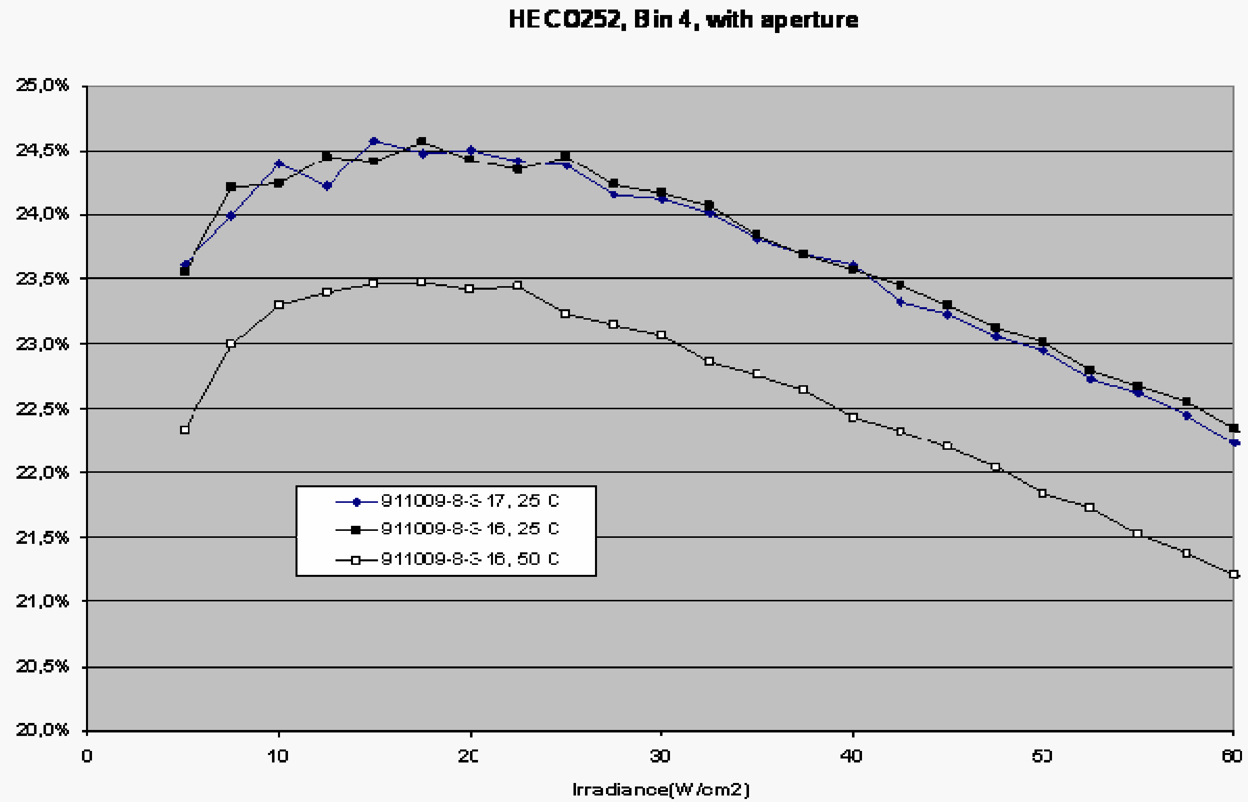


~7500 HECO252 SunPower Cell



Peak of Efficiency (5 -10 W/cm² T= 25°C)	25%
Typical Efficiency at 25 W/cm² T= 25°C)	23.5%
Isc	11.3 A
Voc	820 mV
FF	0.77
Imp	10.3 A
Vmp	690 mV

SunPower HECO252 Solar Cell: Efficiency versus irradiance and temperature



$$\frac{dI_{sc}}{dT} \approx -2mA/°C$$

$$\frac{dV_{oc}}{dT} \approx -0.92mV/°C$$

$$\frac{dEff}{dT} \approx -0.2\%/°C$$

The *PhoCUS-5* Standard Unit (5kWp)

- Solar receiver
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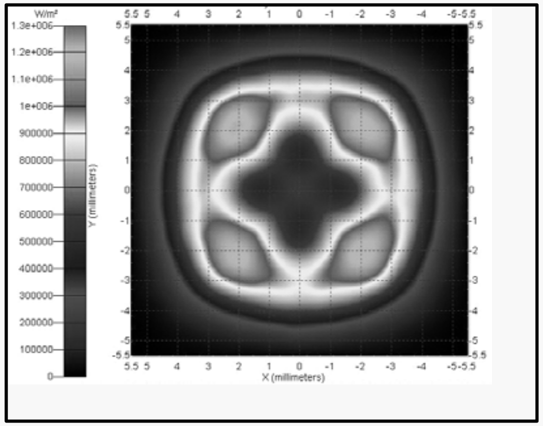
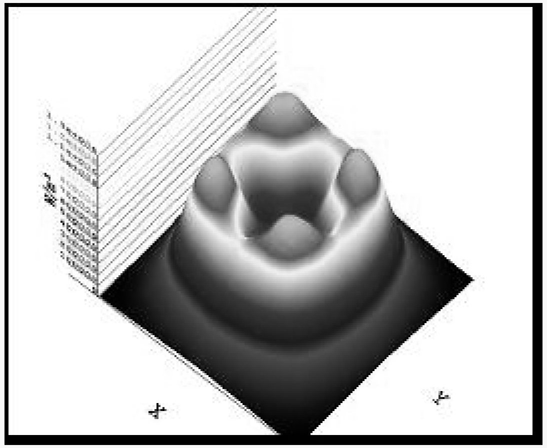
- Photovoltaic module
- System engineering
  - 2-axis tracking structure
  - Power Conditioning Unit

