ENERGY POWER GREENHOUSE (EPG)
Combining Optics, Semiconductor Physics and Biology
to a synergetic TOTAL ENERGY SYSTEM (TES)

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The **EPG-TES** system converts nearly all the incoming photons of the terrestrial solar spectrum into three useful energy forms: electricity, thermal heat and high class biological crop (food).
Unlike conventional solar energy systems, using generally only one part of the solar spectrum to produce one form of energy (Fig.1) the **EPG-TES** uses selectively adapted parts of the spectrum to produce different forms of energy simultaneously within a multifunctional system (Fig.2).

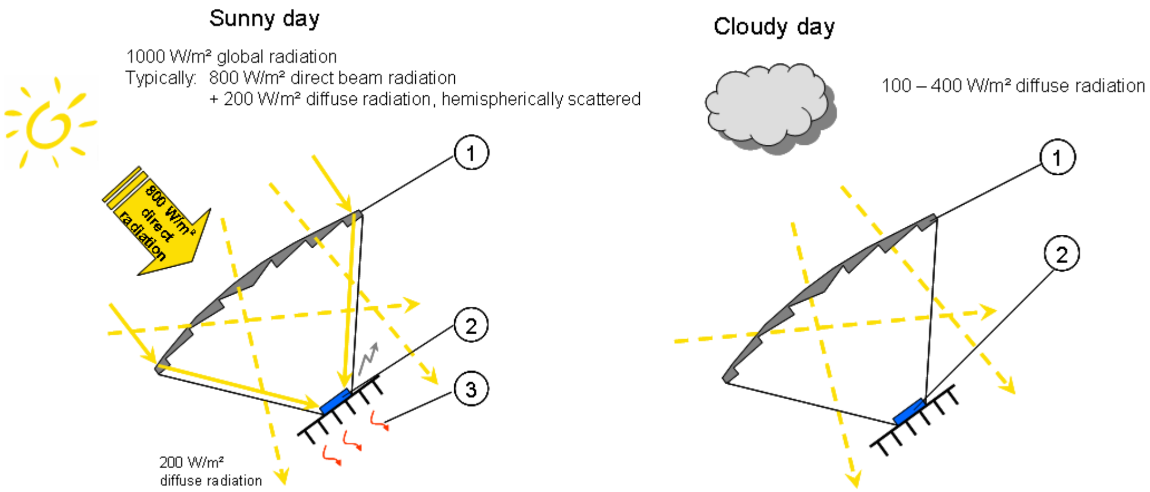


Fig.1: Typical Example - Photovoltaic Concentrator

The optical concentrator lens (1) focuses only the direct part of the Radiation onto a Triple-Junction photovoltaic cell (2). With a typical PV-Cell efficiency of η_{PV} = 37%, the optics efficiency η_{opt} = 90% and intercept losses of 3%, the overall efficiency of PV-cell $\eta_{opt} \times \eta_{PV} - 3\% = 30\%$.
The concentrator PV-Cell works only with beam radiation. Therefore, for a 1 m² aperture of the optic 240 W of electricity are produced. The remaining energy of the beam radiation, 560 W, is transformed to heat which is dissipated without usage over the heat-radiator (3). The diffuse part of the radiation, 200 W, is not used.
In case of a cloudy day (Fig.1 right) only diffuse radiation (typically between 100 and 400 W/m²) exists, the system generates no electric power, no heat is rejected.

The Fig.2 shows a multifunctional EPG-TES system with a **Photovoltaic-Concentrator as core component.**

The photovoltaic concentrator is the same as in Fig.1, but the cell (2) is actively cooled from both sides by a special Fluor-Liquid with optical and isolation properties matching the cells need. By this way the heat can be actively used and stored in the storage vessel (2a).

Furthermore the optical-concentrator (1) is placed under a highly transparent (τ = 97% over the whole solar spectrum), self cleaning, long life (over 20 years) Fluorpolymer-film (4) forming a closed greenhouse cover. This protects on the one hand the sensitive PV-Concentrator system against wind and weather and as a consequence it can be built economically as light weight structure requiring only minimal tracking power. The solar cell lying in the liquid immersion is ideally optically matched, protected against mechanic damage and, most important and specific to this system, can expand and retract freely under different temperature regimes without causing destructive stresses to the bridle cell.

