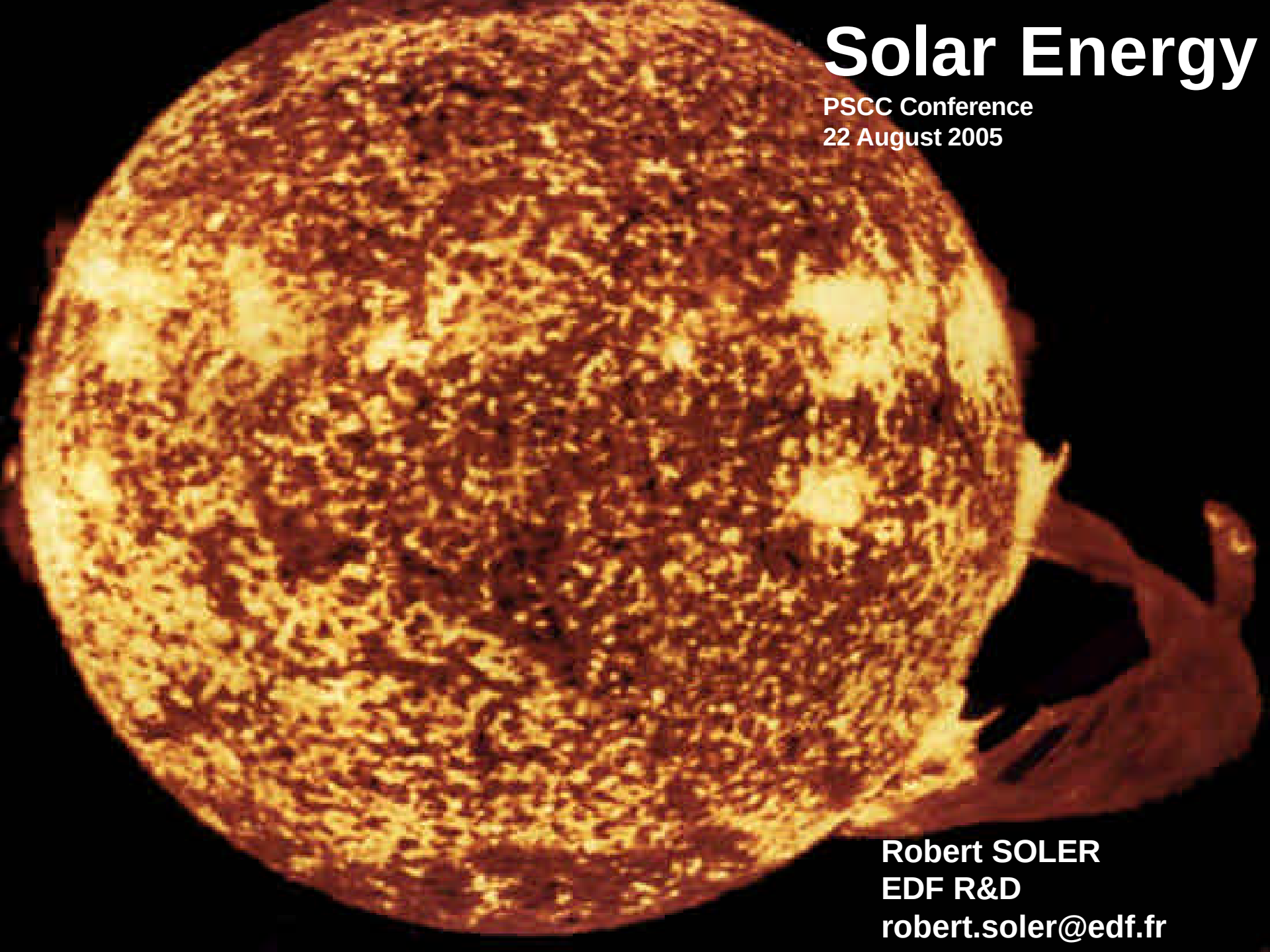


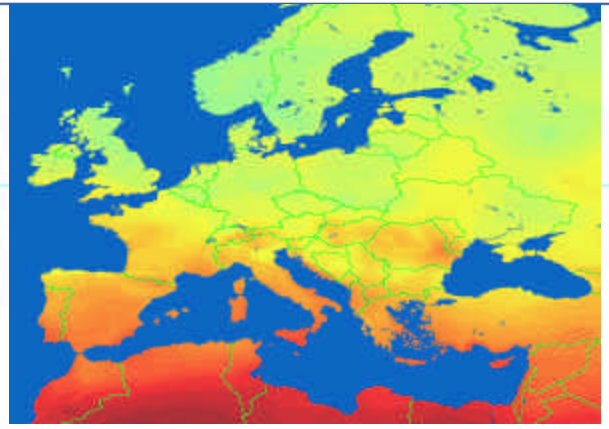
Solar Energy

PSCC Conference
22 August 2005

Robert SOLER
EDF R&D
robert.soler@edf.fr

Solar Energy

I Radiation



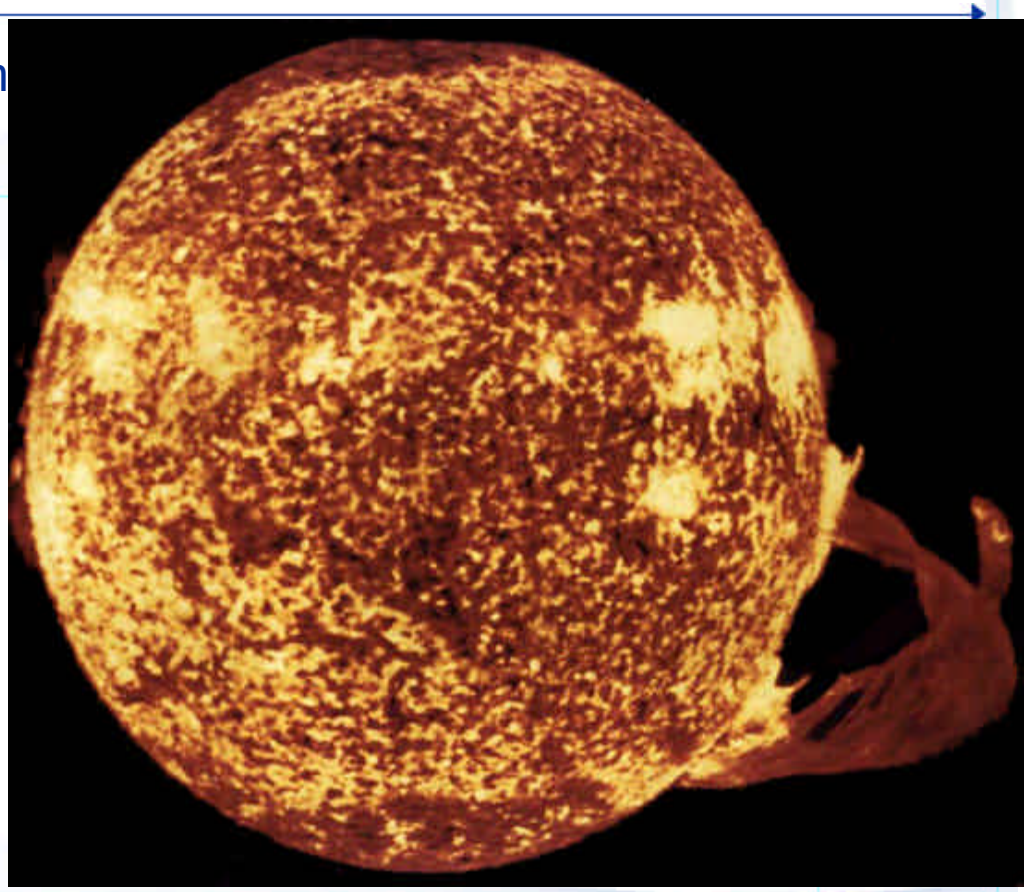
III PV

II Solar thermal

IV CSP

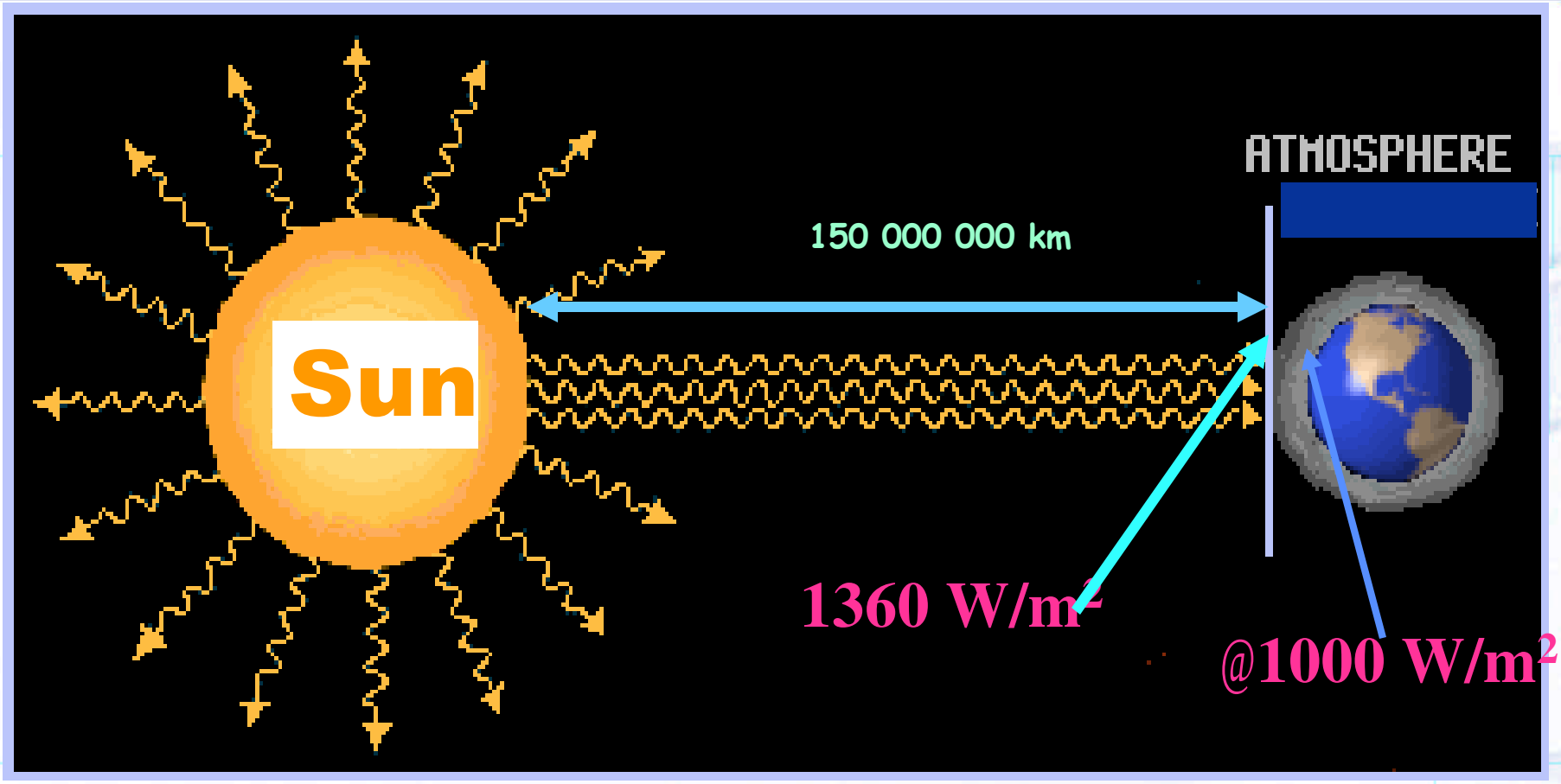
Data relating to the sun

- **Content :**
  - Hydrogen
  - Helium
  - Carbon, Nitrogene + oth
- **Life span : 9 billion years today at half life**
- **Diameter = 1.391.000 km**
- **T° of the core : 15.000.000 K Thermo-nuclear reactions**
- **T° of the surface : 5760 K**

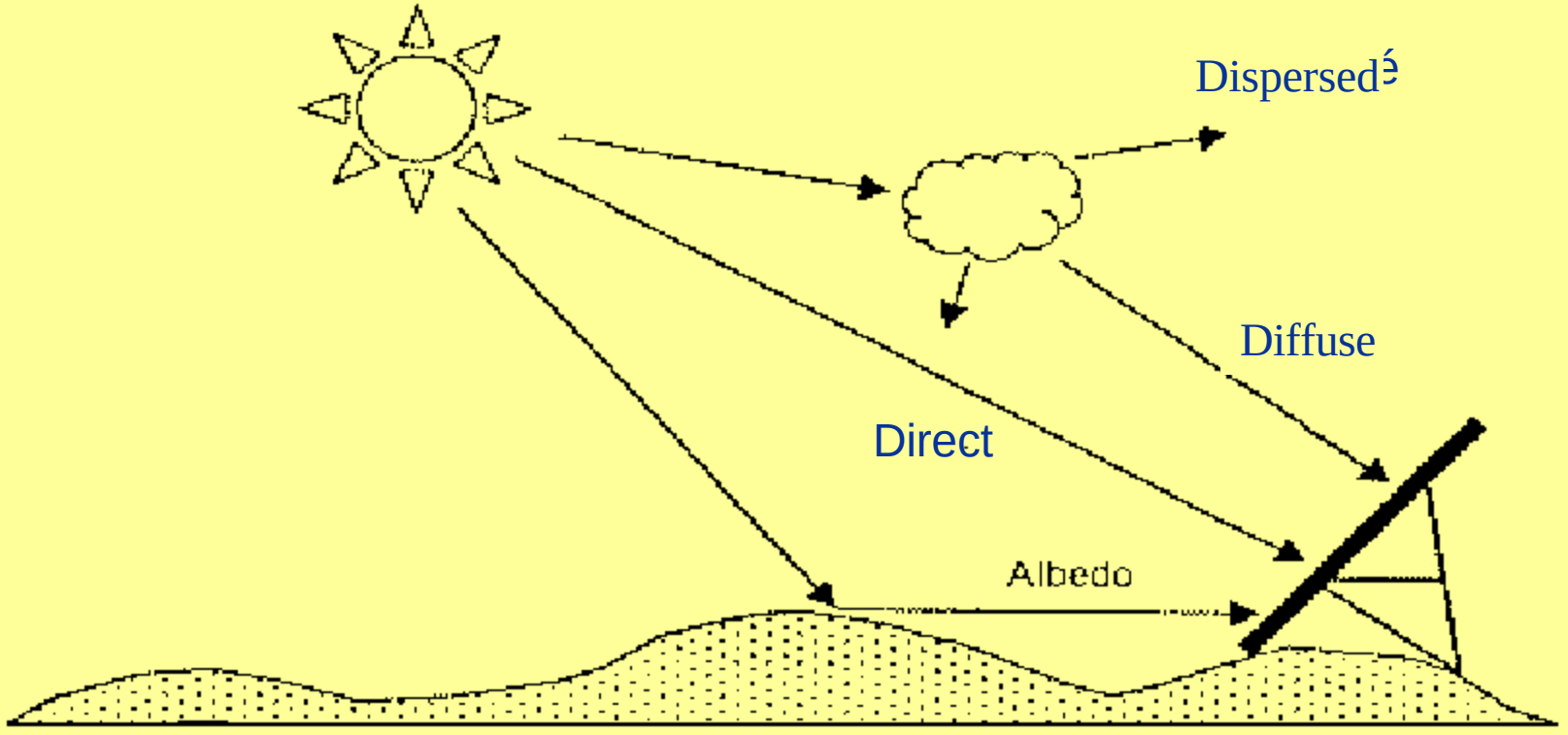


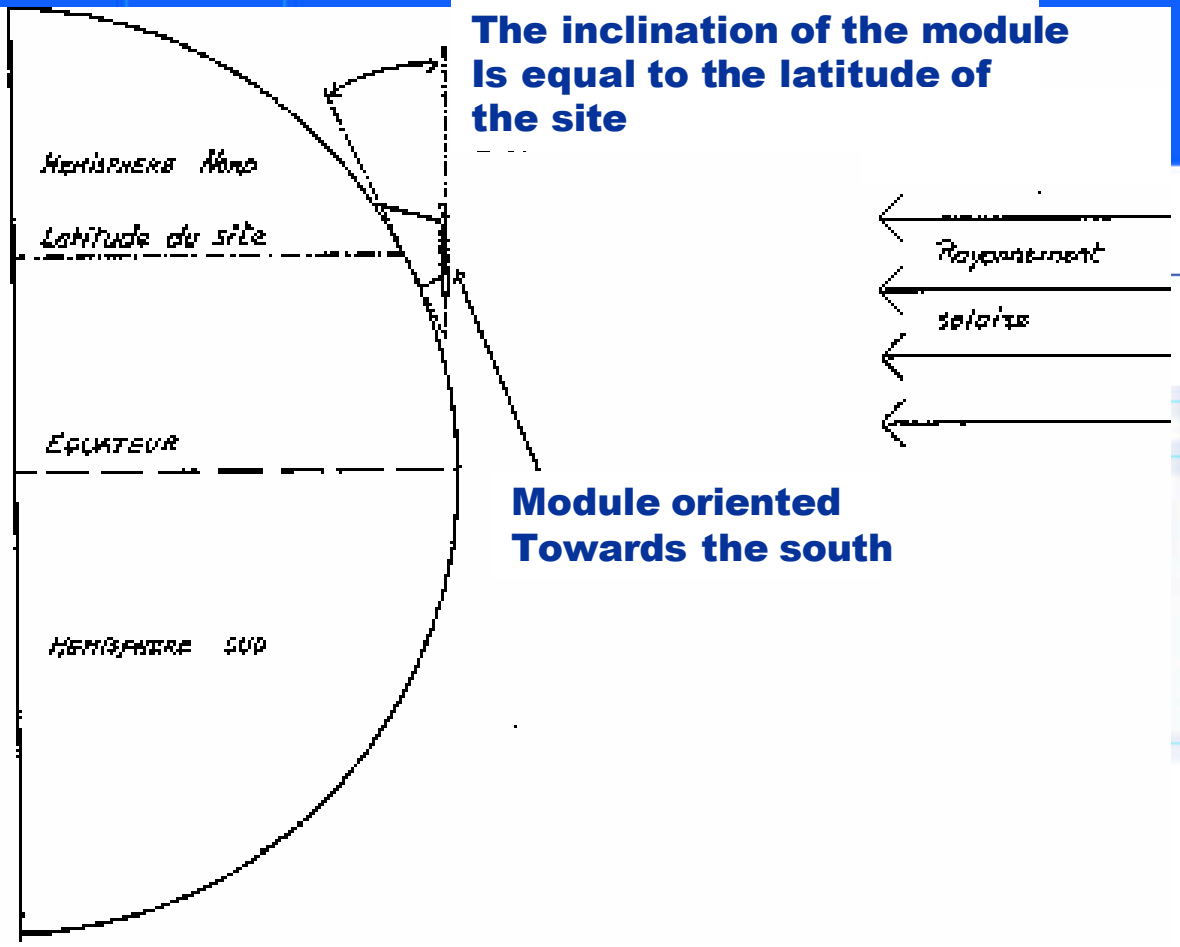
Total power radiated in all directions of space

$3{,}7.10^{23}$ W = 64 070 000 W/m^2



Solar irradiance on the ground :