R&D on optical concentrators



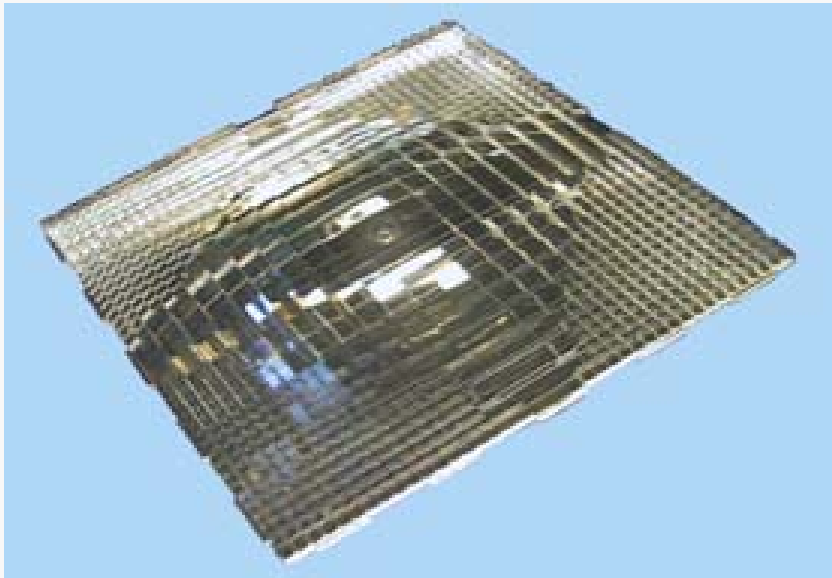


MFFL
(The multi-foci Fresnel lens)

multi foci Fresnel lens, MFFL, since the classic Fresnel lenses give essential chromatic aberrations inducing strongly non-uniform illumination pattern not beneficial to the cell performance

Development and design of low cost refractive prismatic optical devices:

- Optical efficiency of 85%
- Optical properties high stability
- Acrylic material to meet the mass production advantages



BORROMINI S.r.L.