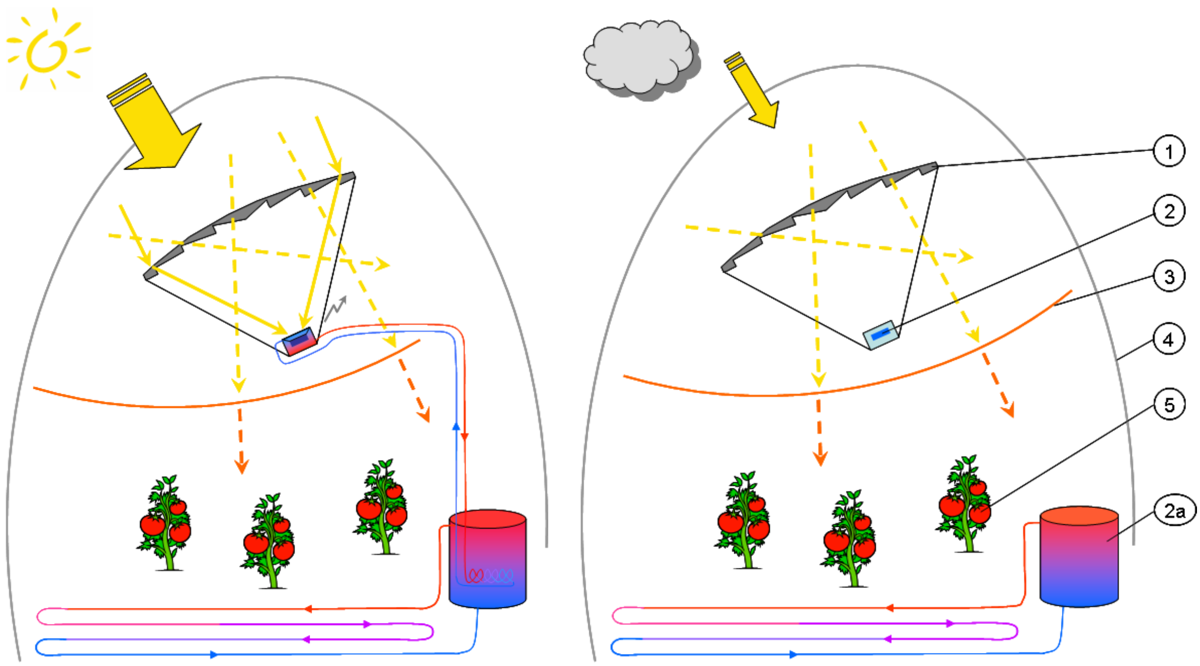


Fig.2: Multifunctional EPG-TES

On the other hand, the diffuse part of the radiation penetrates to the plants (5). Plants prefer diffuse radiation. As can be seen in Fig.3, the response spectrum of the photosynthesis is situate mainly in the regions B + D and as can be seen in Fig.4 the saturation of photosynthesis is reached when the leaves get PAR-light with 300 W/m².

Fig.2 shows, that the system still generates plant growth under cloudy condition and that the stored heat of the actively cooled solar cells may be used to heat the greenhouse or for other applications.