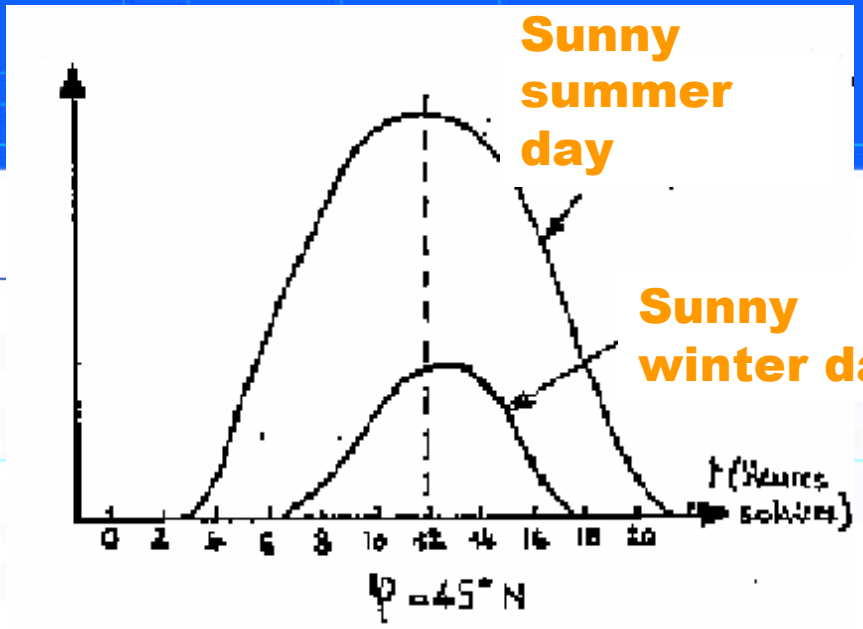
The inclination of the module Is equal to the latitude of the site

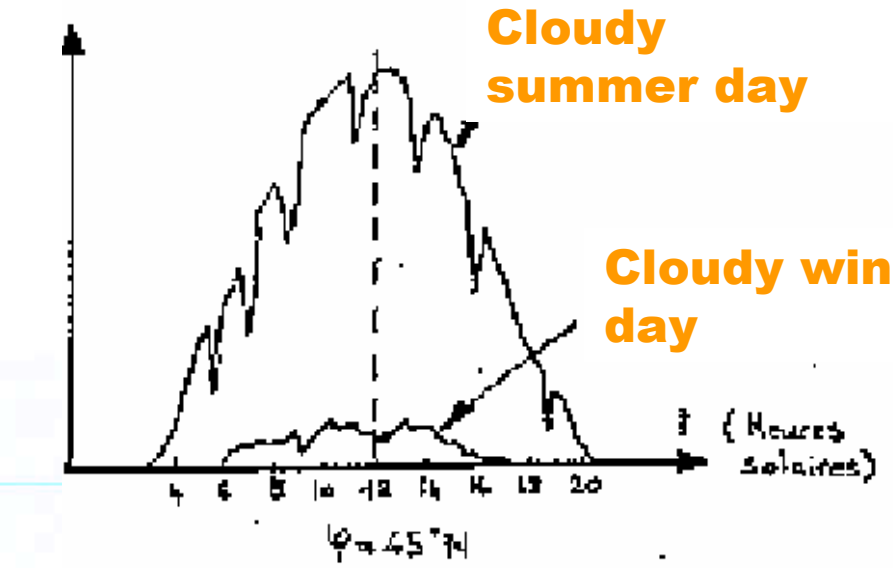
Module oriented Towards the south

Solar radiation

Orientation of the modules

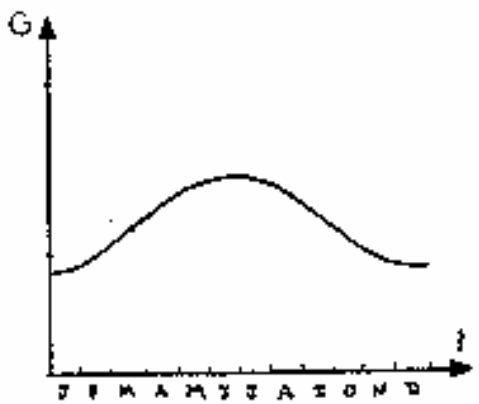
Solar irradiation on the ground depends on



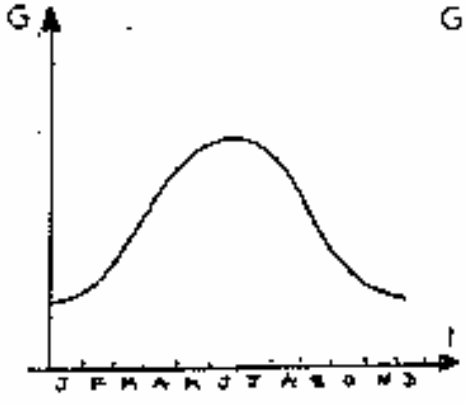


- the time of the day
- the season
- the weather

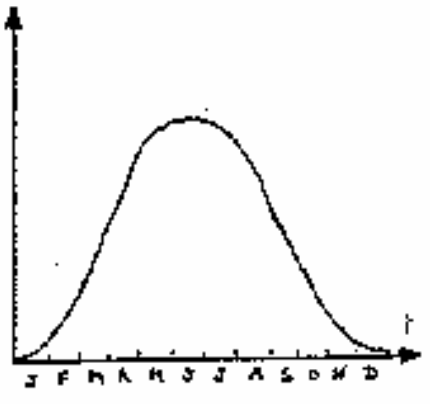
Influence of the latitude



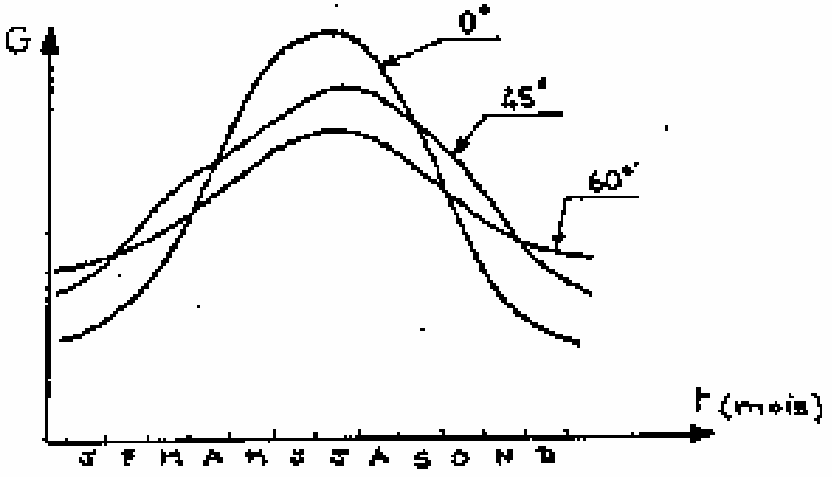
$\varphi < 45°$ N



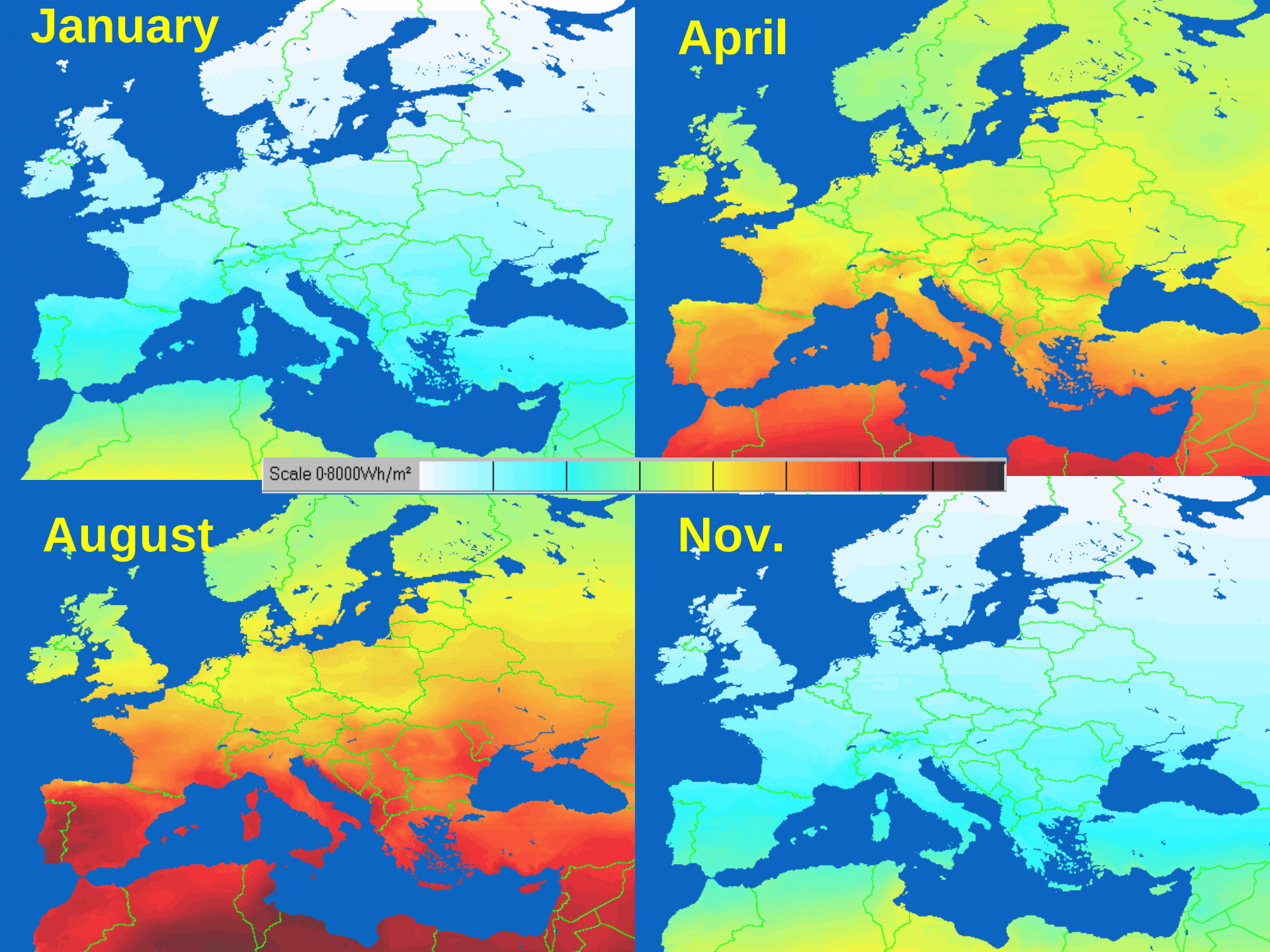
$\varphi = 45°$ N

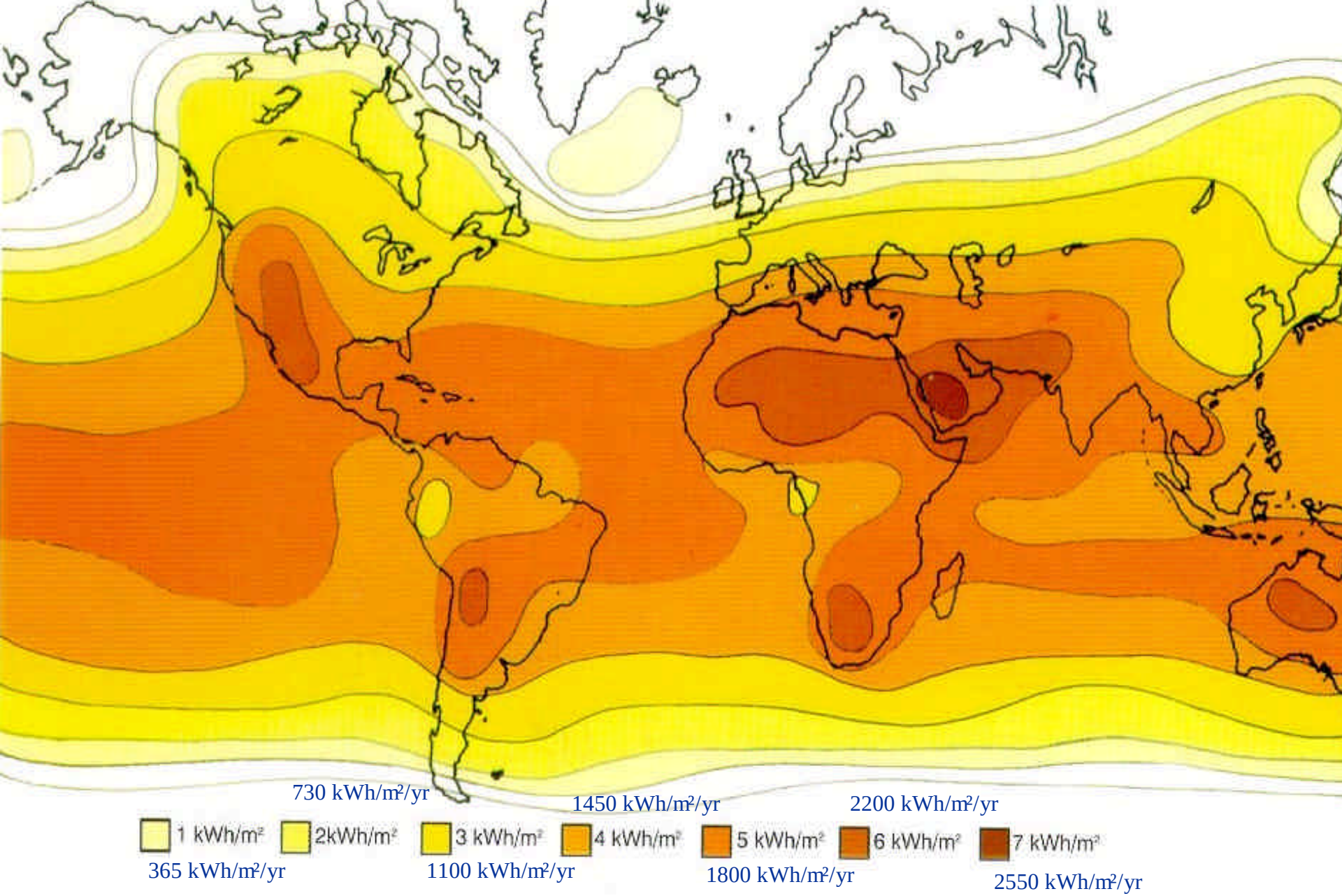


$\varphi = 66°\ 33'$ N (cercle polaire)



$\varphi = 45°$N


January
April
Scale 0-8000Wh/m²
August
Nov.



Principal daily worldwide insolation zones (annual average)

Main applications of solar thermal

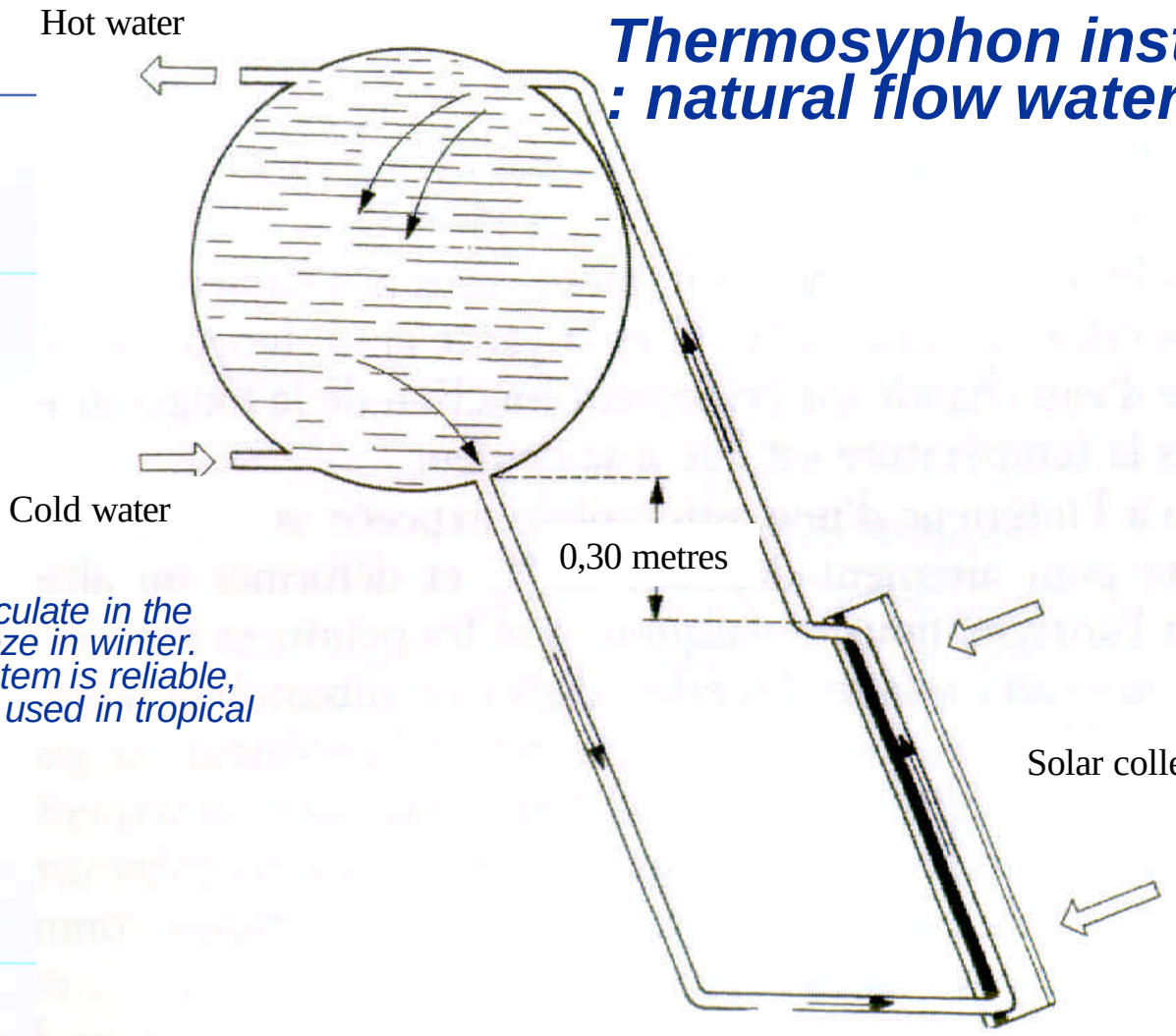
- Domestic water heating
- Solar Heating
- Air conditioning : heating / Cooling

Historical perspective

1891	C. L. Kemp	Patent for a flat collector
1891 - 1900		Flat collectors „Climax" commercialised1600 systems installed in 1900 in CA
1909	W. J. Bailey	Sale of solar domestic water heaters "day and night" 4000 systems installed after 1st world war
1938	MIT	Design and construction of a house equipped with a system that stores hot water in an underground tank of 65 000 L
Post war	MIT	Improvements of the house : auxiliary energy source, … 2 yrs of monitoring : covering ratio = 3/4

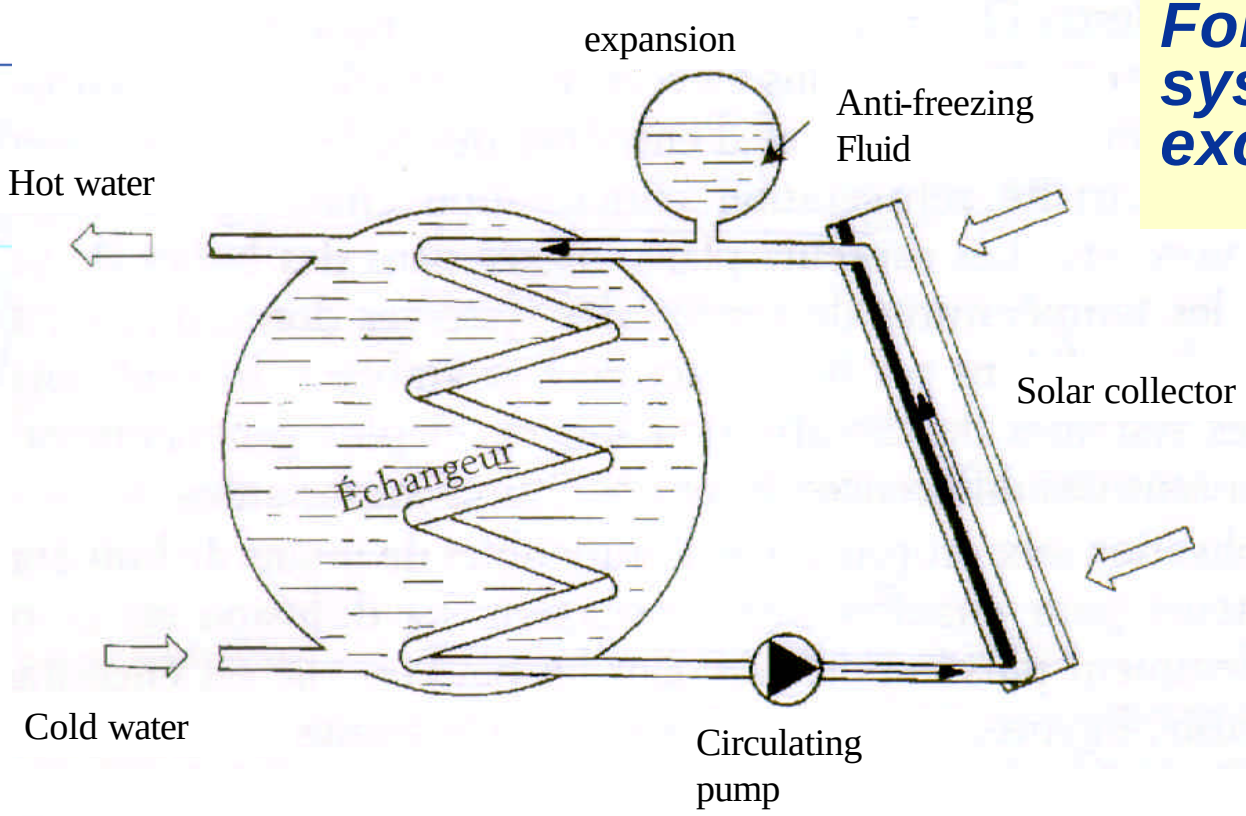
How does it work ?