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sito web: www.borromini.it

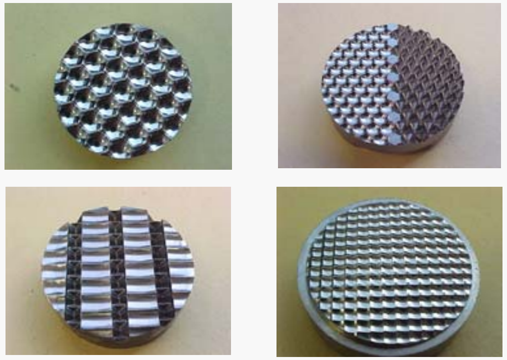
Functional and styling optics

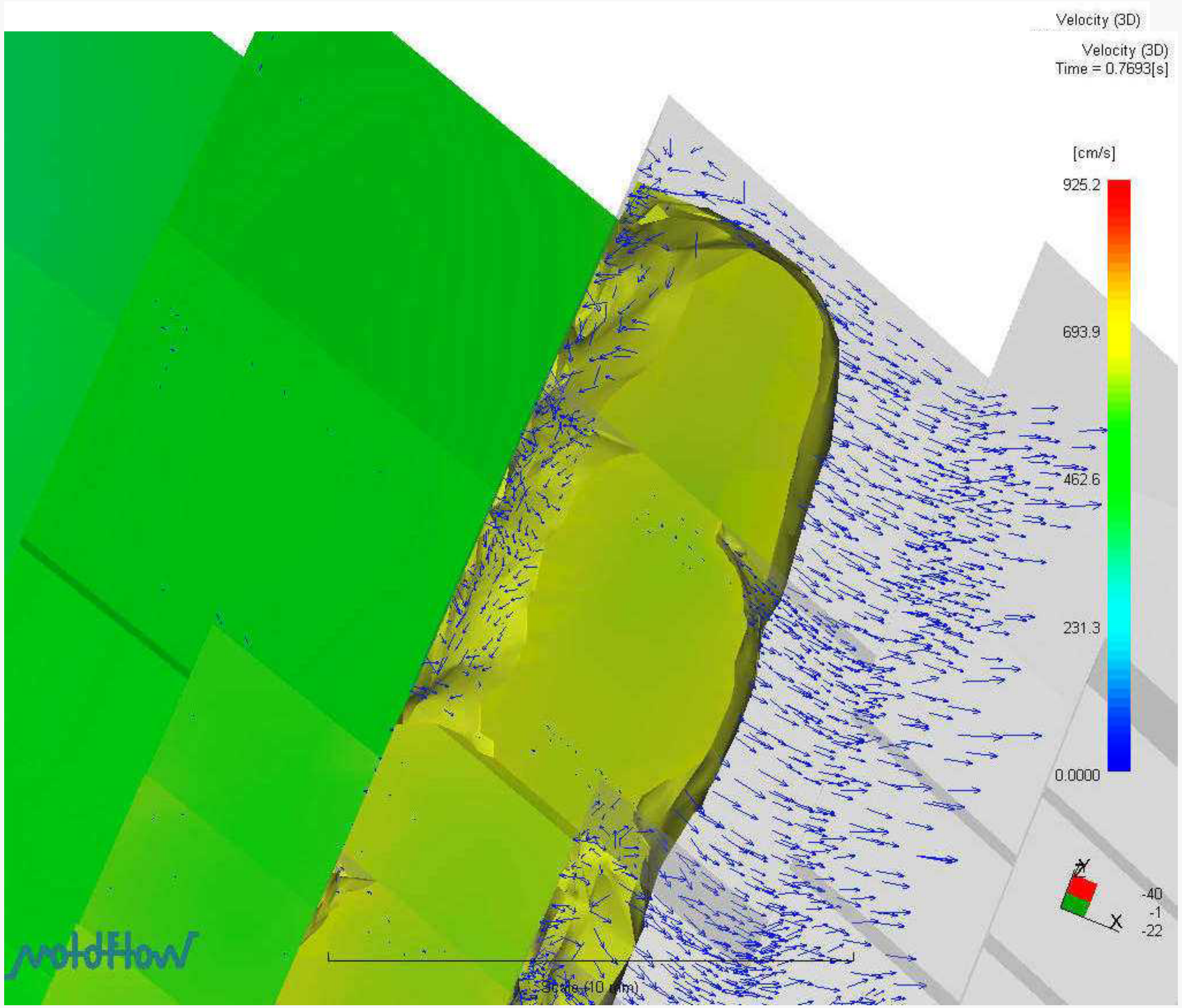
LAMBORGHINI proiettore / headlamp

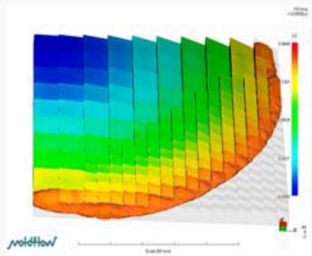
CITROEN C3 PLURIEL proiettore / headlamp

FERRARI proiettore / headlamp

Ottiche su campioni ø 32 mm / Optics on ø 32 mm samples

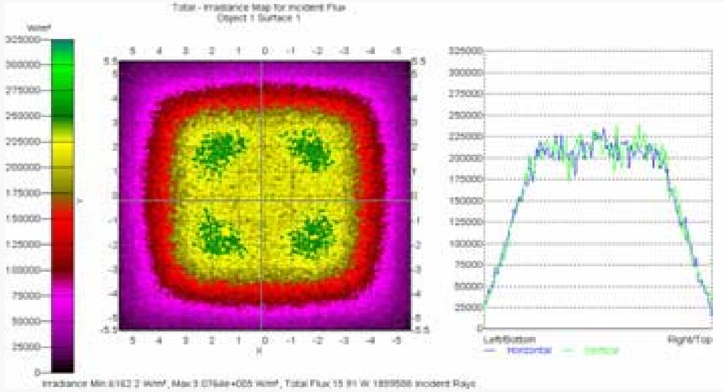



Velocity (3D)
Velocity (3D)
Time = 0.7693[s]
[cm/s]
925.2
693.9
462.6
231.3
0.0000
-40
-1
-22
moldflow



Prismatic Concentrator: First results

Concentrator dimension	15.6x15.6 cm^2
Concentration factor	200
Focal length	22 cm
Focal area	1.21 cm^2
Max thickness	5 mm
Number of prisms 7.8x7.8 mm^2	196
Number of prisms 3.9x3.9 mm^2	816
Material refraction index	1.49
Intrinsic optical losses	13.5 %
Operating optical losses	15.1 %



Efficiency ~ 80% (without ARC)

The *PhoCUS-5* Standard Unit (5kWp)