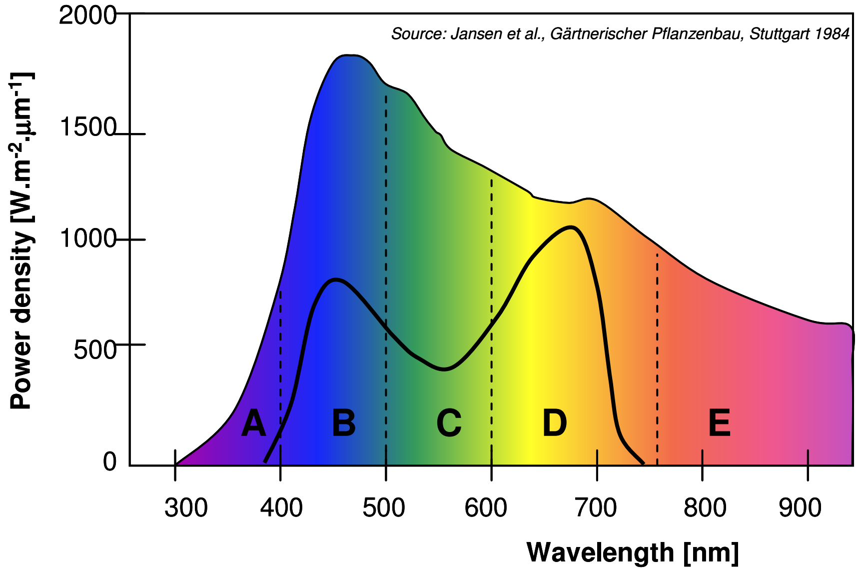


Fig.3: Solar + PAR Spectrum

On a clear day the maximum energy input of the solar radiation which arrives at the surface of the earth amounts to 1,000 W/m^2. This radiation comes in a spectrum as indicated in the Fig.3. Only parts of it are important for plant growth, the Photosynthetic Active Radiation ("PAR") regions, i.e., the absorption spectrum of chlorophyll which determines the photosynthesis process (CO_2-assimilation). In Fig.3 it is marked by the black line.

The solar radiation can be segmented in respect to their contribution to plant cultivation:

A	=	UV-A radiation. Does not effect plant growth, but produces brighter colors, stronger aromas of the agricultural produce and effects natural disinfection.
B + D	=	Most productive spectrum for photosynthesis, wavelength between 400 nm and 750 nm with peaks at 455 nm (blue region) and at 680 nm (orange-red region).
C	=	Only small contribution to photosynthesis.
E	=	No contribution to photosynthesis.

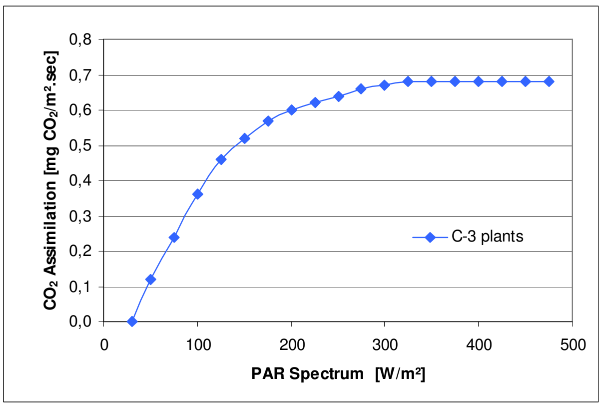


Fig.4: Plant Needs of PAR Radiation

In order to transform the diffuse radiation (~ 200 W/m²) to a PAR-Spectrum a special film (3) closes the space under the solar optics toward the plants. The film is doted with special fluorescence pigments, shifting mainly the biologically relative ineffective green photons of **region C** into the highly effective **region D**. By adding the light penetrating through the interstices of the optics and the greenhouse side walls the plants receive always the optimum PAR-Radiation and therefore generate substantially higher yields compared to classical greenhouses.

The film (3) has additionally other positive effects for the whole system:

1. The optical PV-System is hermetically closed – no dust or dirt deposit.
2. Double layer (3 and 4) avoids moisture condensation and prevents heat losses of the greenhouse.

The Matrix bellow gives a comparison between the conventional PV-concentrator system (System 1, Fig.1) and the EPG-TES PV-Concentrator system (System 2, Fig.2).

	System 1	**System 2**
What part of radiation is used to which extend	• only direct (beam) radiation over the entire spectrum • about 30% are converted to electricity	Whole solar spectrum - direct and diffuse
What is produced	Electricity	Electricity + heat + biological products
Does the system work under diffuse radiation	No	Yes – for the biological part
Benefits of the system	• Electrical power at competitive costs (due to concentration)	• Electrical power under nearly similar conditions as system 1 • Heat for greenhouse or other uses • Bio-organic crop
Utilization of the system	• Large installations for grid injection • Island or home based electricity production	• Large installation for grid connection and production of large amounts of bio-organic food or other products • Smaller installations for local or regional autonomy in power (electricity) and food. • Part of the produced biomass can be used to produce during none sunshine hours electricity via methane, plant oil a.s.o.