Thermosyphon installation : natural flow water heater



- *The water that circulate in the collector may freeze in winter. However, this system is reliable, cheap and widely used in tropical regions*

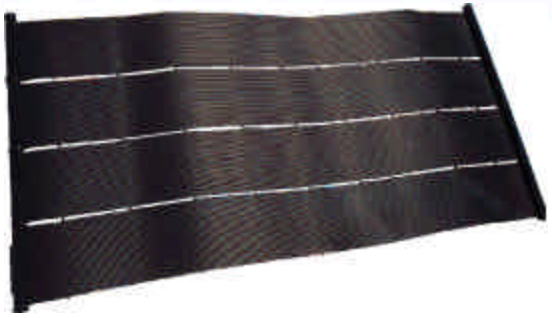
Forced circulation system with heat exchanger



Solar collectors

Three categories

Collectors without glass cover



• Water at a temperature 20°C > to the ambiant

Application :
Heating of swimming pools

Flat collectors

• Water at a temperature 30°C à 70 °C > to the ambiant

Applications : Water heating for domestic uses

Vacuum tubes

• Water at a temperature 70°C > to the ambiant

Application :
Solar air conditionning

(source Giordano)

Roof integrated

On a support structure

(sources Tecsol, Giordano)

The market

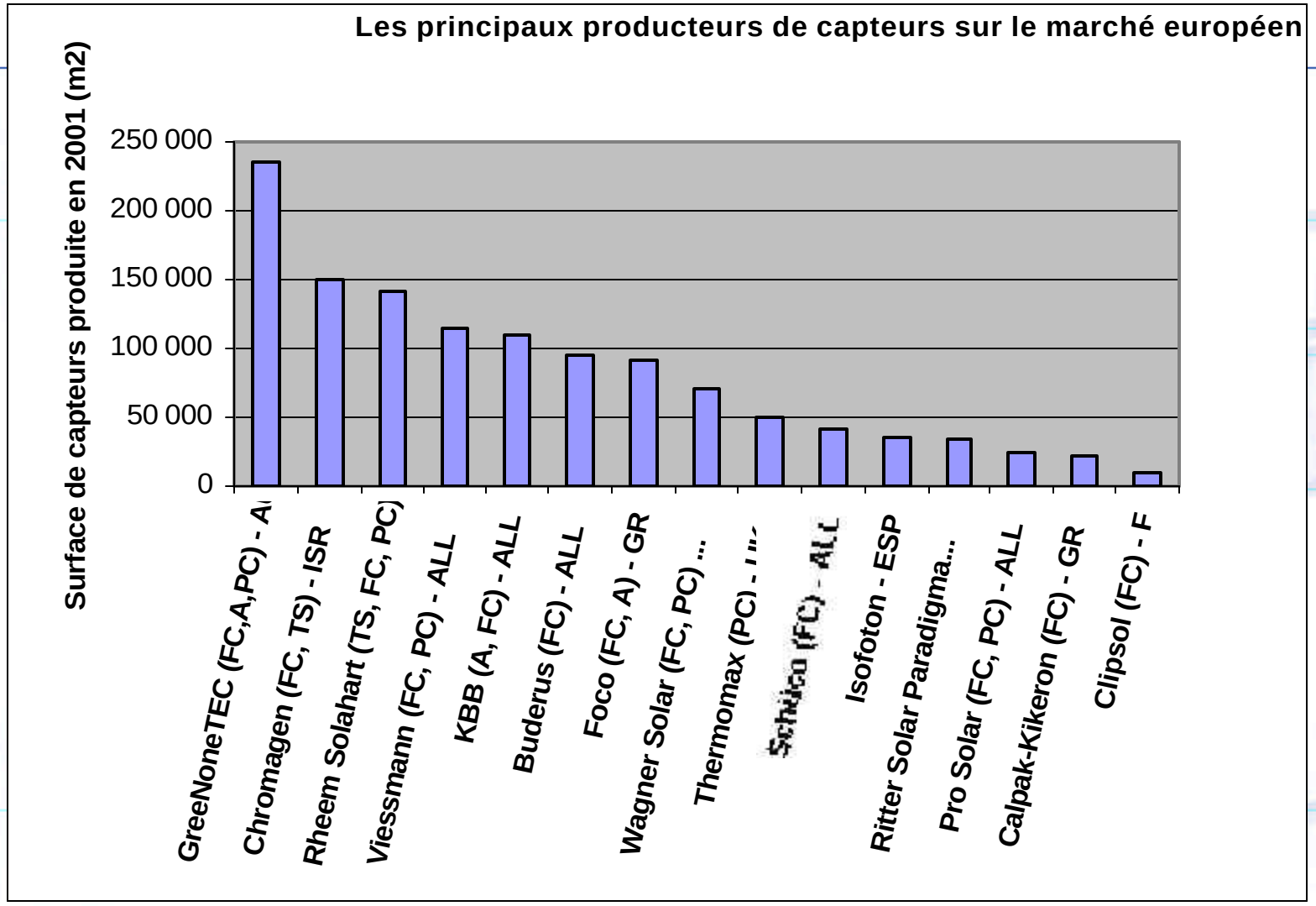
China is the biggest market

- **China (51 Mm² installed – end of 2003) : 59% of the surface installed in the world (85,2 Mm²)**
- **EU : 16%**
  - Germany : 6%
  - Geece : 3%
  - Austria : 2%
- **Japan : 9%**

Increase of the market :

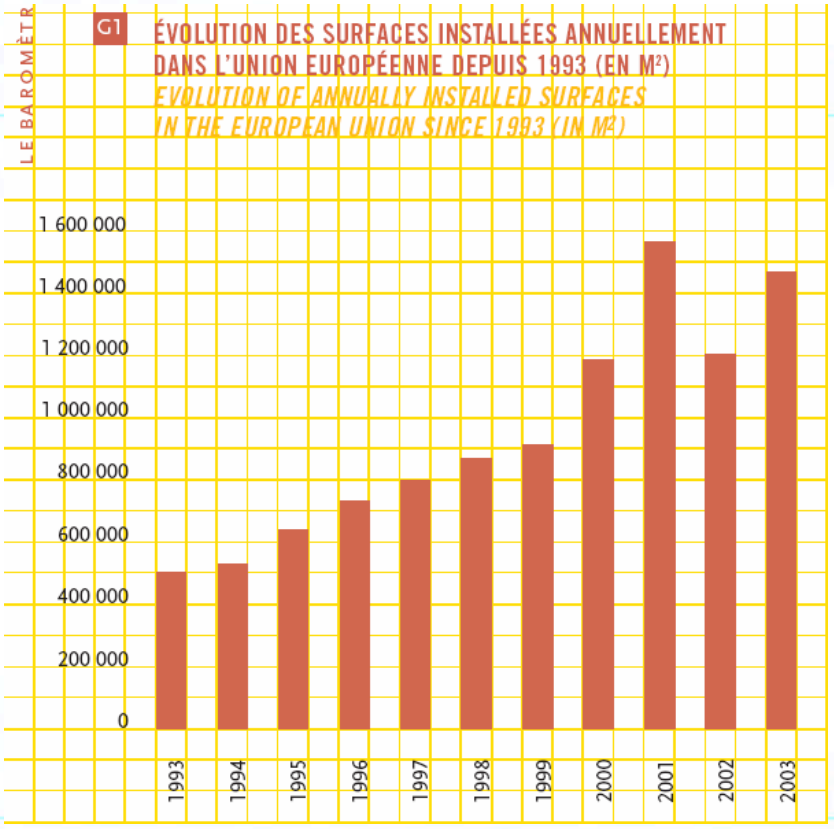
World : 12% p.a. since 1990 (23% in 2003)

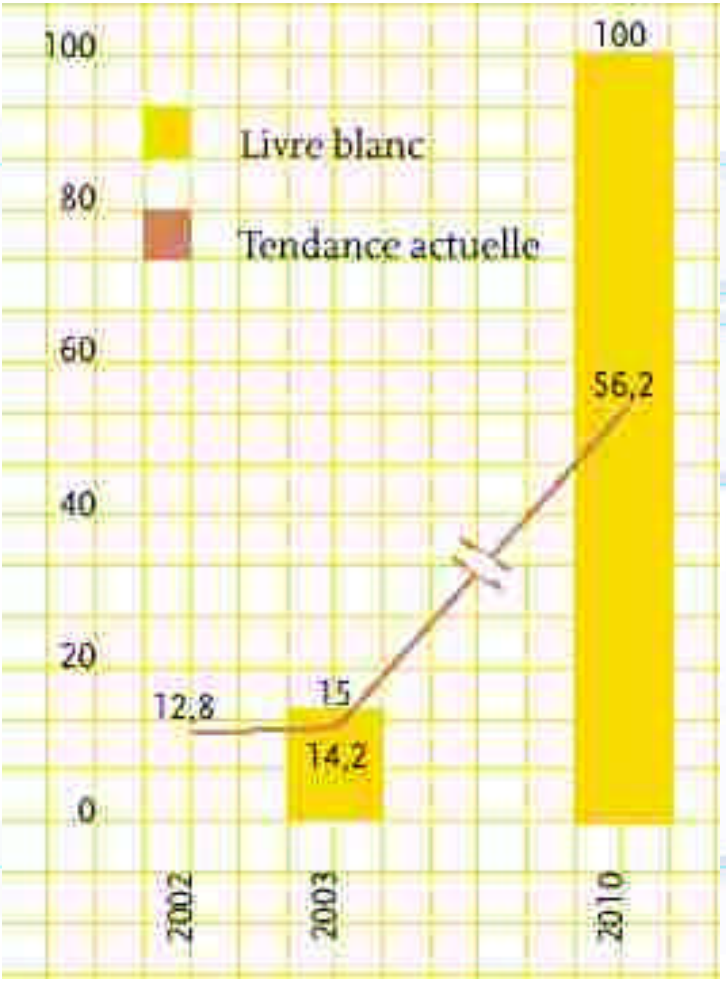
Few manufacturers operate on an international scale



Medium term perspectives

Trend : regular increase of the sales

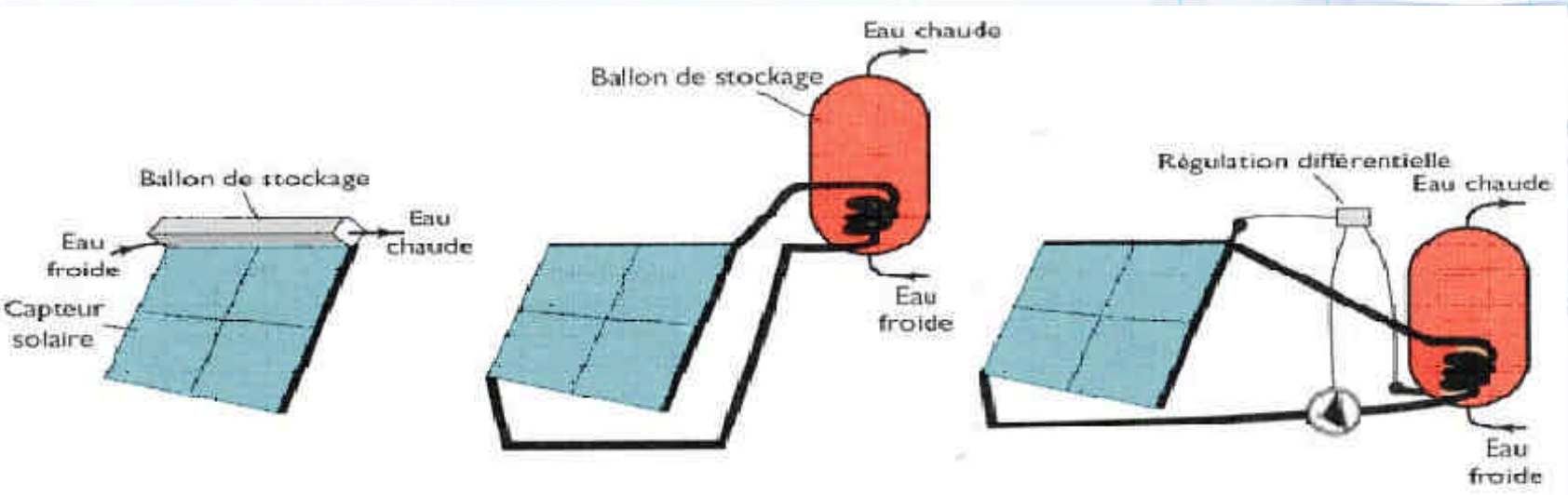




DOMESTIC WATER HEATING

Domestic water heating (for individual use)

The various systems



Domestic water heating (for individual use)

Energetic Ratios

- **Solar Resources *in France* :**

1100 to 1700 kWh/m²/yr

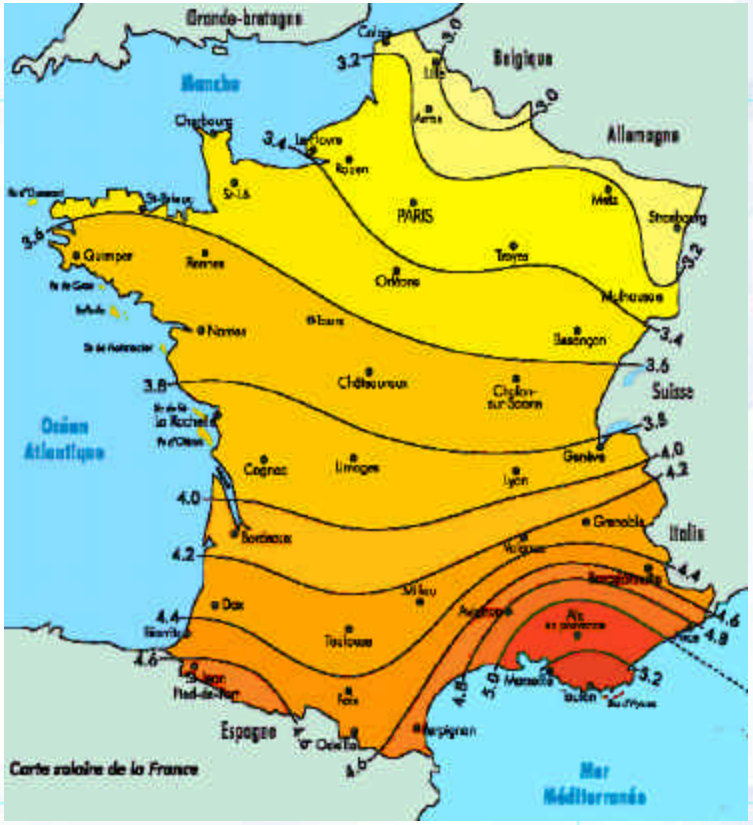
- **Productivity of collectors :**

450 à 700 kWh/m²/yr

- **Covering ratio :**

40 à 60% (of the needs in hot water)

- **A solar water heater avoids the emission of 350 kg CO_2/yr**



(source Tecsol)

Economic aspects
Investment

- **Cost of an installed system : 3500 to 5000 €** (all taxes included)

  Average price for 3-5 m² and a storage tank of 200-300 litres (individual house : 3-4 people),