- Solar receiver
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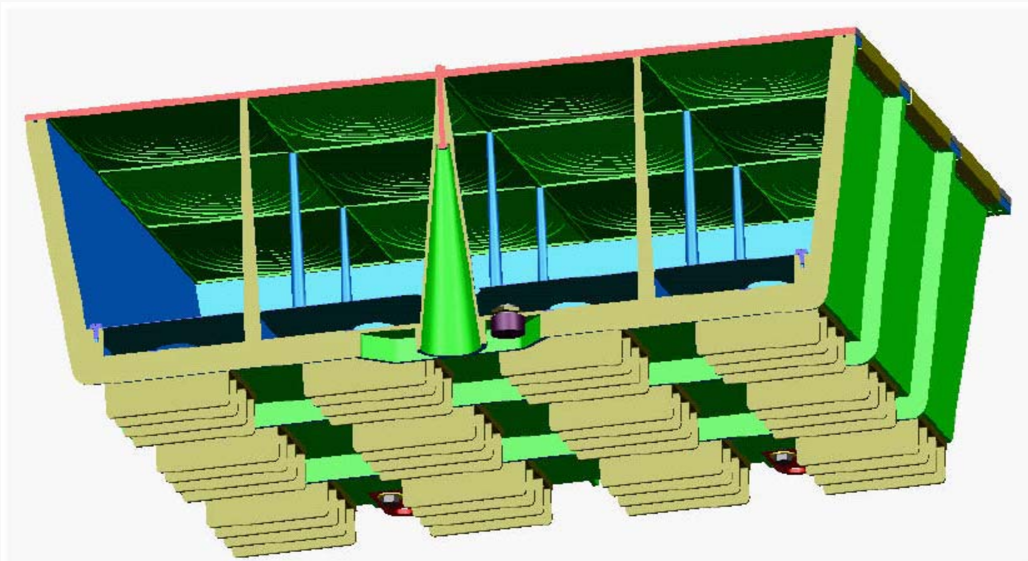
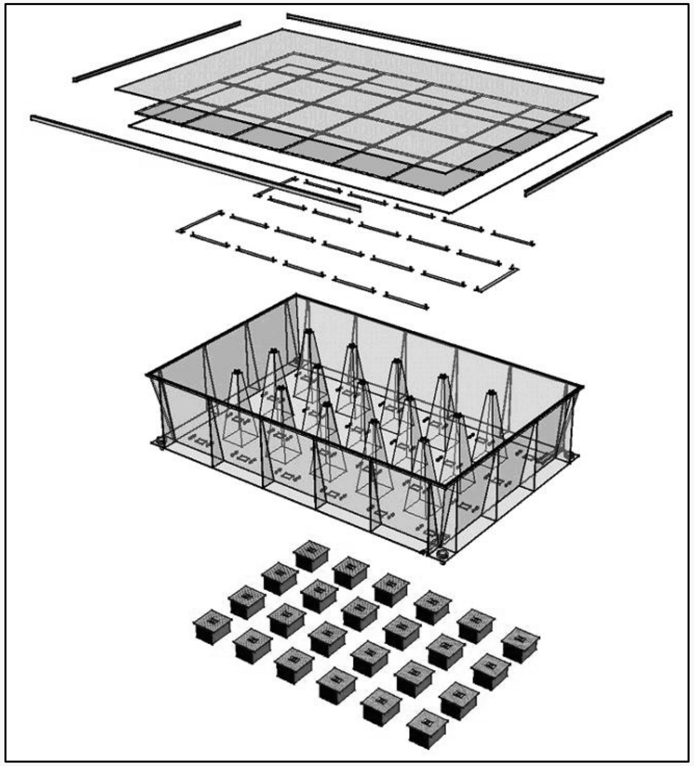
  - Power Conditioning Unit

R&D on PV-C module

Development and design of low cost and high reliability concentrating module (ENEA-ENITECNOLOGIE patent)





Advantages of the plastic housing

a) flexibility for industrial applications;