As a general conclusion it can be stated that the EPG-TES system in comparison to a conventional photovoltaic concentrator system, bears following advantages:

- Makes use of practical the totality of incident solar photons in a closed, interdependent system by producing electricity, heat and biological products. All three quantities are valuable assets. Therefore, not only the overall efficiency but also the overall revenue and economy of the system is strongly enhanced compared to “stand alone” solutions.
- Creates simultaneously the two most important basic needs of human societies, high-value electricity and clean bio-organic food.
- Has the potential to reduce by an order of magnitude the required land foot-print to feed one person, all by creating his energy needs (autonomy).
- Is a complete CO_2-neutral system, requiring much less water compared to conventional greenhouses. Also no fungicides and pesticides are needed.
- The core of the EPG-TES, the solar concentrator, profits from the system in following way:
    1. Light weight, lower cost system because of lack of wind and weather forces.
    2. Protection against dust and dirt.
    3. Heat-sink for the active cell cooling provides heating of the (stratified) storage used to maintain constant temperature in the greenhouse (positive aspect for plants growth and economy).

Short review of Technical Status

Sunvention U.S. is a daughter company of Sunvention International GmbH. Sunvention U.S. has the exclusive rights to market and produce EPG-system in the U.S. and connected countries. Its main scope is to develop the up so far research based EPG-developments to a commercial product. In this context, Sunvention U.S. concentrates on EPG-TES systems using the highly efficient Triple-Junction cells of Boeing-Spectrolab combined with a system of point focusing lenses (Sunflower II and Sunflower III).
The development and deployment of this technology is taking place at Sunvention US Head Quarter near Greencastle, Indiana (cf. Fig.5).