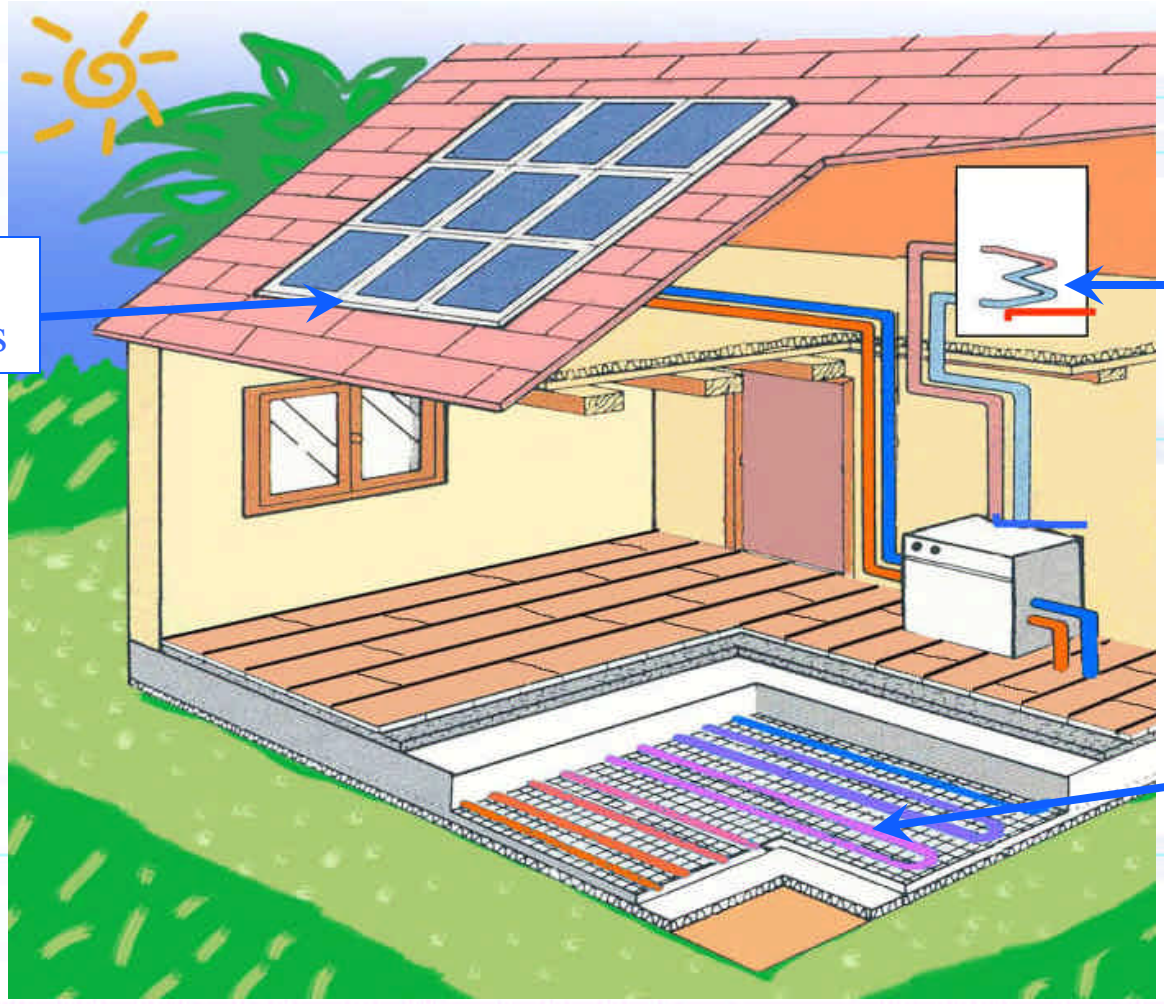
- **or 1000 €/m² of collector (all taxes included)**

(source ADEME 09/2003)

SOLAR COMBINED SYSTEMS

Solar combined systems

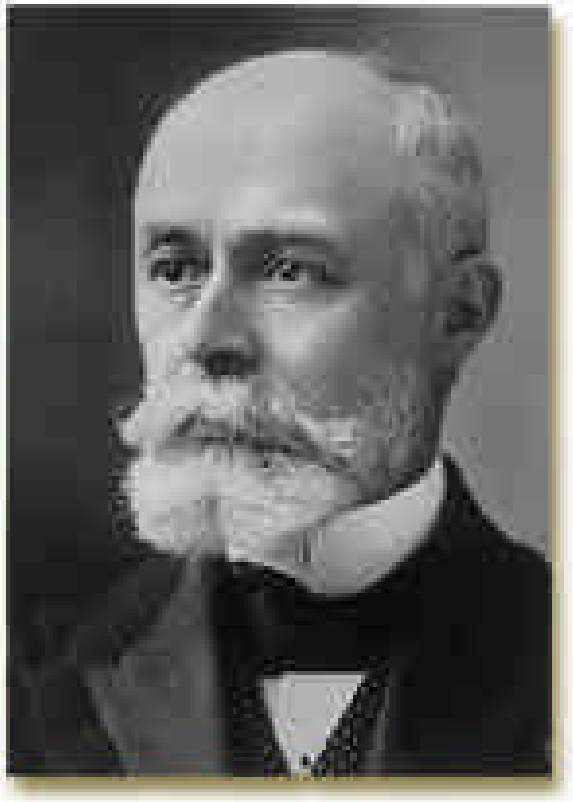
16000 € for a house of 140 m²



Historical perspective

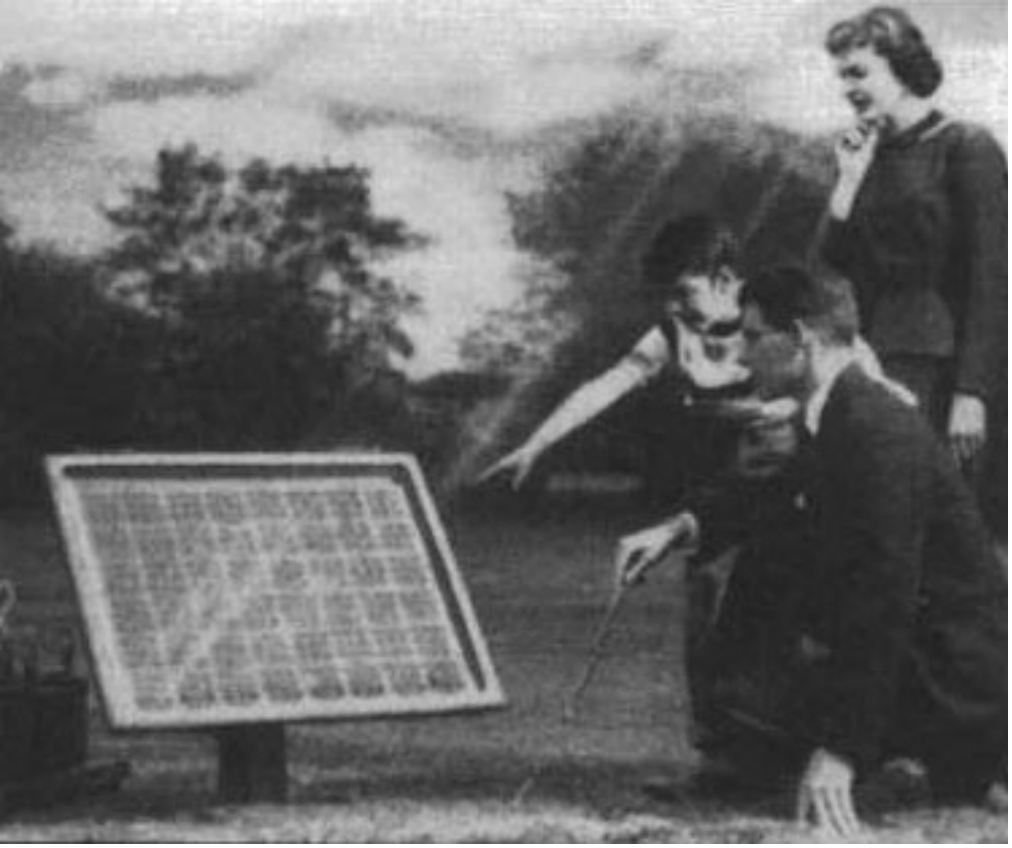
1839 – Antoine Becquerel discovers the photovoltaic effect

Direct conversion of sunlight into electricity



- Necessity of a material that absorbs the sunlight and transforms the absorbed energy in electrical energy

Bell Solar Battery



SIMPLE AND EFFICIENT—The *Bell Solar Battery* is made of thin, specially treated strips of silicon, an ingredient of common sand. It needs no fuel other than the light from the sun itself. Since it has no moving parts and nothing is consumed or destroyed, the *Bell Solar Battery* should theoretically last indefinitely.

New Bell Solar Battery Converts Sun's Rays Into Electricity

Bell Telephone Laboratories demonstrate new device for using power from the sun

Scientists have long reached for the secret of the sun. For they have known that it sends us nearly as much energy daily as is contained in all known reserves of coal, oil and uranium.

If this energy could be put to use there would be enough to turn every wheel and light every lamp that mankind would ever need.

Now the dream of the ages is closer to realization. For out of the Bell Telephone Laboratories has come the *Bell Solar Battery*—a device to convert energy from the sun directly and efficiently into usable amounts of electricity.

Though much development remains to be done, this new battery gives a glimpse of future progress in many fields. Its use with transistors (also invented at Bell Laboratories) offers many opportunities for improvements and economies in telephone service.

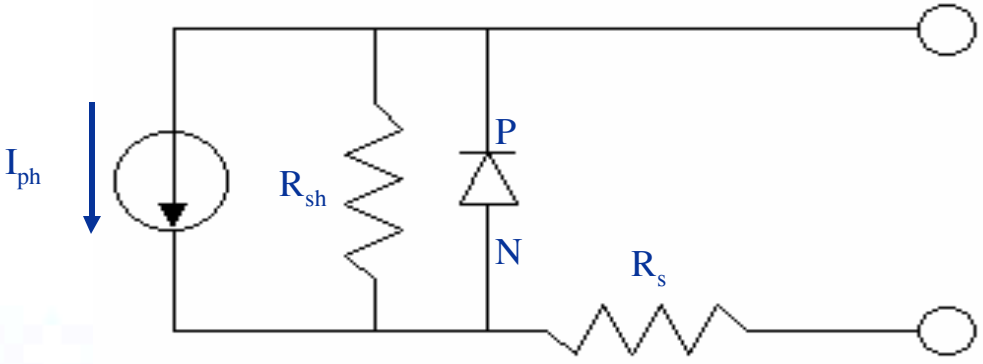
A small *Bell Solar Battery* has shown that it can send voices over telephone wires and operate low-power radio transmitters. Made to cover a square yard, it can deliver enough power from the sun to light an ordinary reading lamp.

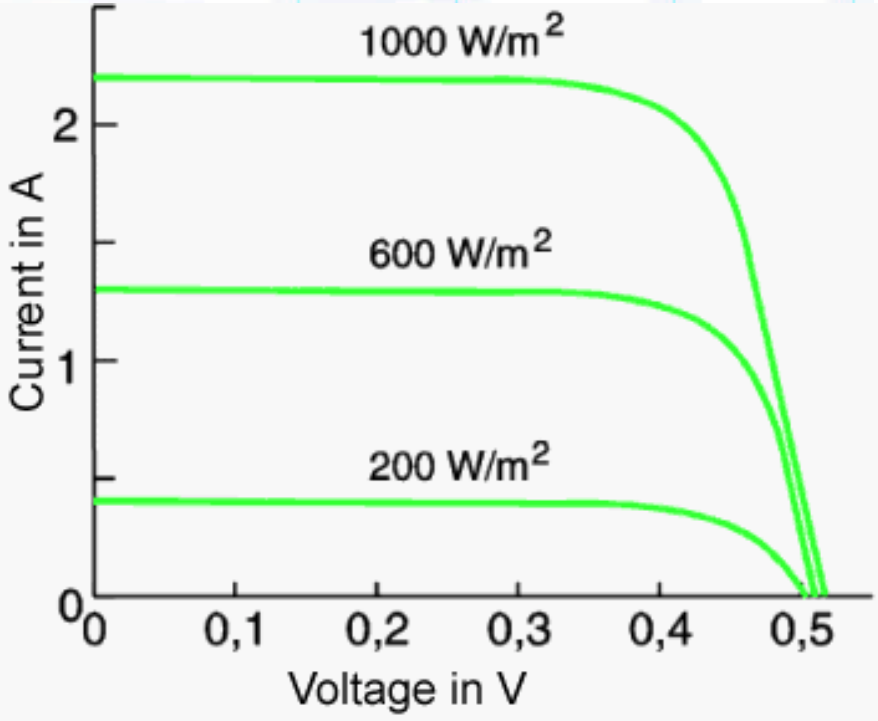
Great benefits for telephone users and for all mankind will come from this forward step in harnessing the limitless power of the sun.

BELL TELEPHONE SYSTEM

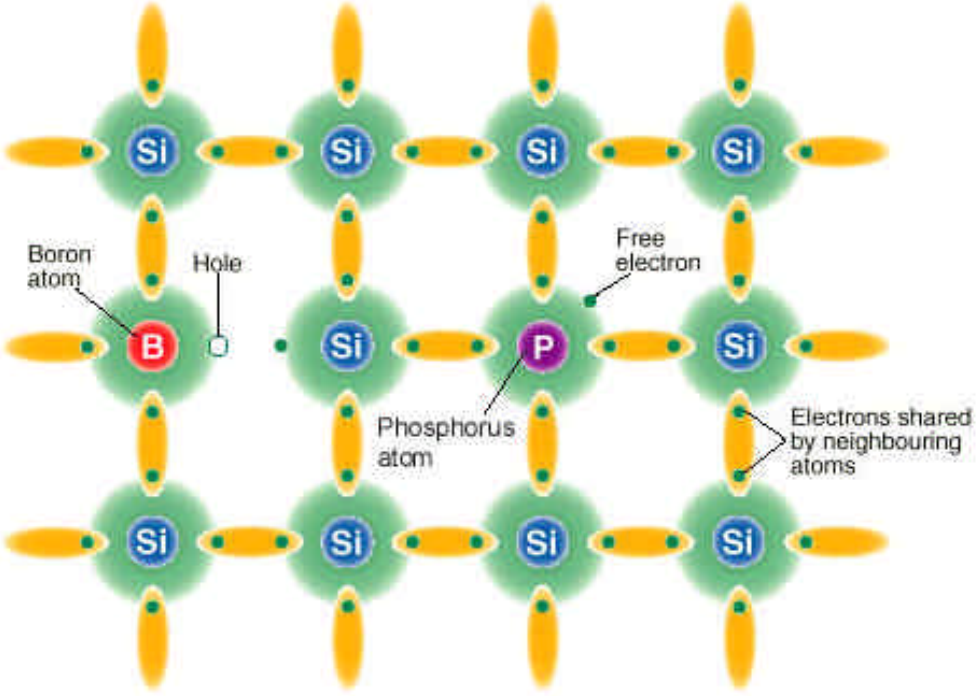
Development

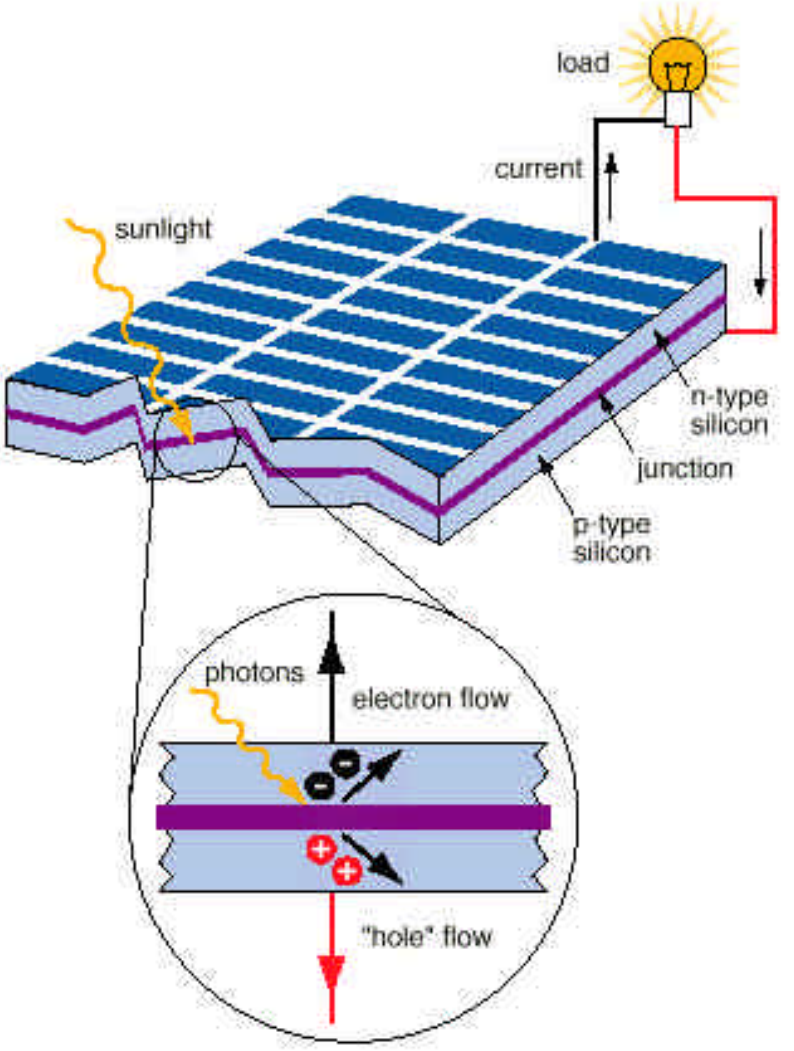
I-V Caracteristic of a PV cell





How does it work ?

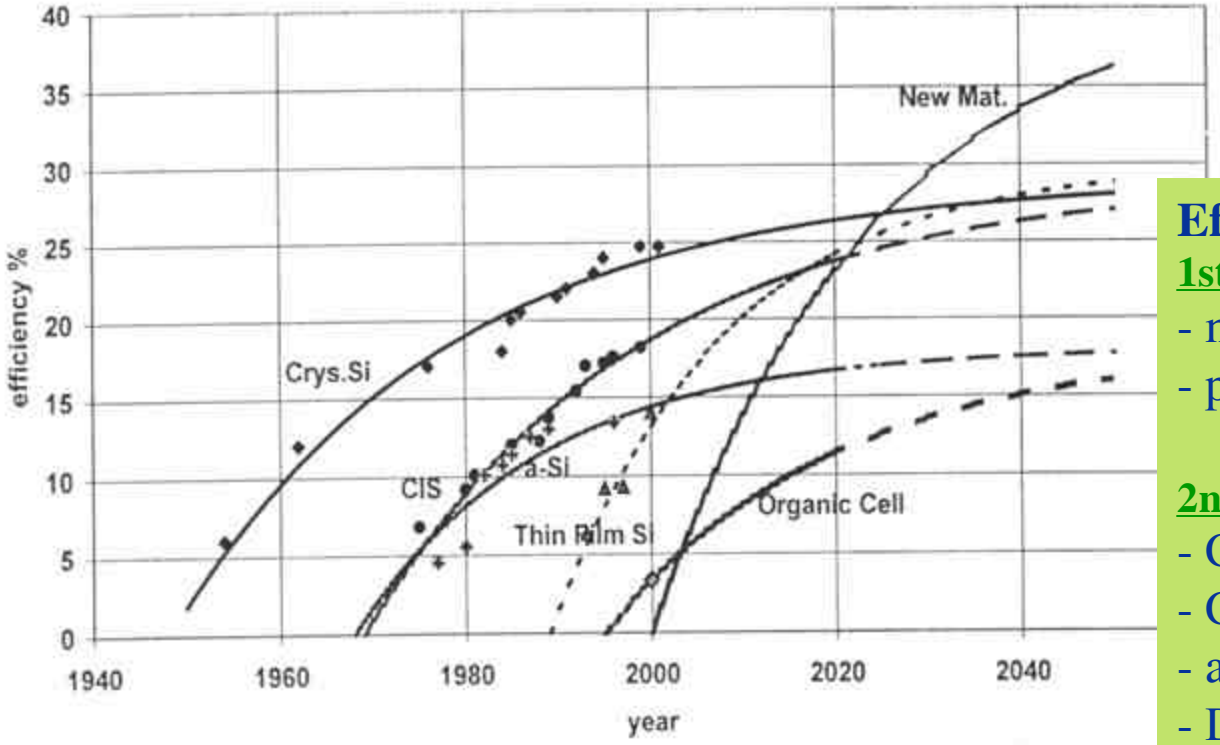




3 generations of cells

Generation of cells	Technology	Development status	Horizon for industrialisation
1st : Cristalline Silicon	•monocristaline Silicon	•Industrial / mass	• Now
	• polycristalline Silicon	•Industrial / mass	• Now
	• Ribbons	•Industrial / mass	• Now
2nd : Thin films	•Amorphous Silicon	•Industrial / mass	• Now
	•CIS	•Industrial & pilot	• Now & < 5 yrs
	•CdTe	•Industrial	• Now
3rd generation	•Dyes (organic cells)	•Applied Research	• < 10 yrs
	•Advanced concepts	•Theoretical research	•2040 - 2050

Efficiencies



Efficiencies :

1st gen.