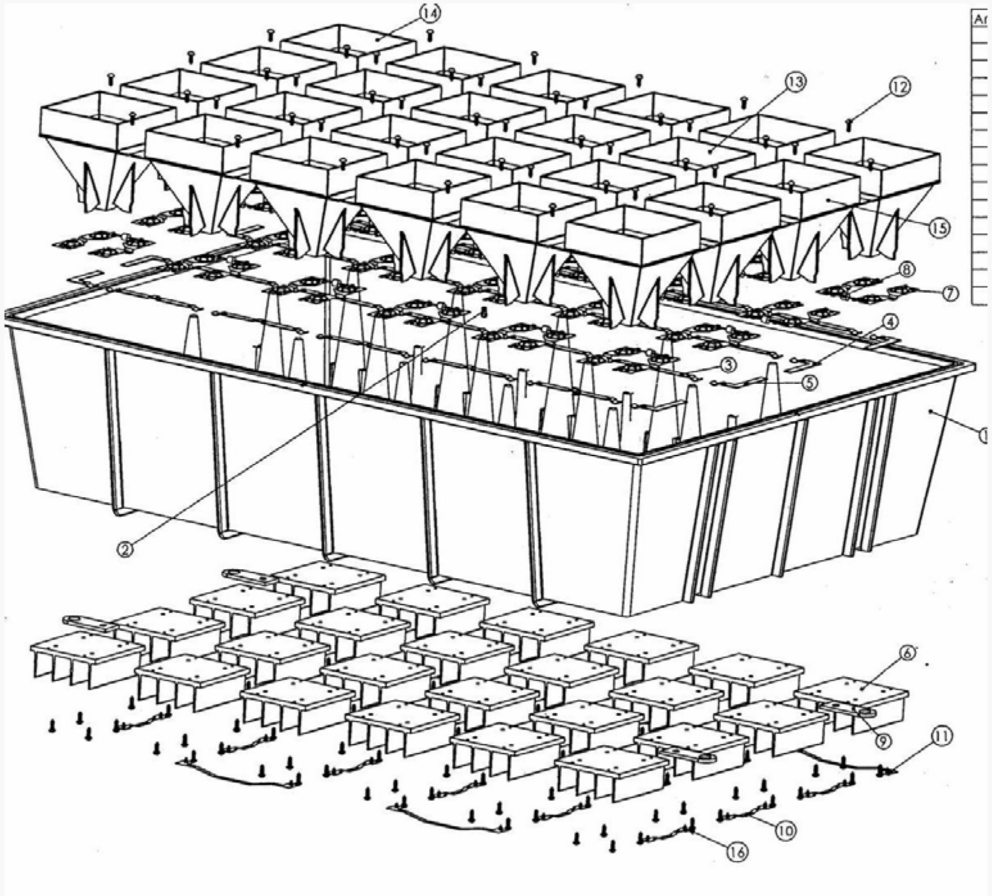
b) the potential low manufacturing costs and electrical insulation;

c) the low weight;

d) durability against aging due to environmental agents.

PV-C Module developed: main technical features (optical efficiency 85%)

Dimensions	1x0.68 m^2
Number of series connected cells	24 (6x4)
Module V_{oc} (S.O.C)	19 V
Module I_{sc} (S.O.C.)	6.6 A
Module peak power (S.O.C.)	103 W
Module max nominal efficiency	~20 %



Secondary optical Elements

In collaboration with EniTecnologie

Paper 2BV.4.5

The *PhoCUS-5* Standard Unit (5kWp)

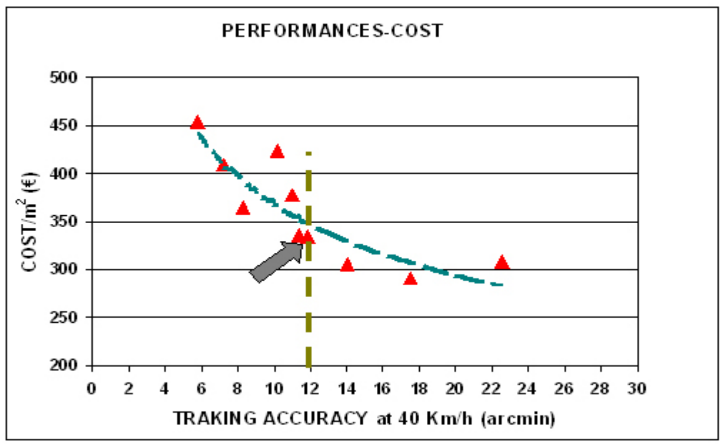
- Solar receiver
- Optical concentrator
- Photovoltaic module
- System engineering
  - 2-axis tracking structure
  - Power Conditioning Unit

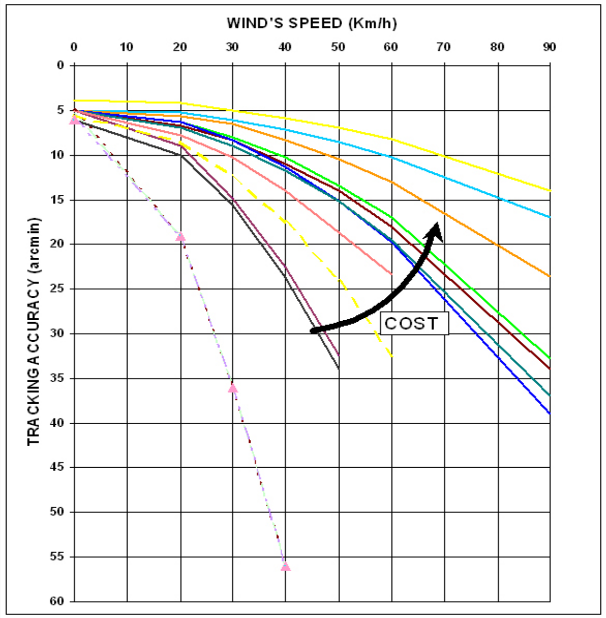
2-axis tracking structure Design criteria