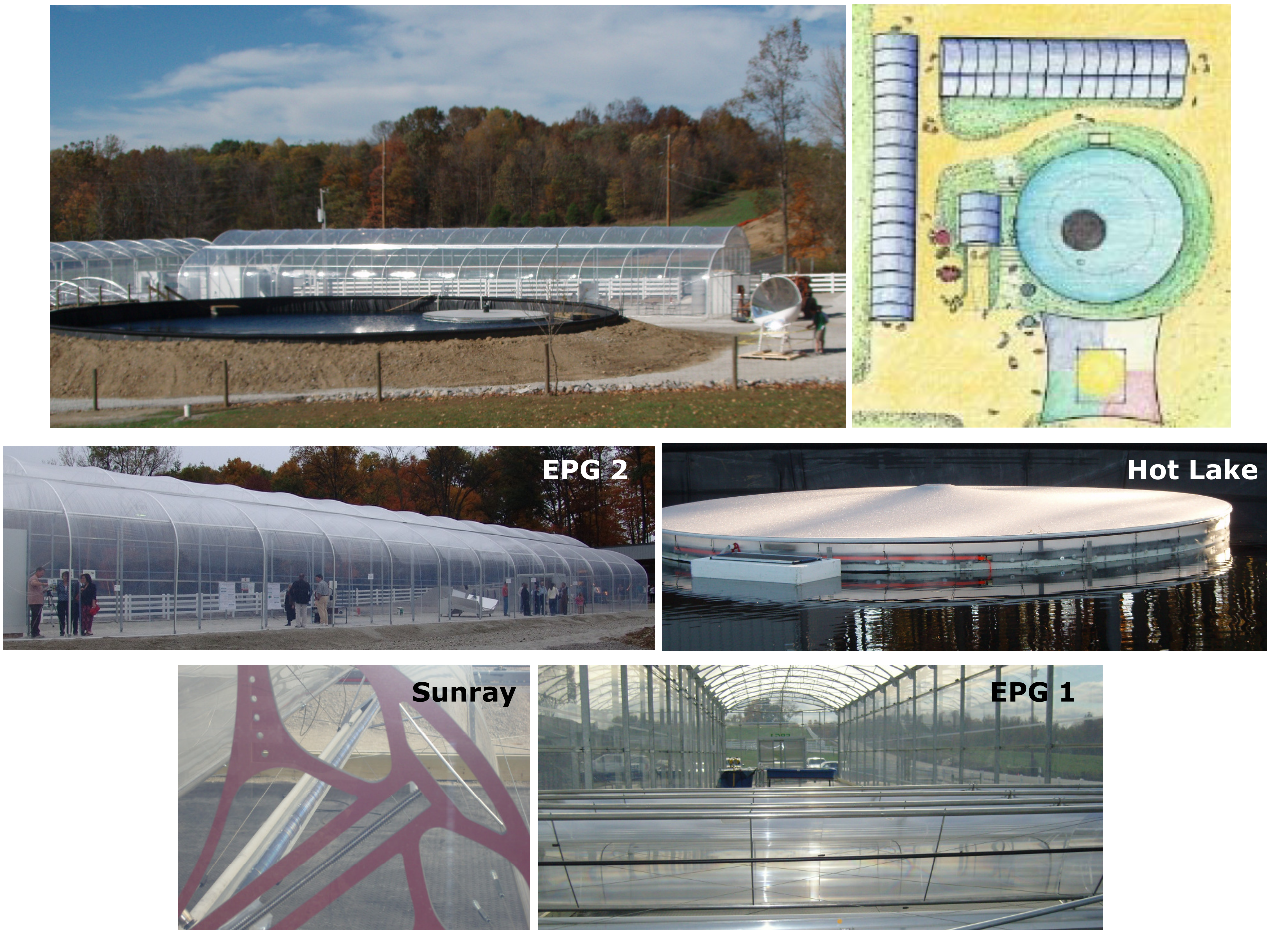


Fig.5: Sunvention U.S. Head-quarter and Pilot Installation

Fig.6: Test-Stand of Linear Fresnel-Lenses with actively cooled Silicon concentrator cells.

Reached electric efficiency (optics + PV cells)	η_{el}	=	10%
Reached thermal efficiency (40℃ cooling Temperature)	η_{th}	=	60%
Total Efficiency	$\boldsymbol{\eta_{total}}$	**=**	**70%**

Targeted efficiency with optimised silicon concentrator cells	η_{el}	=	17%
Targeted thermal efficiency (40℃ cooling Temperature)	η_{th}	=	60%
Total Efficiency	$\boldsymbol{\eta_{total}}$	**=**	**77%**