- mc-Si : 20 % (24,7 %)
- pc-Si : 15 % (20,3 %)

2nd gen.

- CIS : 11% - (18,4 %)
- CdTe : 7-9 % (16,5 %)
- a-Si : 5-7 %
- Dyes : 5 % (10,1 %)

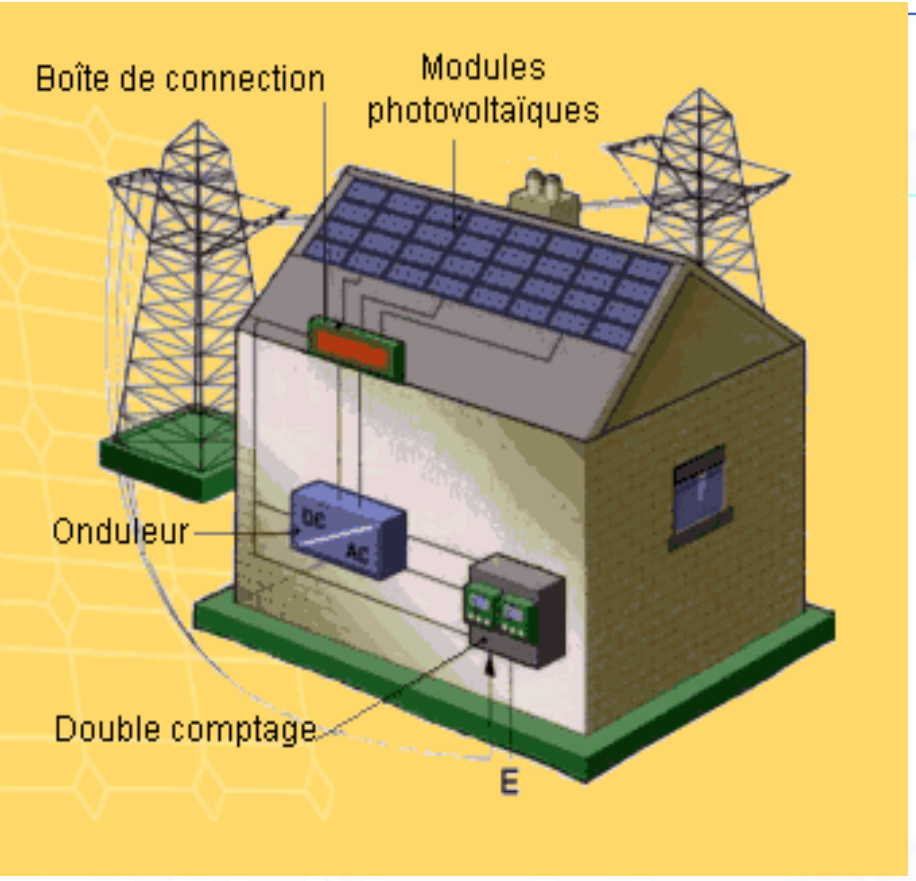
Source ISE

PV systems

3 main categories

- Autonomous systems for isolated sites
- Decentralised systems connected to the grid
- PV plants connected to the grid

Decentralised systems



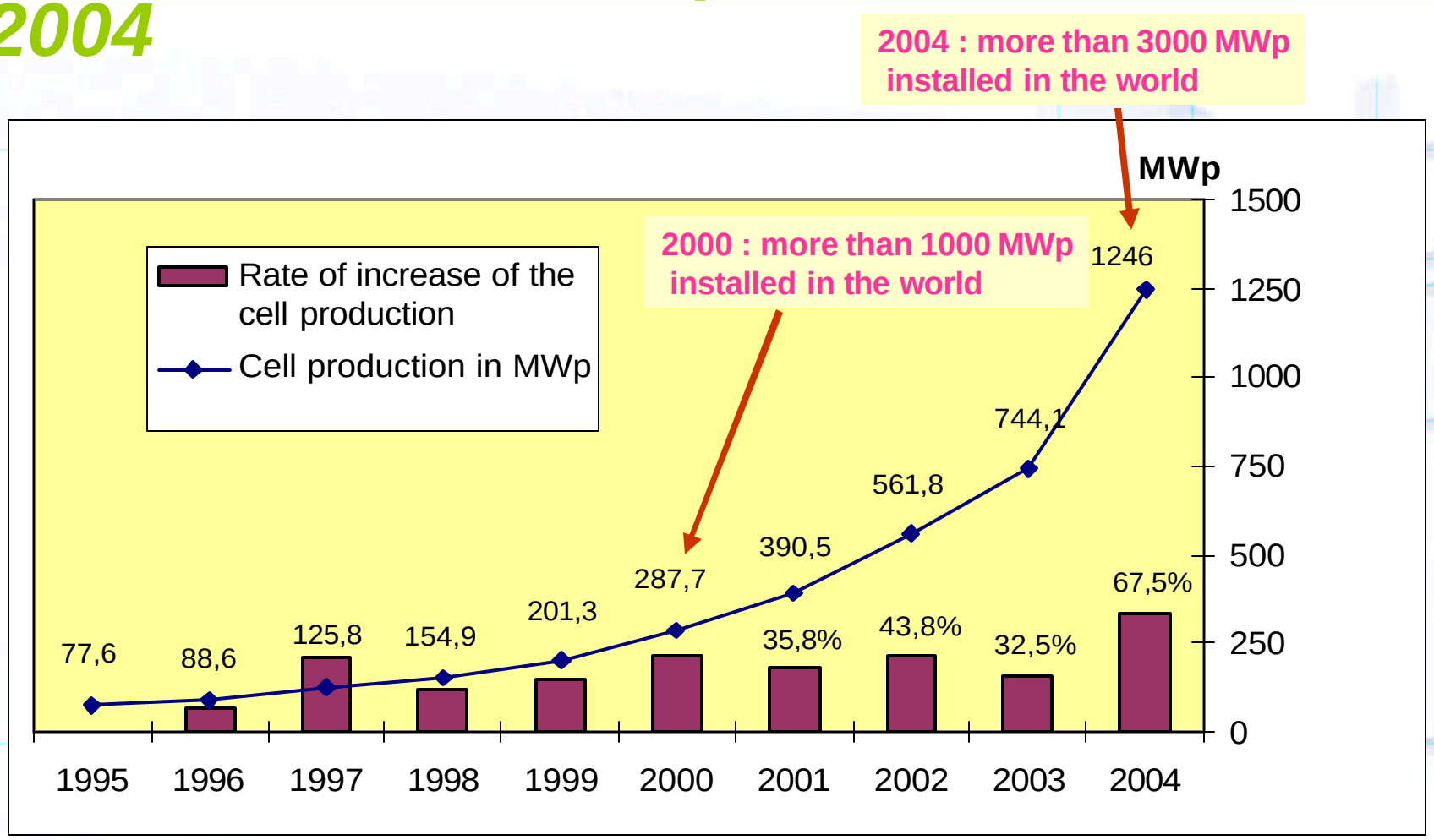
PV plants

Lieu	Ville/Région Pays	Construction	Puissance (MWc)
Mühlhausen	Allemagne	2004	6,3
Bürstadt	Allemagne	2004	5
Espenhain	Allemagne	2004	5
Springerville	USA (AZ)	2001-2004	4,59
Geiseltalsee, Merseberg	Allemagne	2004	4
Göttelborn	Allemagne	2004	4
Hemau	Allemagne	2003	4
SMUD Rancho Seco	USA (CA)	1984-2000	3,9
Dingolfing (toît solaire)	Allemagne	2004	3,3
Serre	Italie	1995	3,3

The production of PV cells

The market

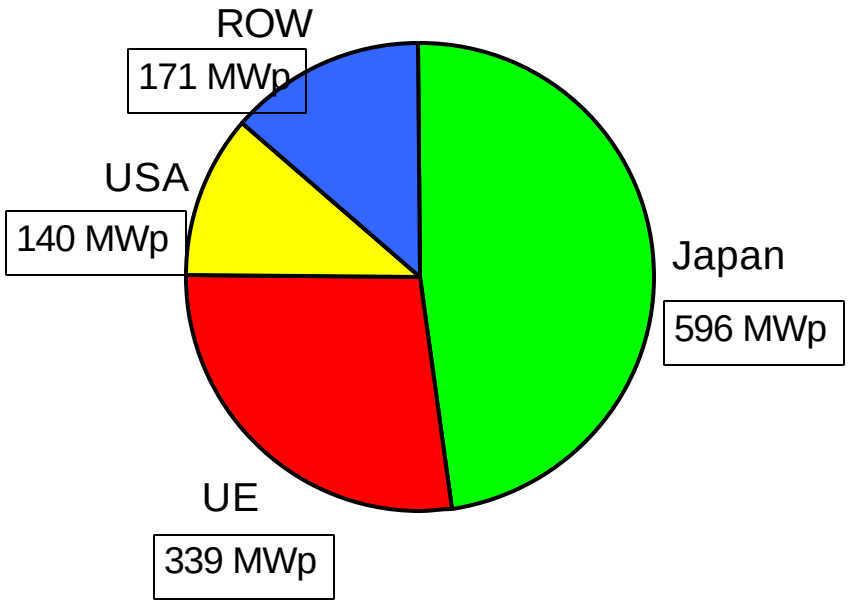
Increase of the cell production : 68 % in 2004



Geographical share of the production

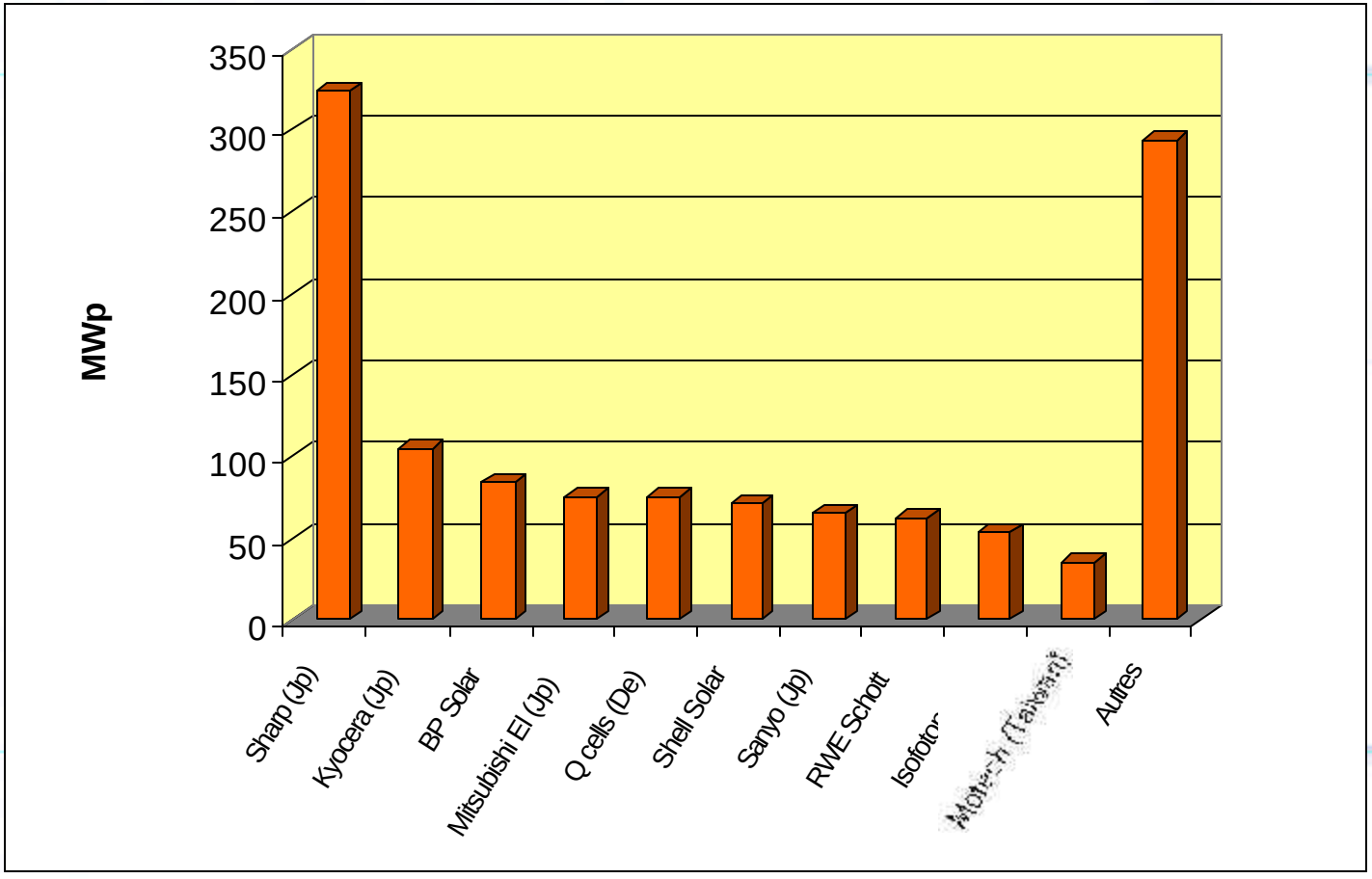
Japan world leader

Total 2004 production : 1246 MWp



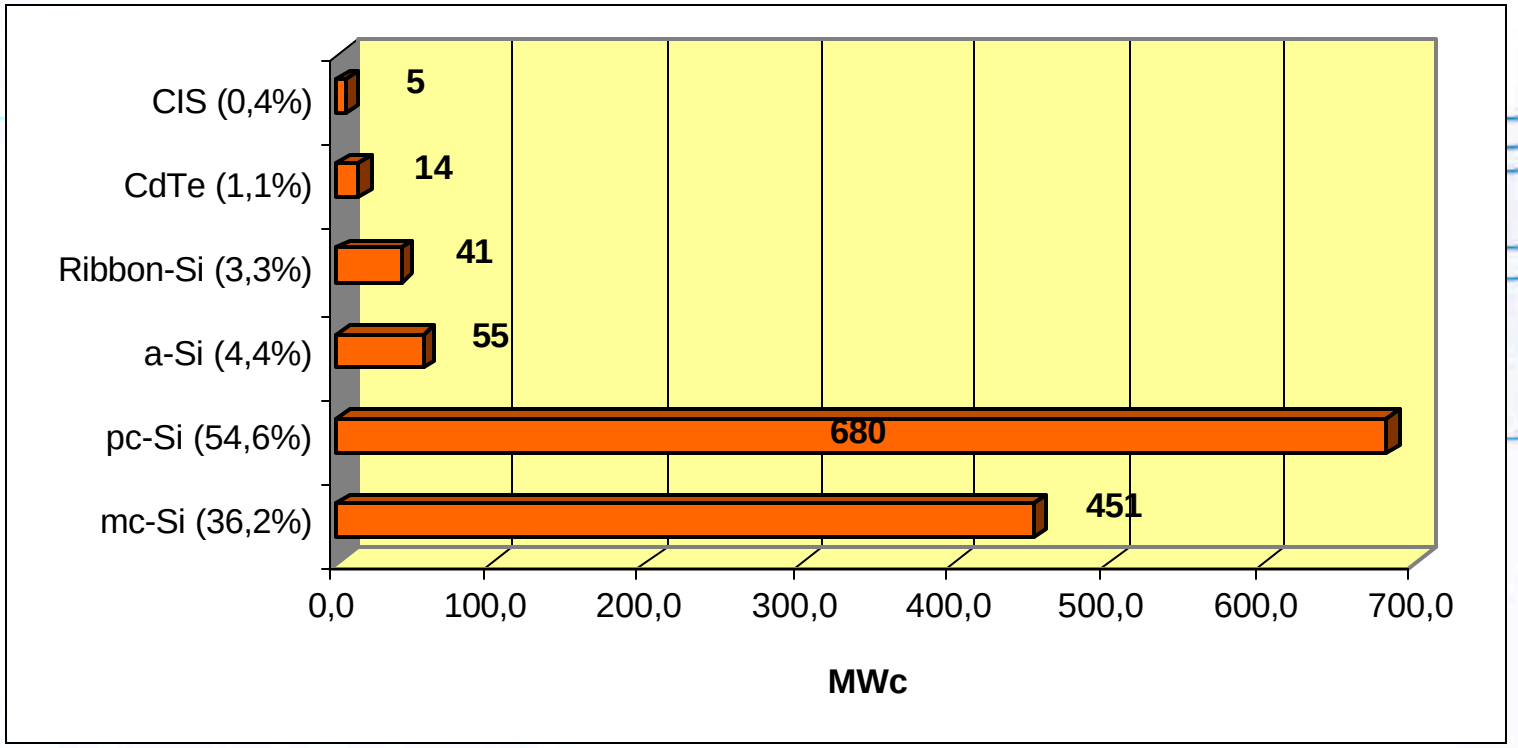
Manufacturers

86 % of the production is concentrated on 10 industrial groups



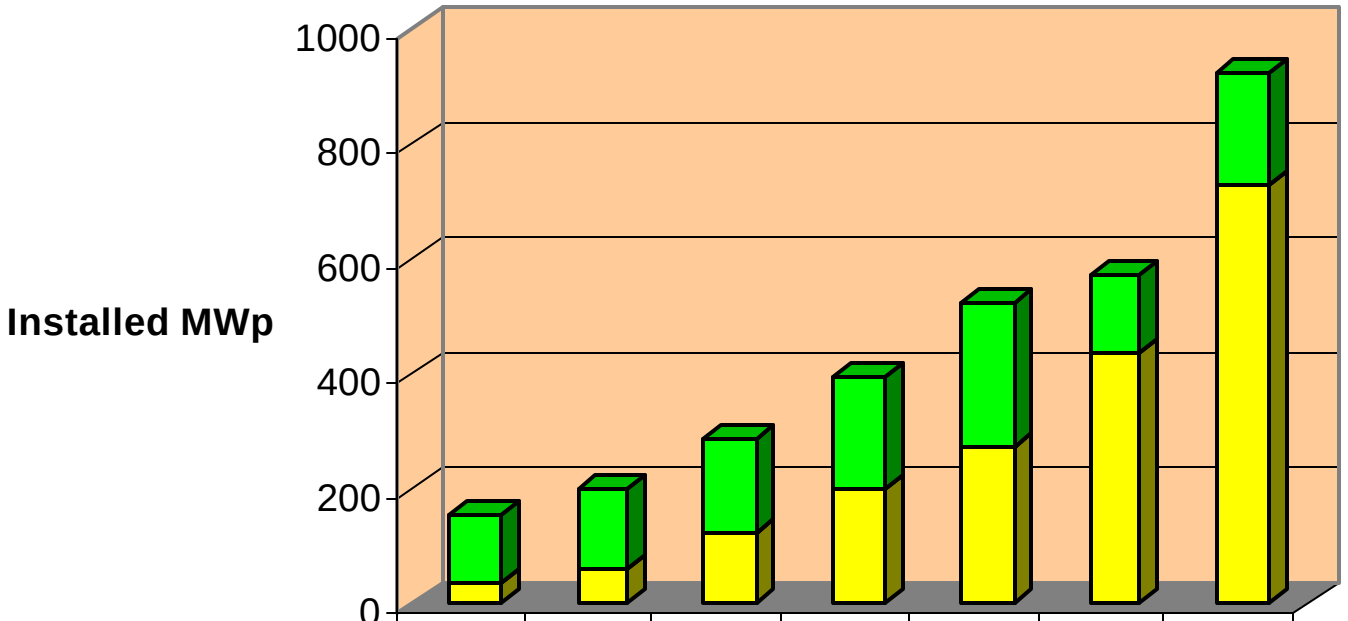
Technologies

Si represents about 99 %



PV installations

Grid connected systems represent 79% of the installations in 2004



	1998	1999	2000	2001	2002	2003	2004
Isolated	115	139	163	191	250	134	195
Grid connected	38	62	125	204	275	440	732