- Low investment and O&M costs (free-maintenance and low energy consumption)
- Modular to reduce the transportation and installation costs
- Reliability, accuracy and precision level was defined owing to a detailed cost/benefit analysis

Selection of the reduction gears systems

The comparison has been done on the basis of the maximum achievable stiffness /tracking accuracy and the corresponding total cost





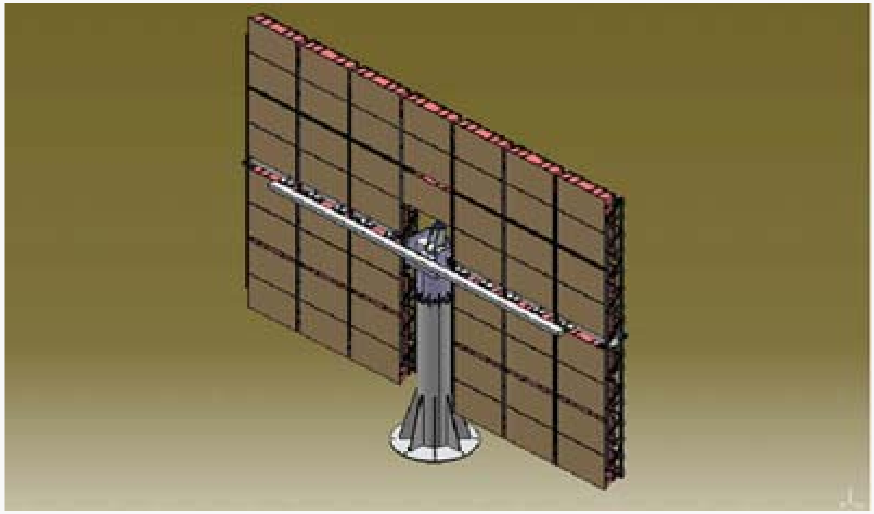
<u>Tracking accuracy versus wind speed</u>

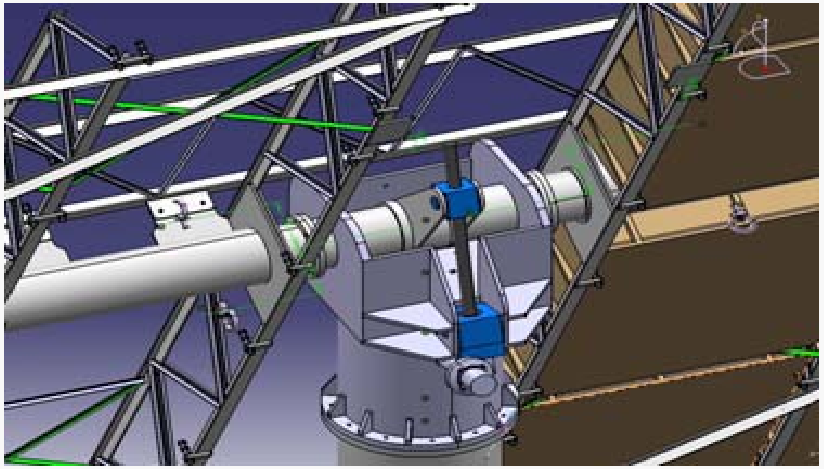
- Up to 40 km/h ± 0,2°;
- From 40 to 60 km/h <±0,3°;
- From 60 to 90 km/h <±0,7°;
- Greater than > 90 km/h homing in safety popsition

Design of double axis Tracking structure

Main features

- Pedestral supporting on the top a network structure of about 32m^2
- Tracking driving based on electromechanical devices;
- Control system based on open / closed loop logic
- Normal operation up to 40 km/h wind mean speed;