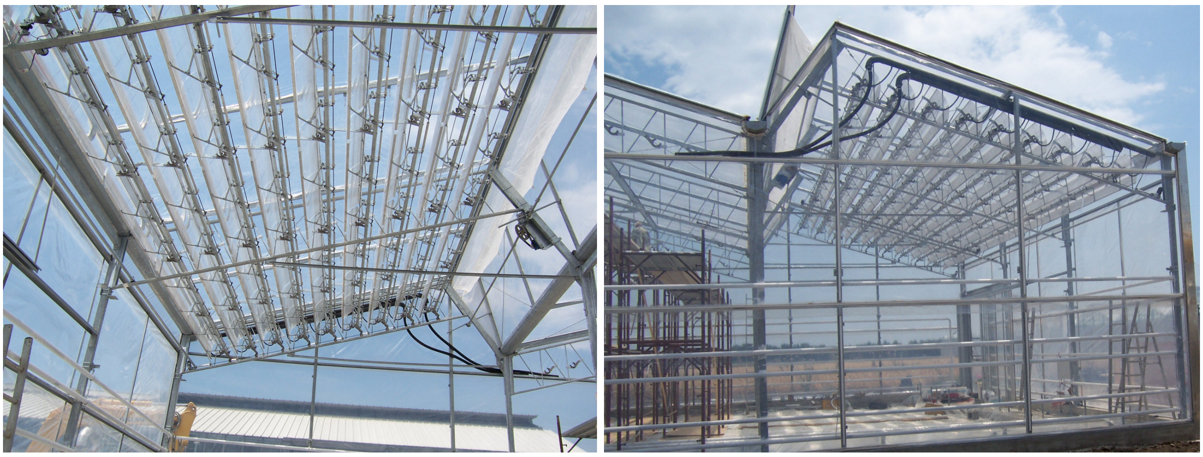


Fig.7: Linear-Fresnel lenses installed in Pilot Greenhouse

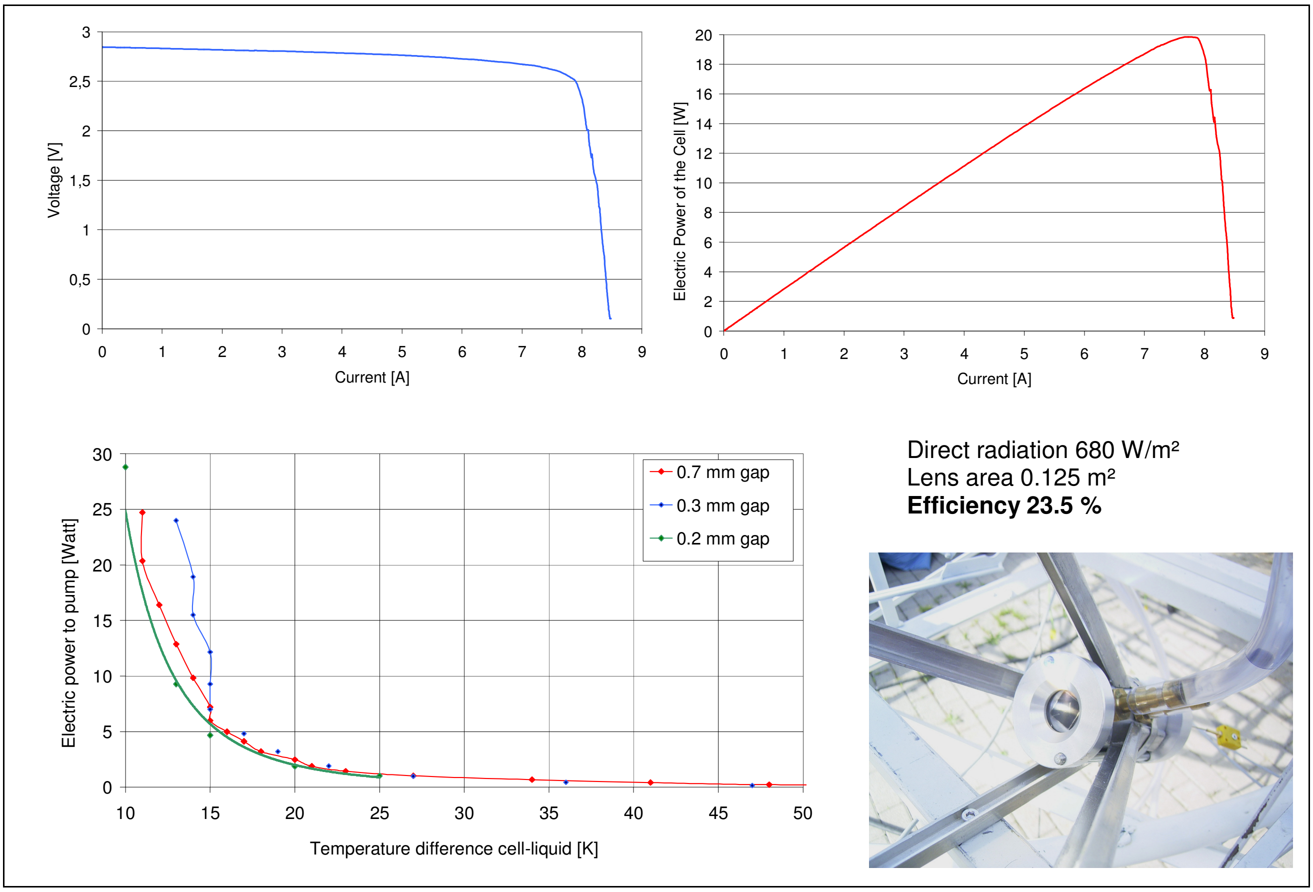


Fig.8: Point-Focus Test Concentrator combined with Triple-Junction cell and active cooling in Fluor-Liquid immersion

Reached electric efficiency (optics + PV cells)	η_{el}	=	23.5%
Reached thermal efficiency (60℃ cooling Temperature)	η_{th}	=	65%
Total Efficiency	$\boldsymbol{\eta_{total}}$	**=**	**88.5%**