Market concentrated over 3 geographical areas

Market of PV installations depending on the world regions in 2004

MWp	PV installé en 2004	Cumulé en 2004	Taux de croissance 2003-2004
Germany	366	776	89%
Total UE	441	1003	78%
Japan	277	1137	32%
USA	84	359	31%
TOTAL WORLD	927	3177	41%

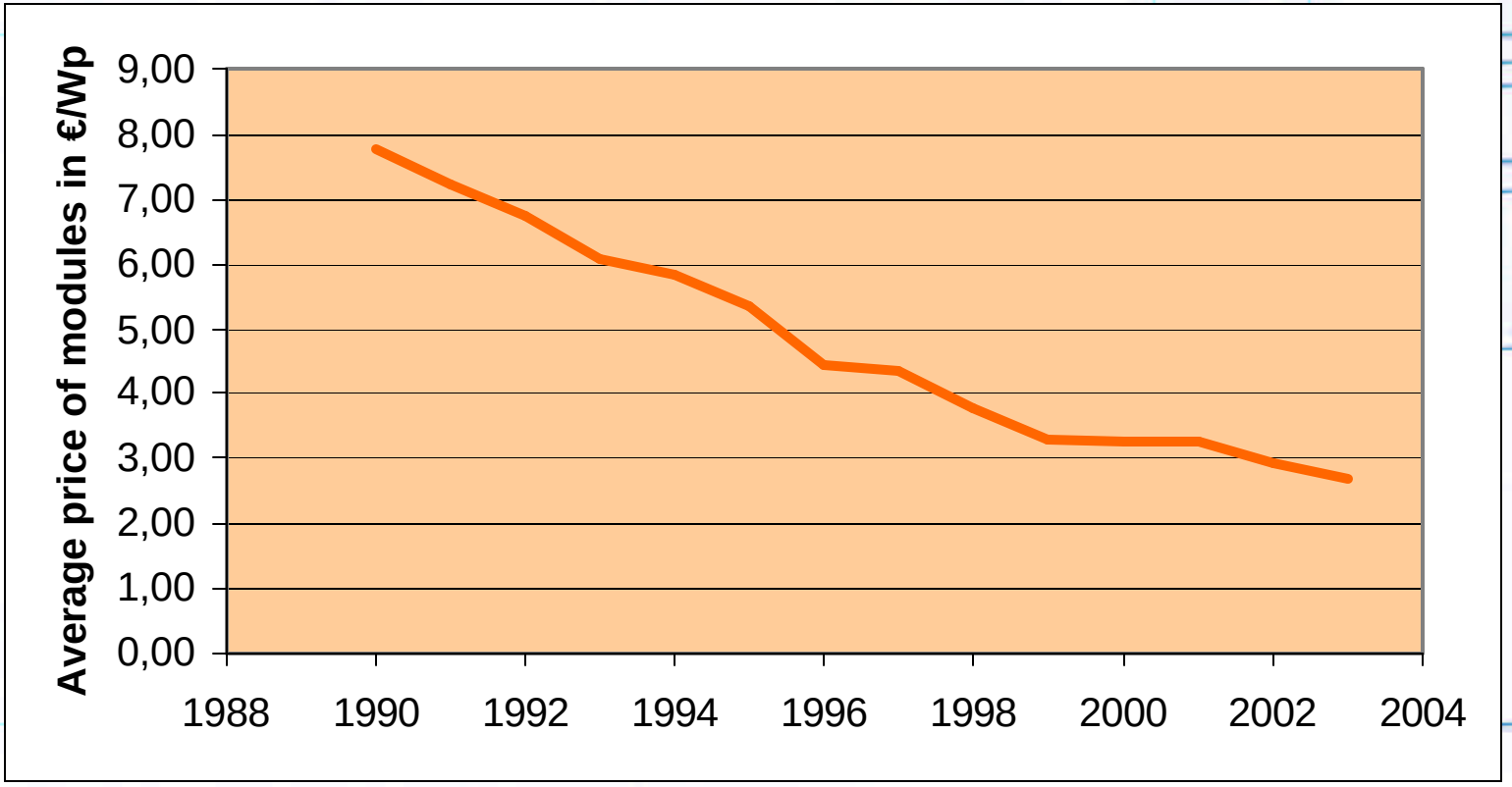
Germany : the new feed-in tarriff is the only incentive

Feed-in tariff per kWh	< 30 kWp	30 – 100 kWp	> 100 kWp
On top of buildings	0.574 € (0.70 $)	0.546 € (0.67 $)	0.540 € (0.66 $)
Façade-integrated	+ 0.05 € (0.06 $)		
Free-range	0.457 € (0.56 $) no limit to system size		

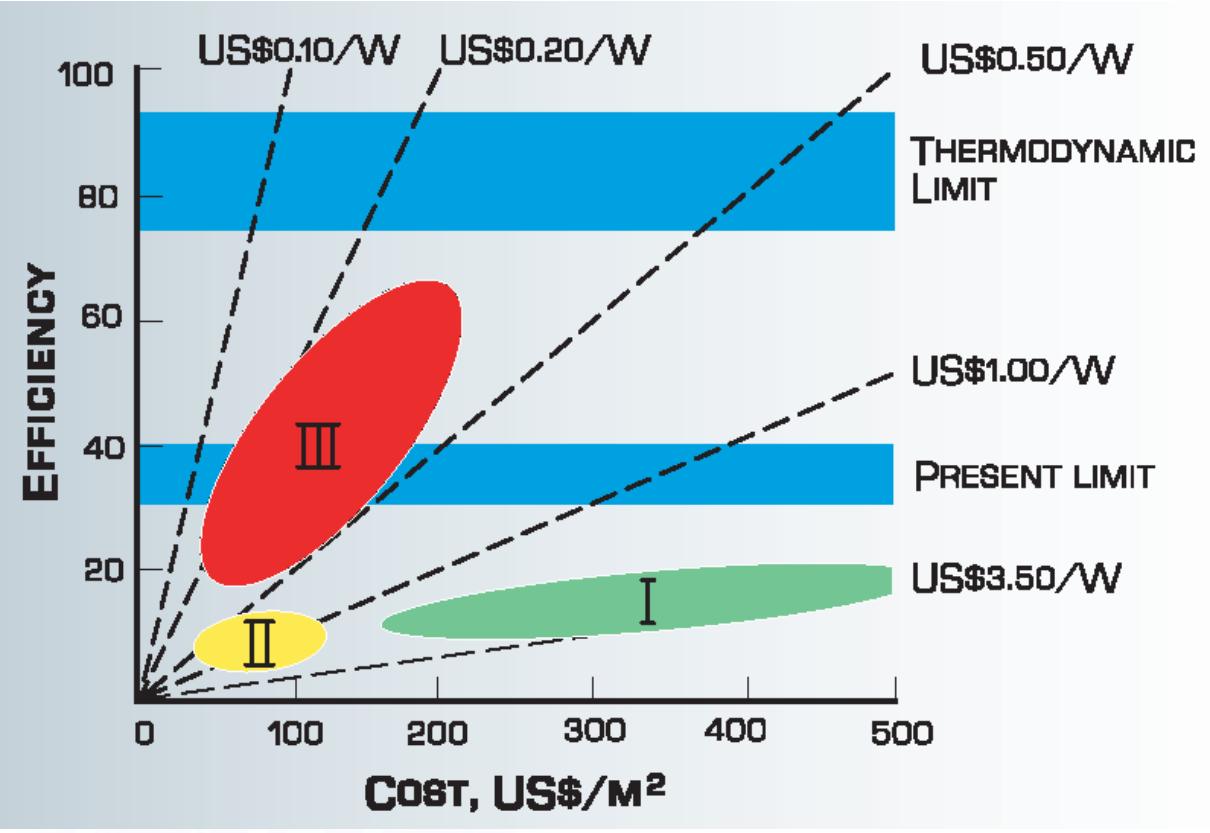
Prices and cost of MWh

Price of a PV module (pc-Si) ~ 2,70 €/Wp

Evolution of the price of PV modules from 1990 to 2004
(in 1976 : 59 €/Wc)



Future of the 3 generations

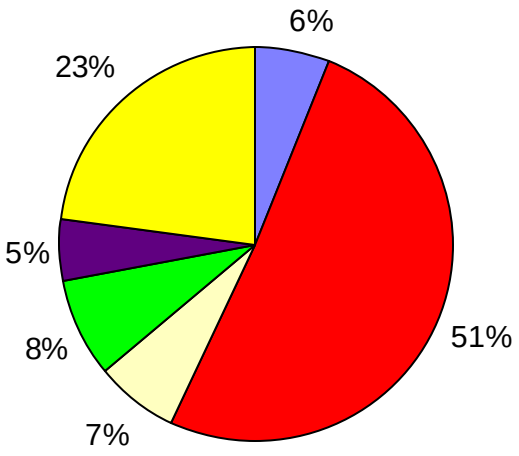


1st generation : c-Si : mc/pc-Si

2nd generation : thin films: a-Si, CIS, CdTe, µc-Si

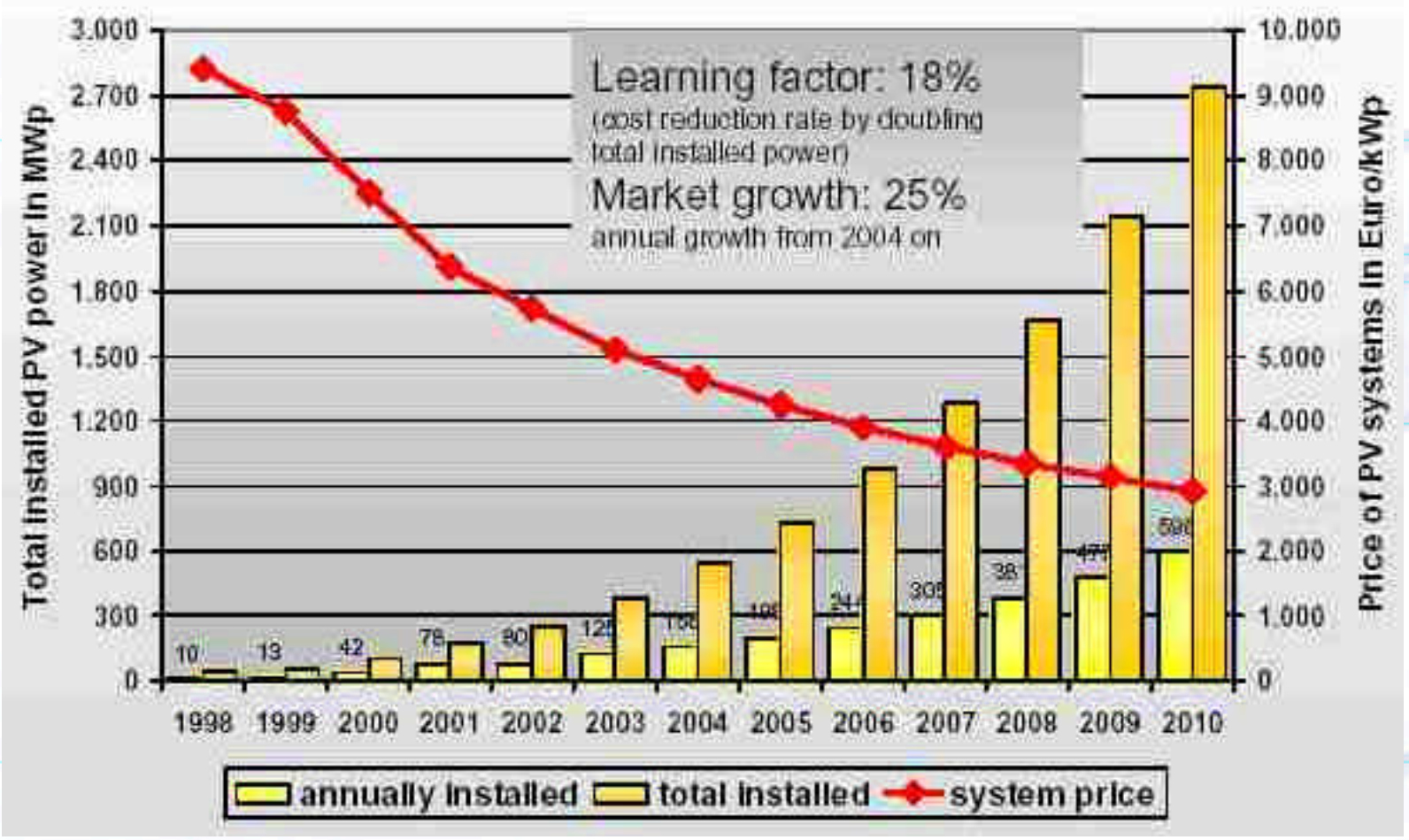
3rd generation : organics and advanced concepts

Cost of PV systems



- **Grid connected : 4 à 9 €/Wp**
  - Residential and commercial : 5 à 9 €/Wp
  - Plants : 4 à 5 €/Wp
  - Costs dépend on the maturity of the local market and on other factors (integration, …).
- **Isolated sites : much more expensive but often competitive**
  - Up to 1 kWc : 10 à 18 €/Wp
  - Above 1 kWp
    - *DC Systems : 10 à 13 €/Wp*
    - *AC Systems : 13 à 17 €/Wp*
    - *high reliability Systems : 20 €/Wp*

Learning curve



Source : BSi

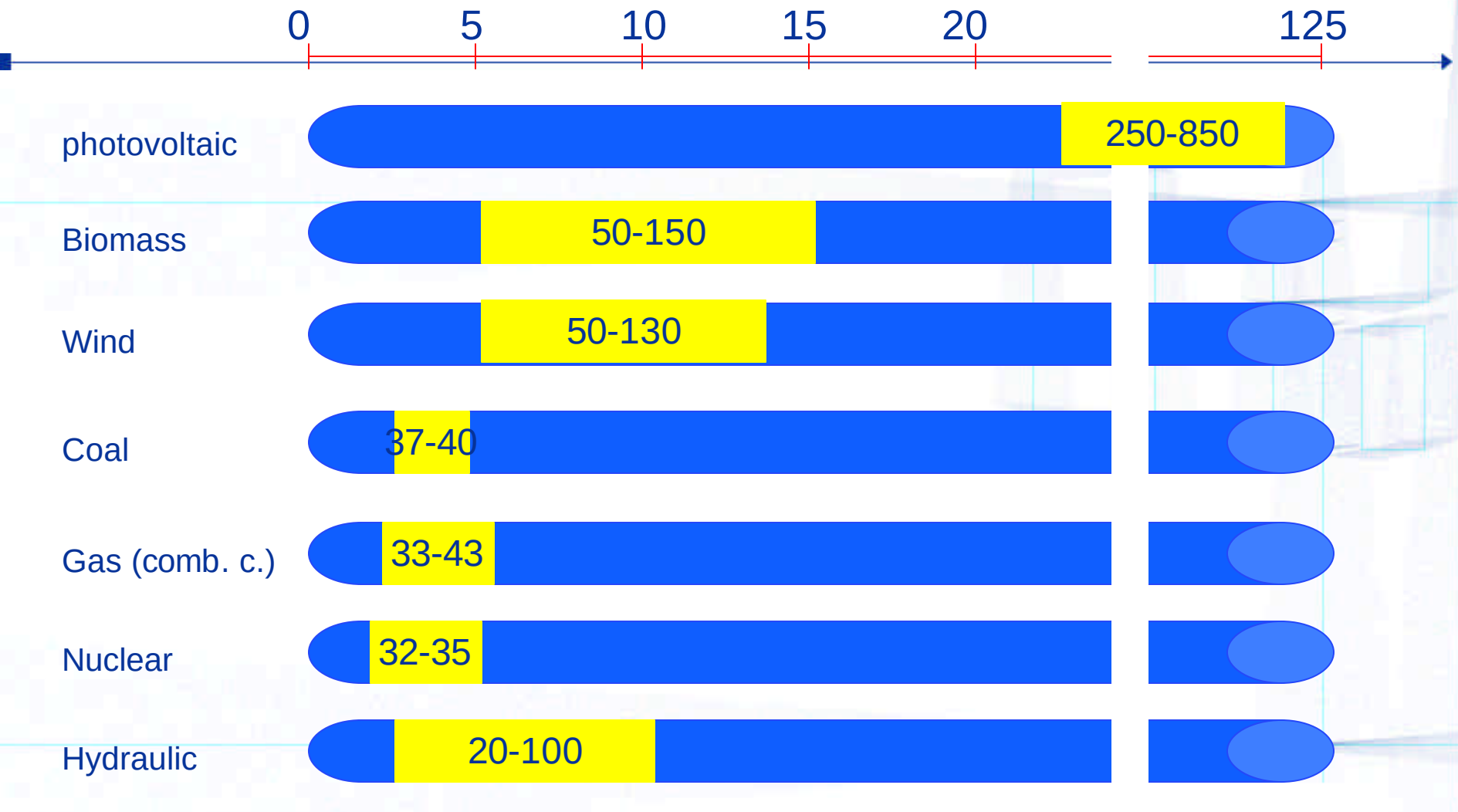
Costs of generation

- **Cost of generation depends on :**
  - the latitude of the site
  - the orientation of des modules
  - the size of the system

- **France : the costs vary from 265 €/MWh to 860 €/MWh**
  - 265 €/MWh : 1 MWp system installed in Nice, optimal orientation
  - 860 €/MWh : residential system installed in Lille, façade