Main construction peculiarities

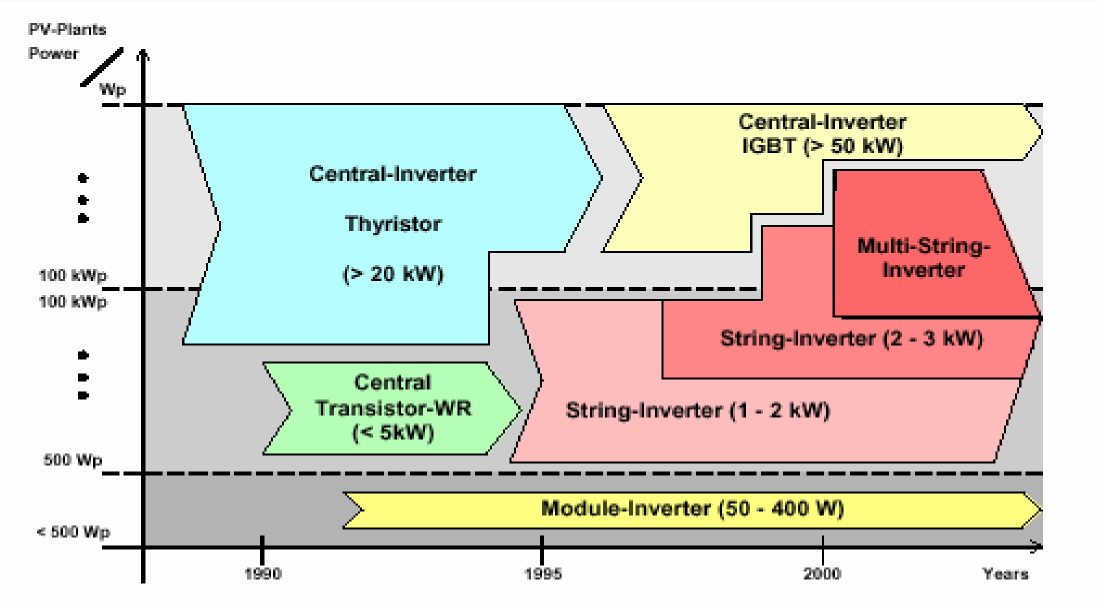
- High stiffness-weight ratio of the mechanical carpentry;
- Hot zinc-plating against corrosion;
- Azimuth motion by an epicycloid reduction gear
- Altitude motion by a linear actuator

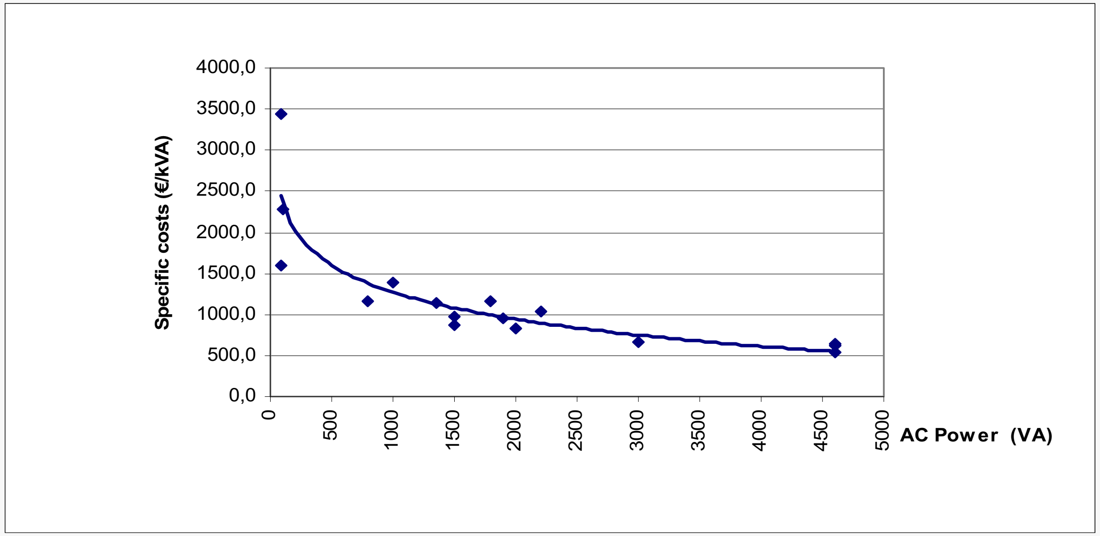
Tracking System main parameters

Panel dimension	32 m^2
Approximate panel weight	1500 kg
Tracking speed	15 °/h
Pointing speed	3 °/min
Tracking accuracy	+/- 0.2 °

Power Conditioning Unit
Design criteria

- Low Voltage inverter (Distributed electrical lay-out / reduction of dc cabling cost /
  reliability)
- Multi- string concept (MPPT on single string/
  electrical mismatch losses reduction)
- Small size inverter (to get the advantages of inverter developed for the diffuse generation)





(1-5 kVA) inverter technology and cost trend

Installation of the first prototype (Portici)

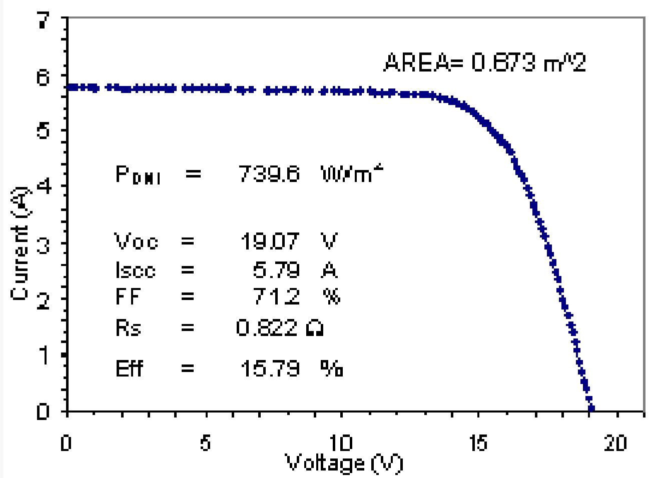
1: Reduction gears system box assembling