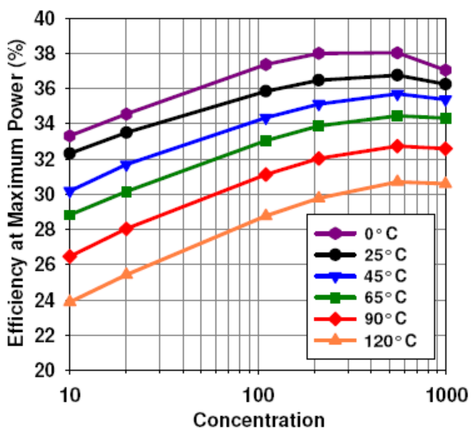
Planned next steps

a - Develop double Axis tracking lens Concentrator system Sunflower II

Fig.9: Double Axis tracking lens Concentrator system Sunflower II

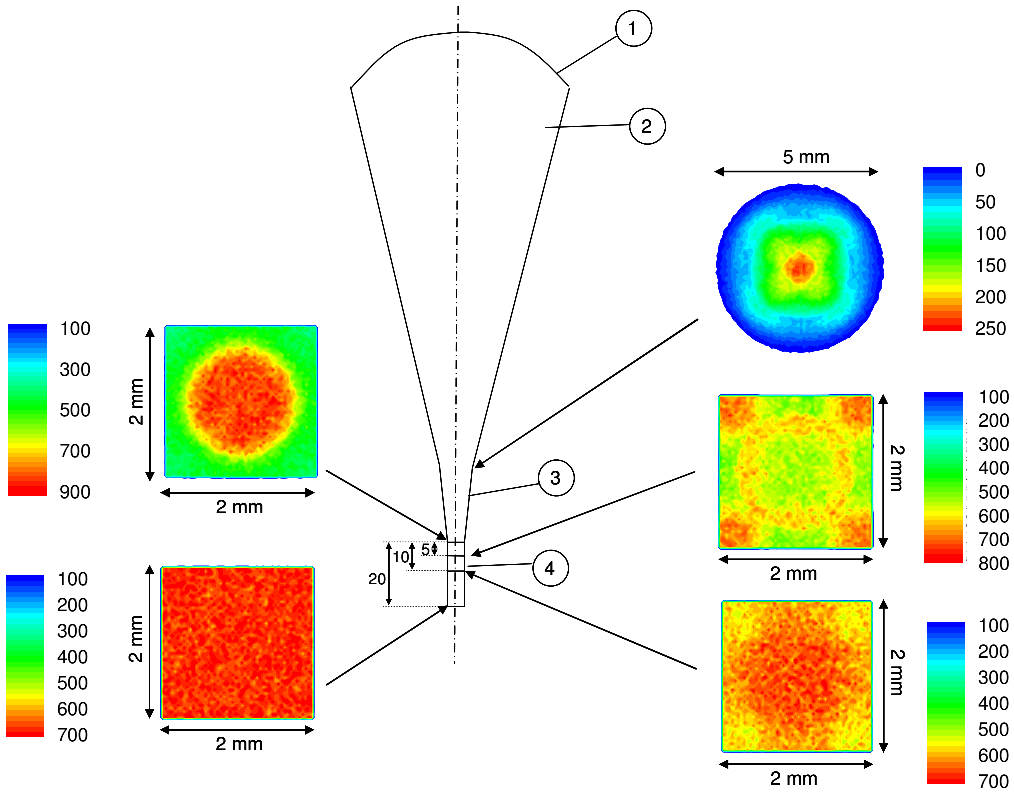
Targeted optical efficiency (lens + homogeniser)	η_{opt}	=	85 %
Targeted electric efficiency (η_{opt} x cell efficiency 36%)	η_{el}	=	31 %
Targeted thermal efficiency (60°C cooling Temperature)	η_{th}	=	65 %
Total Efficiency	$\boldsymbol{\eta_{total}}$	**=**	**96 %**

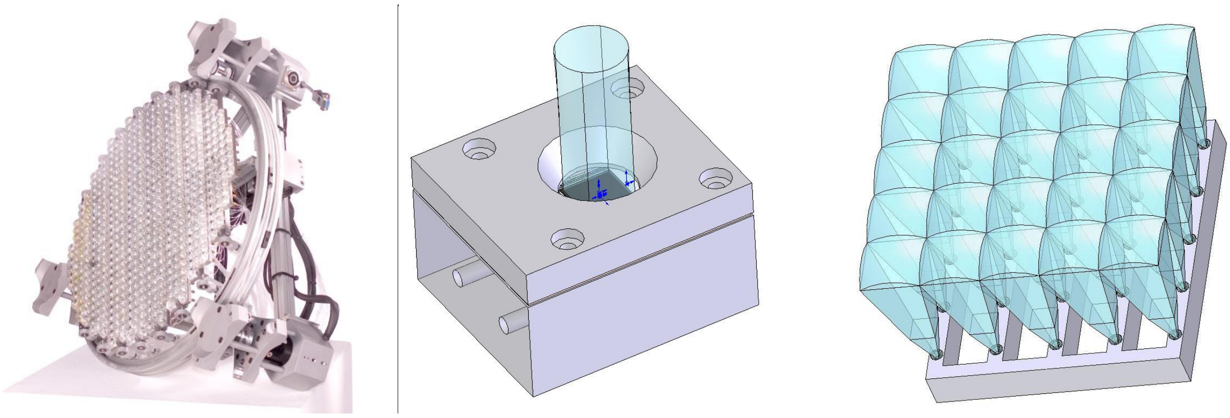
The higher electric efficiency will be reached due to optimized lens and the use of a radiation homogenizer.