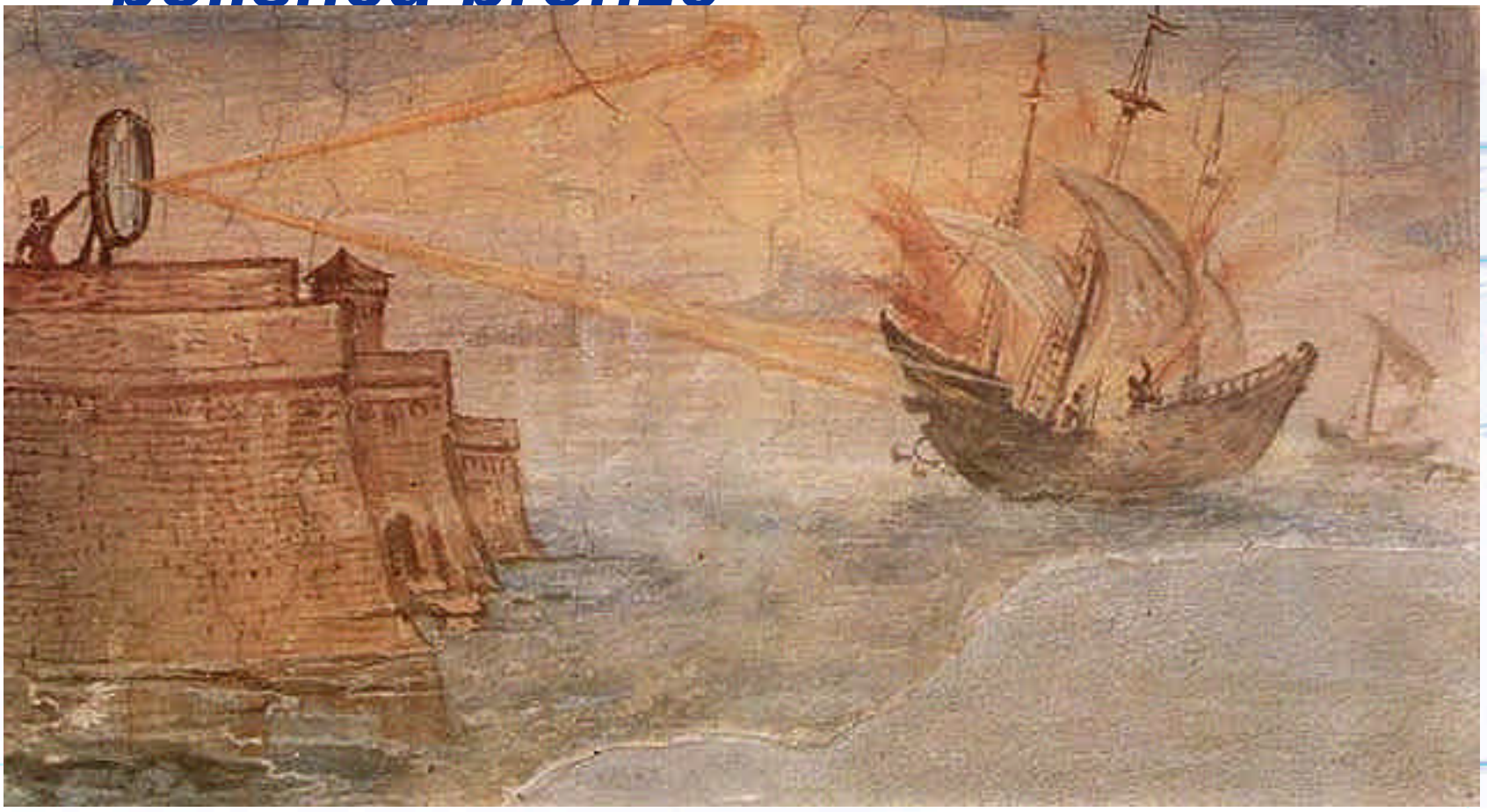
- **Projection 2015 : 145 €/MWh to 510 €/MWh**

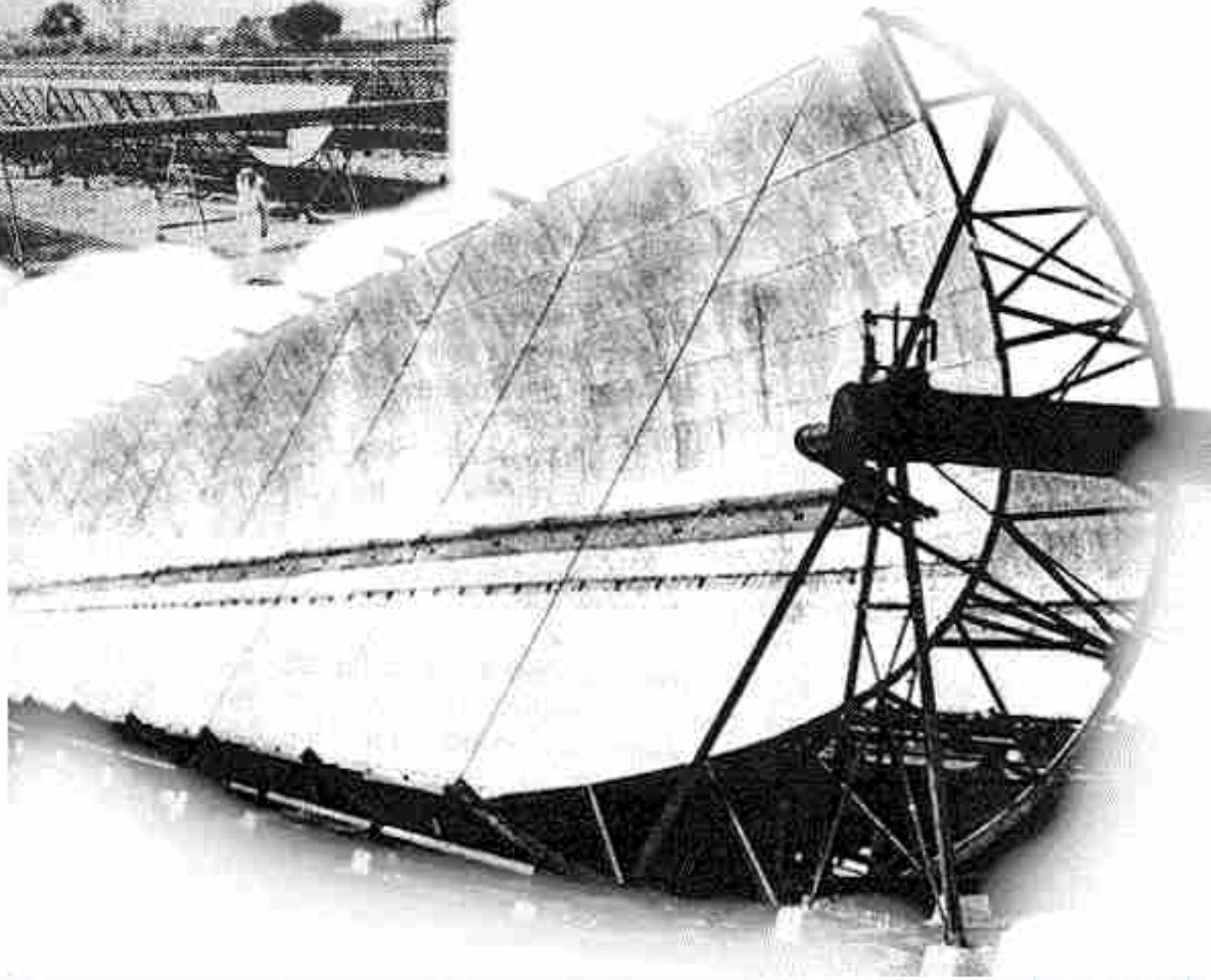
Cost of generation
(in €/MWh)



D'après le Débat national sur le developpement durable : « Energies, comprendre pour choisir »

Archimede's parabolic Mirrors in polished bronze





- 1912 : first parabolic trough collector (Schuman) in Maadi, in the suburb of Cairo (62 m long and 4 m of aperture)

- This use of solar energy
  - was stopped due to
- the increasing use of fossil fuels in
  - industry

Parabolic troughs

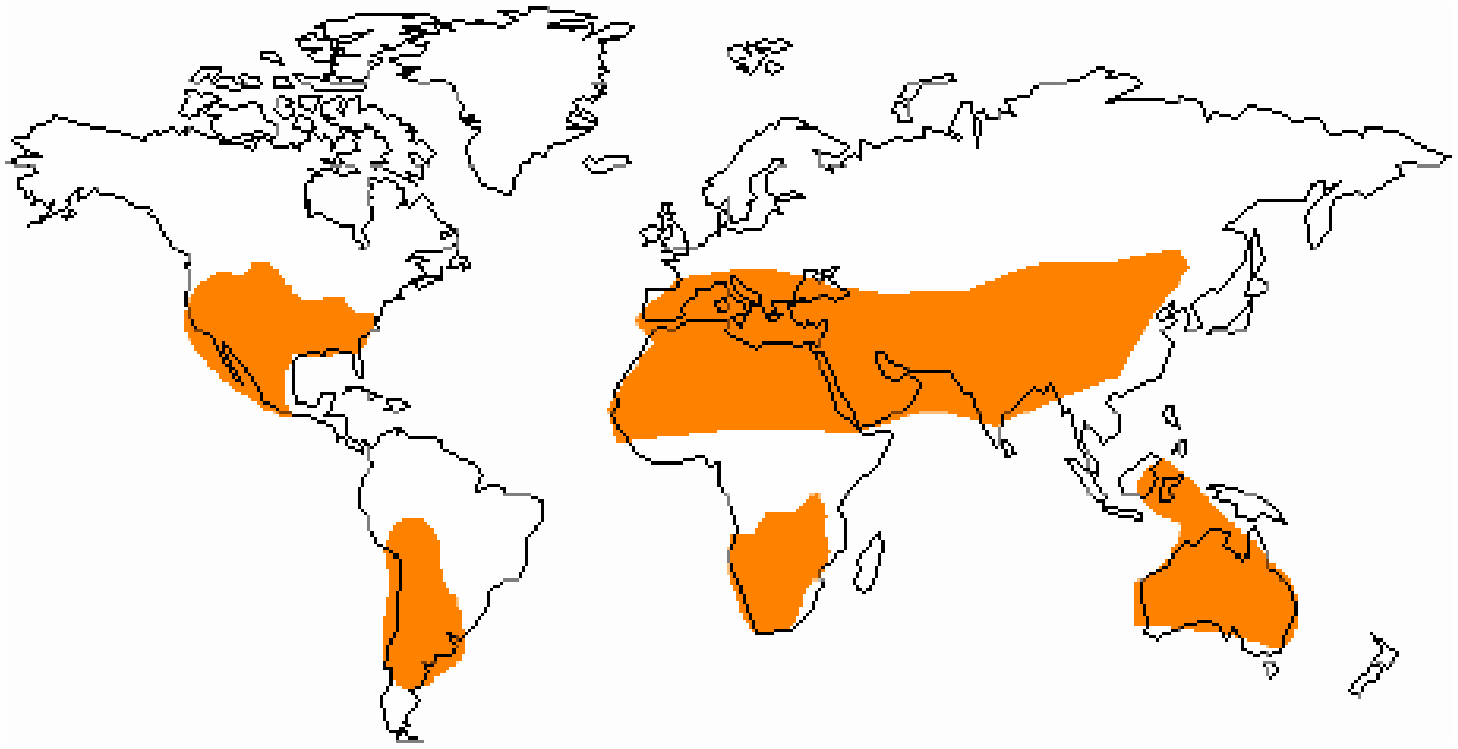
Dish - Stirling

Solar tower

Solar resource

Usable resource : from 1700 to 2900 kWh/m²/yr

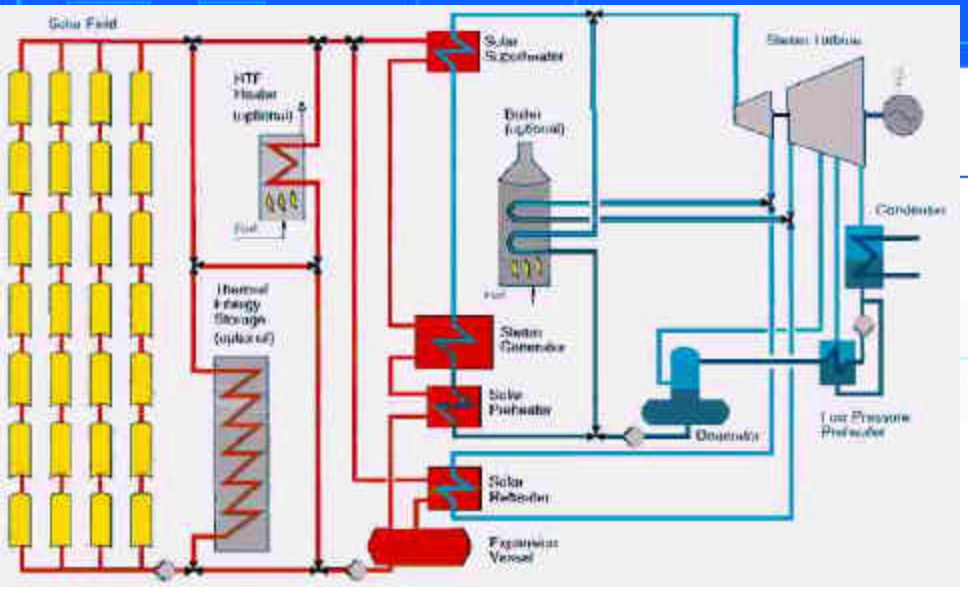
The solar belt



Parabolic Troughs

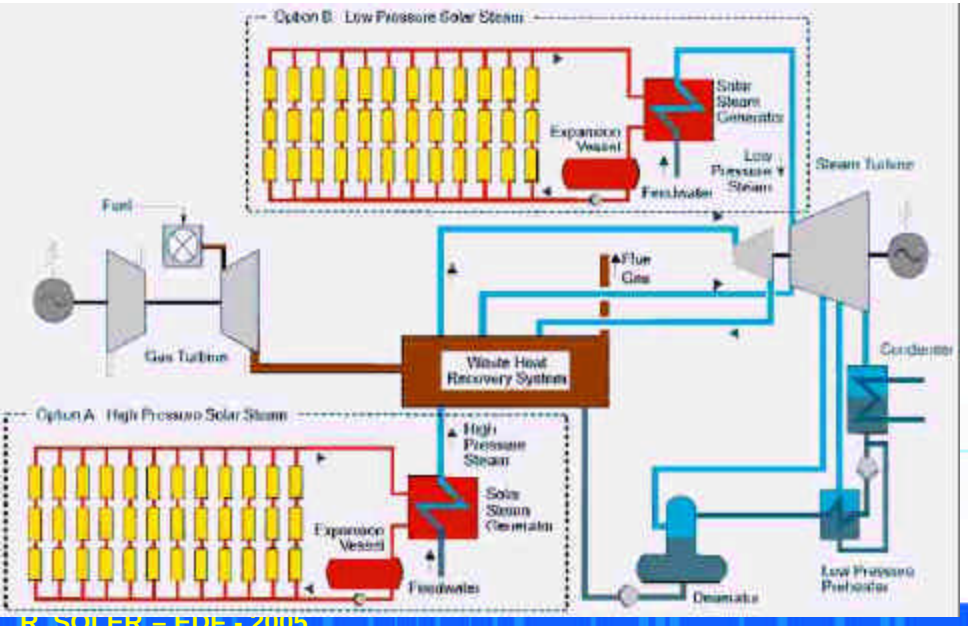
Concentrators

Concentration ratio : 80/1. The temperature of the HTF is about 400°C



SEGS

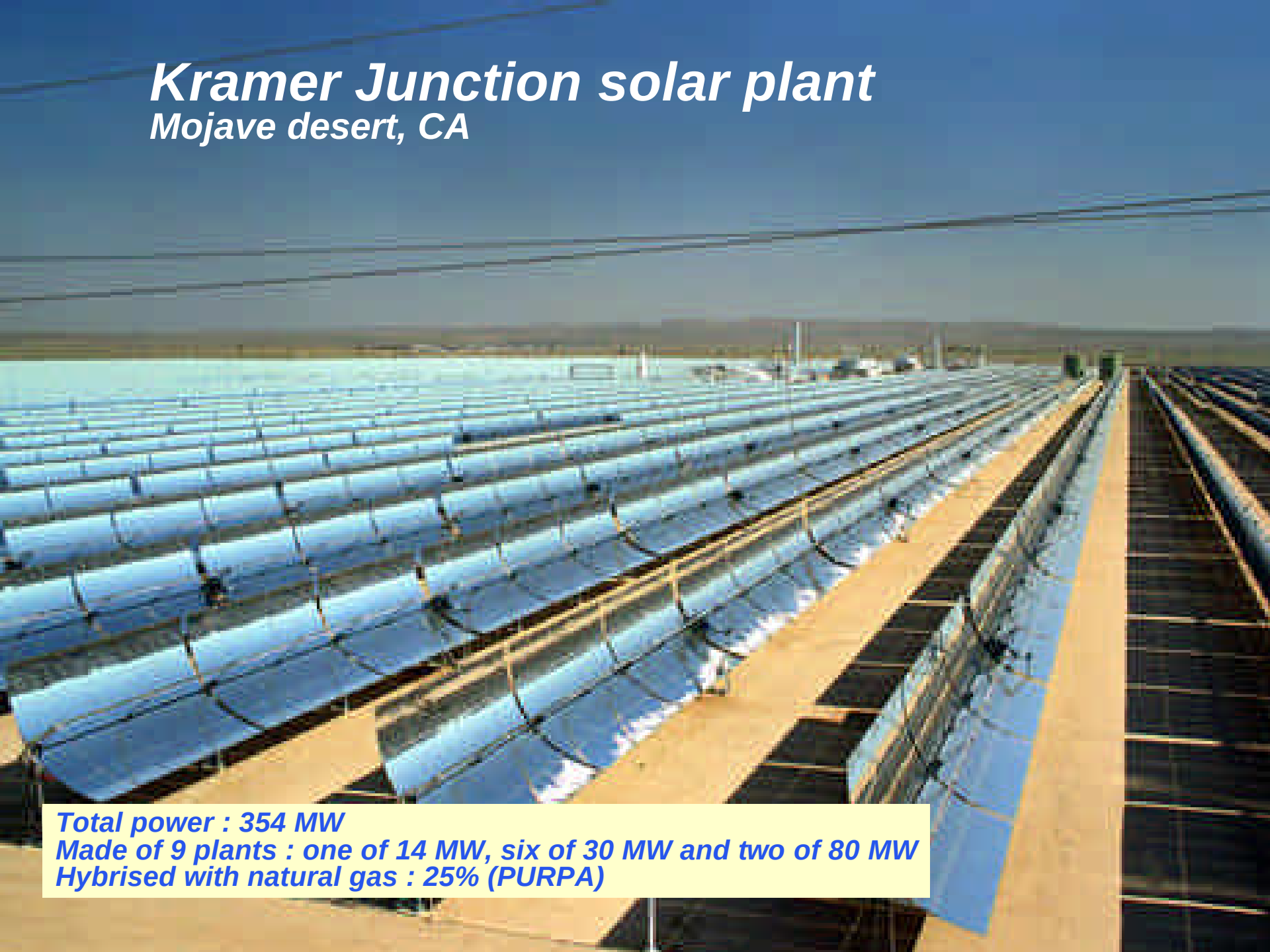
The solar field aims at producing water vapor for a Rankine cycle turbine coupled to an alternator



ISCCS

The solar energy is used to provide additional thermal energy to the exhaust fumes of the gas turbine
It enables to produce more water vapor

Kramer Junction solar plant
Mojave desert, CA



Total power : 354 MW
Made of 9 plants : one of 14 MW, six of 30 MW and two of 80 MW
Hybrised with natural gas : 25% (PURPA)

Kramer Junction from the sky

3 plants in construction

- **Spain, Prov. de Granada : ANDASOL 1 et 2 (2 x 50 MWe)**
  - *Promoter Solar Millenium (D)*
  - *2 x 50 MWe, 2 x 150 GWhe/an*
  - *Cumulated solar field : 1,1 Mm², Molten salt storage : 6 hours*
  - *Subsidies (DGTren : 5 M€ German Ministry)*
  - *Profitability of the project based on the feed-in-tarriff*
  - *2 additional plants planned 1 yr ½ after the beginning of operation of Andasol2*

- **USA, Nevada : Boulder City (50 MWe)**
  - *Promoter : Solargenix*
  - *Power purchase agreements signed with 2 utilities*