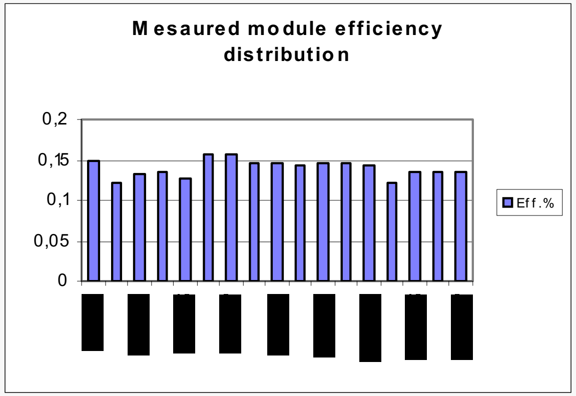
2: Installation of the right side of the supporting structure

3: Installation of the left side of the supporting structure

Heliostat

Portici *PhoCUS* Experimental site





The lower efficiencies for some of the realized modules can be ascribed mainly to the hand-made realization.

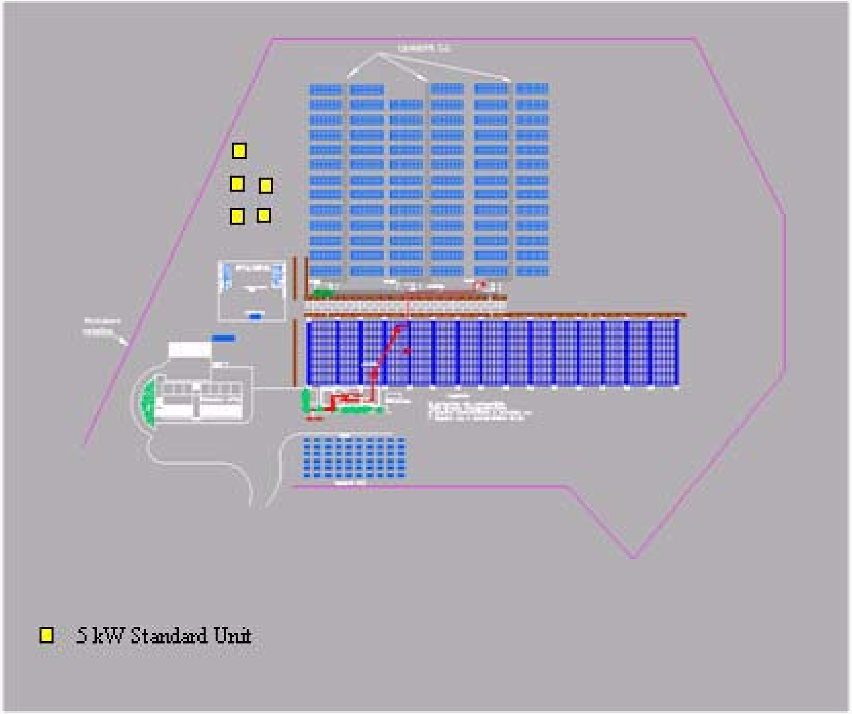
OUTDOOR FACILITIES FOR OPTICAL AND ELECTRICAL CHARACTERIZATION OF OPTICS AND DEVICES

EKO STR-22 Sun-traker

(accuracy 0.01 °)

PhoCUS demonstration and testing (dic2005)

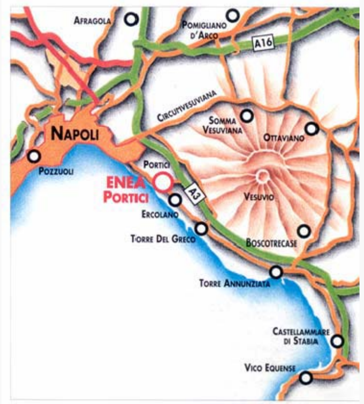
- Pilot Plant
  - Installation Site: Monte Aquilone Enea Test Site
  - Nominal power 25 kW
  - 5 standard units
  - Electrical lay-out : distributed (Low Voltage ring)
  - Geometric lay-out: symmetric-square , GCR (Ground Cover Ratio) 0.15-0.25 : shadowing losses <3%



First evaluations:

- the introduction of Secondary Optical Element (SOE) should make less strict the specification in terms of tracking accuracy, and consequently a simplification in the design of the tracking structure
- the optics efficiency can be increased by making an anti reflective coating on one /both lens sides;
- New hybride Fresnels-Prysmatic lens under development in ENEA
- Realization of the housing by thermoplastic process should lead to a better alignment between optics and cell and reduce the intrinsic module losses;
- better results are expected by improving the cell contact
- different materials and different assembling procedure of the tracking structure could improve the quality of the system

Thanks for your attention



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e-mail: roca@portici.enea.it