Source: Spectrolab

b – Develop novel Generation of Double Axis tracking “Multifunctional CPC” Optics combined with Triple junction cell





<u>Fig.10</u>: CPC Optic

Targeted optical efficiency (lens + homogeniser)	η_{opt}	≥	95 %
Targeted electric efficiency (η_{opt} x cell efficiency 36%)	η_{el}	≥	34 %
Targeted thermal efficiency (60℃ cooling Temperature)	η_{th}	=	60 %
Total Efficiency	η_{total}	≥	**94 %**

The “multifunctional CPC” optic avoids the Fresnel and partial reflection losses of the Fresnel lenses. Furthermore its “inbuilt” capacities are: concentration, homogenizing and shaping (rectangular) of the photon-flux.

EPG-TES Economics

The economics gained by EP-Greenhouses are assessed by way of the following example (see Table 1):

- Yields (kg/m²) should increase significantly in a greenhouse located in a sun-rich region which is equipped with solar energy systems due to moderate temperatures for better plant growth as well as prolonging the growing season. Conservatively, yields of 40 to 50 kg/m^2 should be achievable thus higher than the yields achieved in Spain and also higher than those in The Netherlands with the heating-supported longer planting season.
- Quality of the agricultural produce should be excellent since the fluoropolymer foil allows the UV-A radiation to enter the EP-Greenhouse, important for the color and aroma of the crop as well as acting as a natural disinfectant in the greenhouse. Thus the good market prices realized for agricultural produce in The Netherlands should be achieved.
- The variable cost will be less than that for greenhouses in The Netherlands since heating cost will be lower due to solar-generated thermal energy. Thus the variable cost for the EP-Greenhouse is assessed at about € 15 per m^2.
- The fixed cost component in the EPG is higher due to maintenance of the higher investment (energy systems).

	Almeria, Spain	**Netherlands**	**EP-Greenhouse, Spain**
Yield (kg/ m^2)	16	26	40 – 50
Market price (€/kg)	0.66	1.62	1.62
Gross income (€/m^2)	10.6	42.1	64.8 – 81.0
Variable costs (€/m^2)	3.8	26.5	15
Fixed costs (€/m^2)	2.7	5.5	15
Net income (€/m^2) (bef. capital cost)	4.1	10.1	34.5 – 51.0

Table 1: Net income - EPG-greenhouse potential vs. conventional greenhouse

Based on these components the additional net income potential from agricultural produce cultivated in EP-Greenhouses is assessed to be about € 20 to 40 per m^2 and year.

The economics of an EP-Greenhouse is assessed for the following example:

- The EPG has a size of 1,300 m^2 and an electricity peak performance of 100 kWp.
- The location is Southern Spain with about 3,400 hours of sunshine per year compared to about 1,600 hours in Southern Germany.
- Employed are the energy systems with the 36% Triple-Junction cells.
- Additional income from the agricultural business is € 20/m^2.year, the lower end of the € 20 to € 40/m^2.year range.
- PV-generated electricity is fed into the grid at €c 0.41/kWh.

The assessed economics of the EP-Greenhouse are summarized in table 2.

Greenhouse paramters	
Size of greenhouse (sqm)	1,300
Electricity output (MWh/year)	231
Thermal energy ouitput (MWh/year)	521
Additional investment (€-000s)	502
Economics	
Sales, Expenses, Cashflow(€-000s/year)	
Additional income from the agricultural buisness	26
Income from electricity (MWh/Jahr)	96
	122
Amortization (1)	25
Maintenance (2)	10
	35
Additional net income	87
Additional cashflow	112
Unit Cost and Return	
Cost of electricity (€c/kWh) (3)	15.20
Cost of electricity (€c/kWh) (3)	4.03
Pay-back period (years)	4.48
Return on investment bef. taxes	22%
(1) Amortization period (years)	20
(2) Maintenance (as % of investment)	2.00%
(3) (amortization + maintenance)/kWh	
(4) (amortization + maintenance - add. Income from agro. produce)/kWh	

Table 2: Economics of the EP-Greenhouse Assessed