- **USA, Arizona : 1 MWe**
  - *Promoter : APS*
  - *Designer : Solargenix*

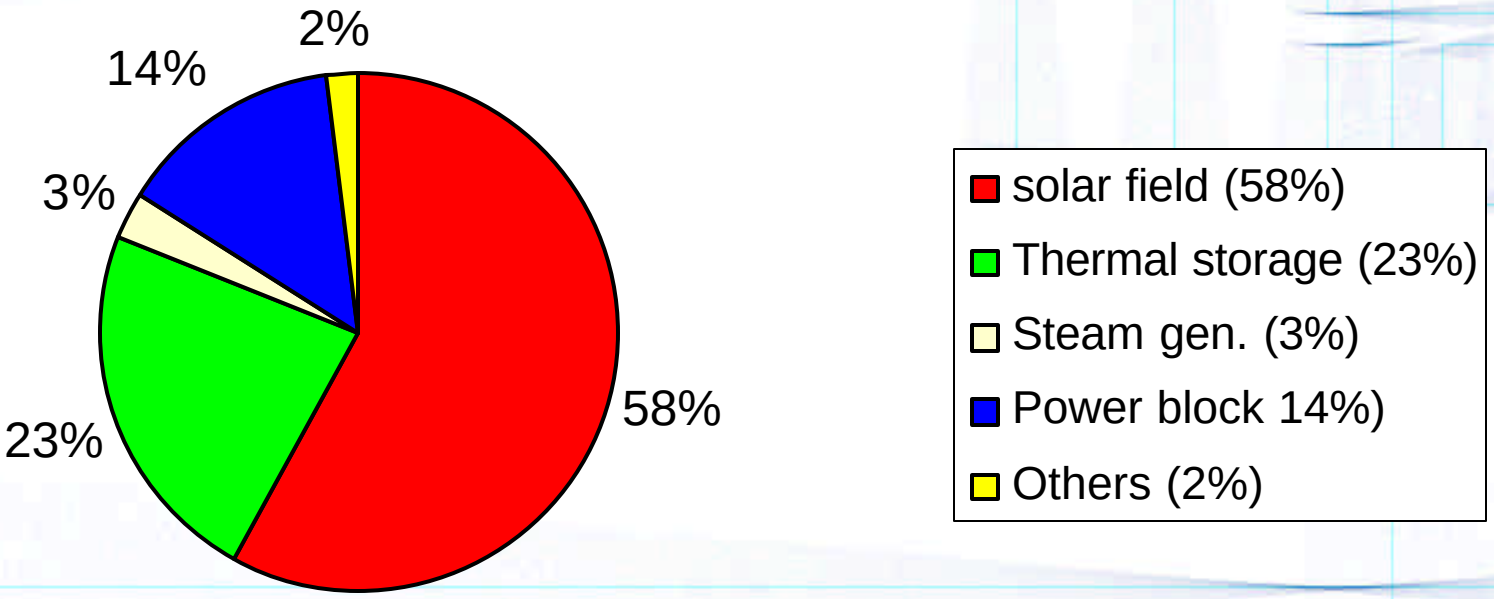
Parabolic trough plants : costs and performances

Performances et coûts	SEGS VI (Hybride) 1989 30 MWe	Présent 2005 – 2006 100 MWe	Court terme 2010 150 MWe	Moyen terme 2020 400 MWe
Cycle	Rankine	Rankine	Rankine	Rankine
Rendement annuel net	10,6%	14%	15,4%	15,5%
Stockage	0	12 hrs	12 hrs	12 hrs
Disponibilité	22/34% **	54%	56%	57%
Coût d'investissement		4,80 €/W	3,55 €/W	3,20 €/W
Coût de production Californie (2700 kWh/m²/an) France (1850 kWh/m²/an)	 120 €/MWh 175 €/MWh	 104 €/MWh 150 €/MWh	 72 €/MWh 105 €/MWh	 63 €/MWh 90 €/MWh
O&M		28 €/MWh	18 €/MWh	14 €/MWh

** mode solaire / mode hybride

The solar field is the highest part of the investment cost

Breakdown of the cost of a PT plant 100 MWe - 12hrs storage



Objective for the future : lower the cost of generation by 20 to 30%

- **Increase of the size of plants**
  - *from 80 MWe (SEGS VIII et IX) up to 400 MWe*
- **Increase capacity factor and dispatchability**
  - *By adding a reliable thermal storage*
  - *By increasing the size of the solar field in order to fill the storage*
- **Focus research on**
  - *The use of other HTF*
    - Water steam : Direct Steam Generation
    - Molten salts ?
  - *Development of a reliable thermal storage*
  - *Reduction of O&M costs*
  - *Reduction of the costs of components (collectors, absorbers)*

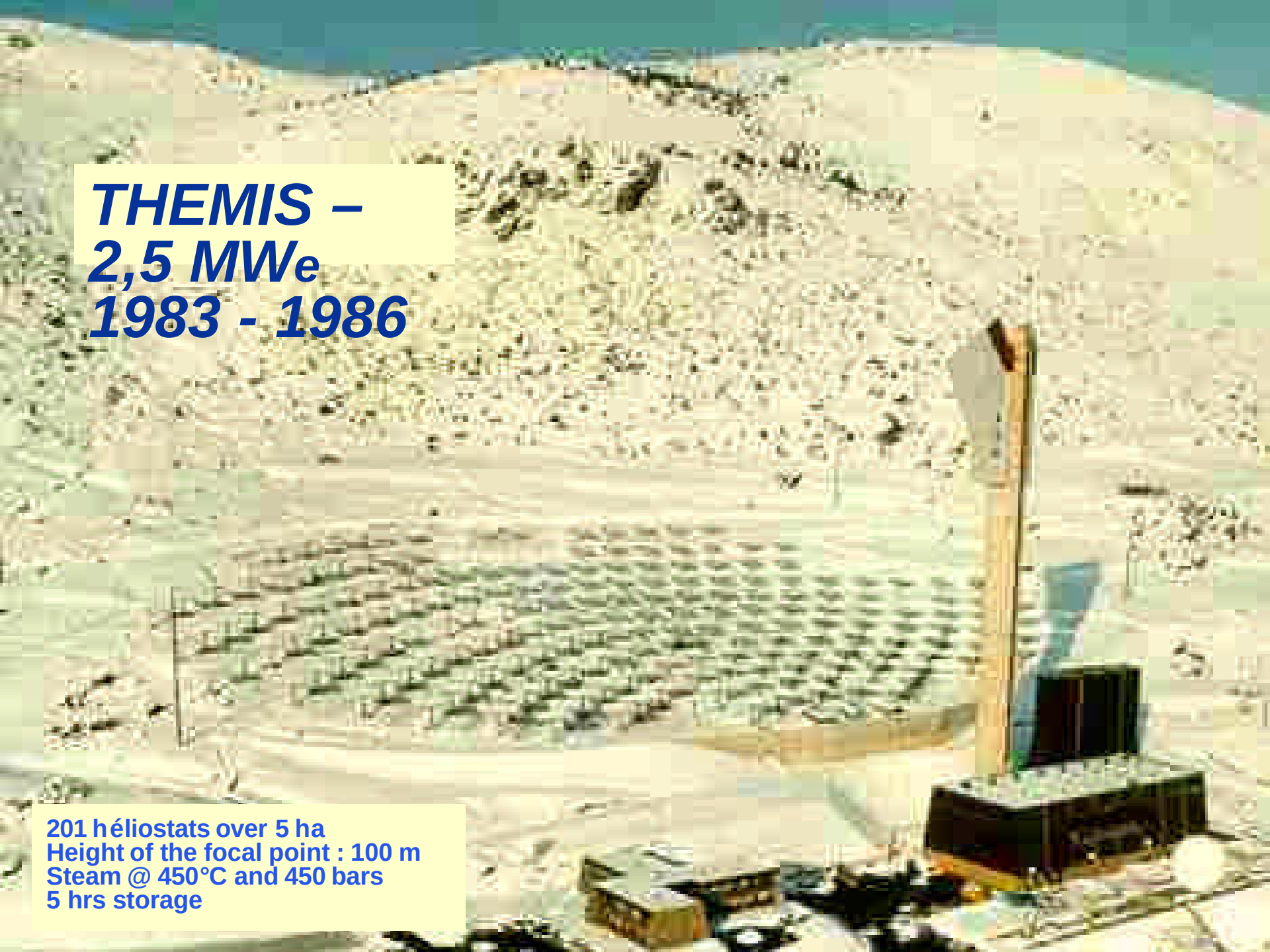
Central Receiver plants

Solar towers

- Concentration ratio : 300/1 to 800/1

Expériences pilotes

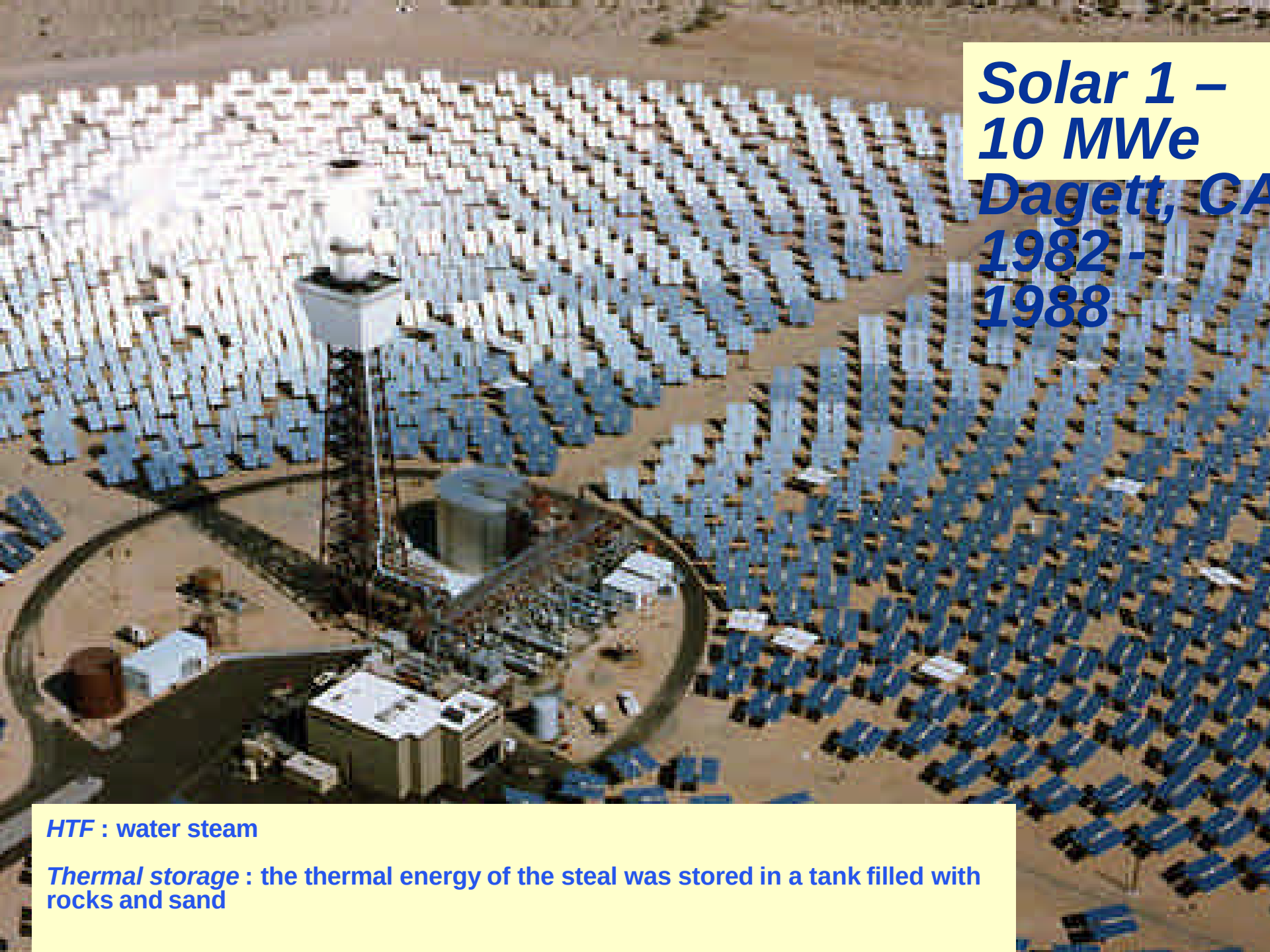
Project	Country	Power (MWe)	HTF	Storage medium	Start of operation
SSPS	Spain	0,5	Liquid Sodium	Sodium	1981
EURELIOS	Italy	1	Steam	Nitrate salt / Water	1981
SUNSHINE	Japan	1	Steam	Nitrate salt / Water	1981
Solar One	USA	10	Steam	Oil / Rocks	1982
CESA-1	Spain	1	Steam	Nitrate salt	1983
MSEE/Cat B	USA	1	Nitrate	Nitrate salt	1984
THEMIS	France	2,5	Molten salts	Hi-Tec	1984
SPP-5	Russia	5	Steam	Water / Steam	1986
TSA	Spain	1	Air	Céramic	1993
Solar Two	USA	10	Molten salts	Nitrate salt	1996


THEMIS –
2,5 MWe
1983 - 1986
201 héliostats over 5 ha
Height of the focal point : 100 m
Steam @ 450°C and 450 bars
5 hrs storage

SPP5

5 MWe, 1986
Crimea

- HTF : water-vapor



Solar 1 – 10 MWe Dagett, CA 1982 - 1988

HTF **: water steam**

Thermal storage **: the thermal energy of the steal was stored in a tank filled with rocks and sand**

Solar 2 – 10 MWe
Dagett, CA
1996 - 1999

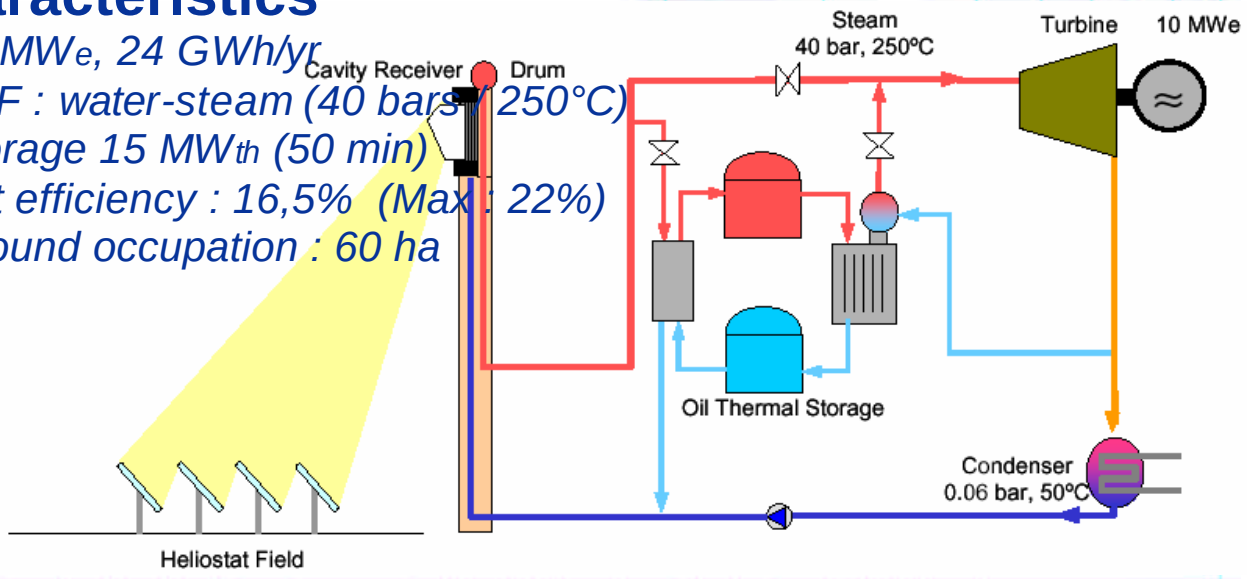
Refurbishment of Solar 1

HTF **: molten salts**
Thermal storage **: 3 hrs with 2 tanks (cold and hot)**

A plant under construction : PS10

- **Promoter : Abengoa Group**
- **Subsidies**
  - *UE : 5 M€*
  - *Gouvernment of Andalousia : 2 M€*

- **Technical characteristics**
  - *11 MWe, 24 GWh/yr*
  - *HTF : water-steam (40 bars / 250°C)*
  - *Storage 15 MWth (50 min)*
  - *Net efficiency : 16,5% (Max : 22%)*
  - *Ground occupation : 60 ha*

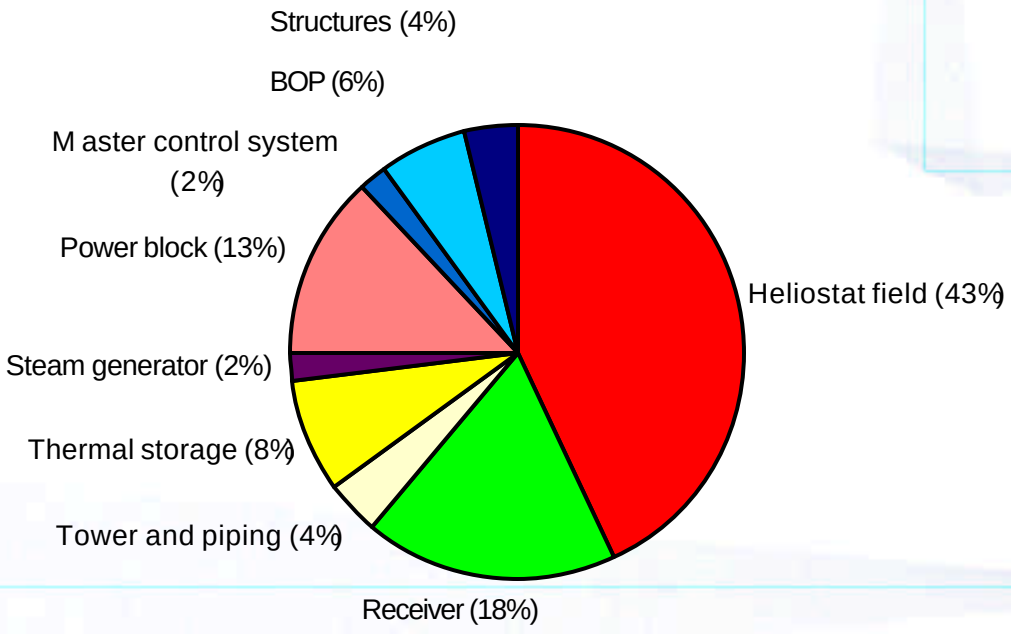


CRS plants : costs and performances

Performances et coûts	Solar Two 1996 10 MWe	Présent 2005 – 2006 15 MWe	Court terme 2010 100 MWe	Moyen terme 2020 200 MWe
Cycle	Rankine	Rankine	Rankine	Rankine
Rendement annuel net	7,9%	13%	16%	16,5%
Stockage	3 hrs	16 hrs	13 hrs	17 hrs
Disponibilité	21%	75%	73%	73%
Coût d'investissement		5,50 €/W	4,60 €/W	3,60 €/W
Coût de production Californie (2700 kWh/m²/an) France (1850 kWh/m²/an)		 143 €/MWh 208 €/MWh	 68 €/MWh 100 €/MWh	 55 €/MWh 80 €/MWh
O&M	194 €/MWh	29 €/MWh	15 €/MWh	13 €/MWh

The heliostat field is the highest component of the investment cost

Breakdown of the cost of a solar tower 15 MWe



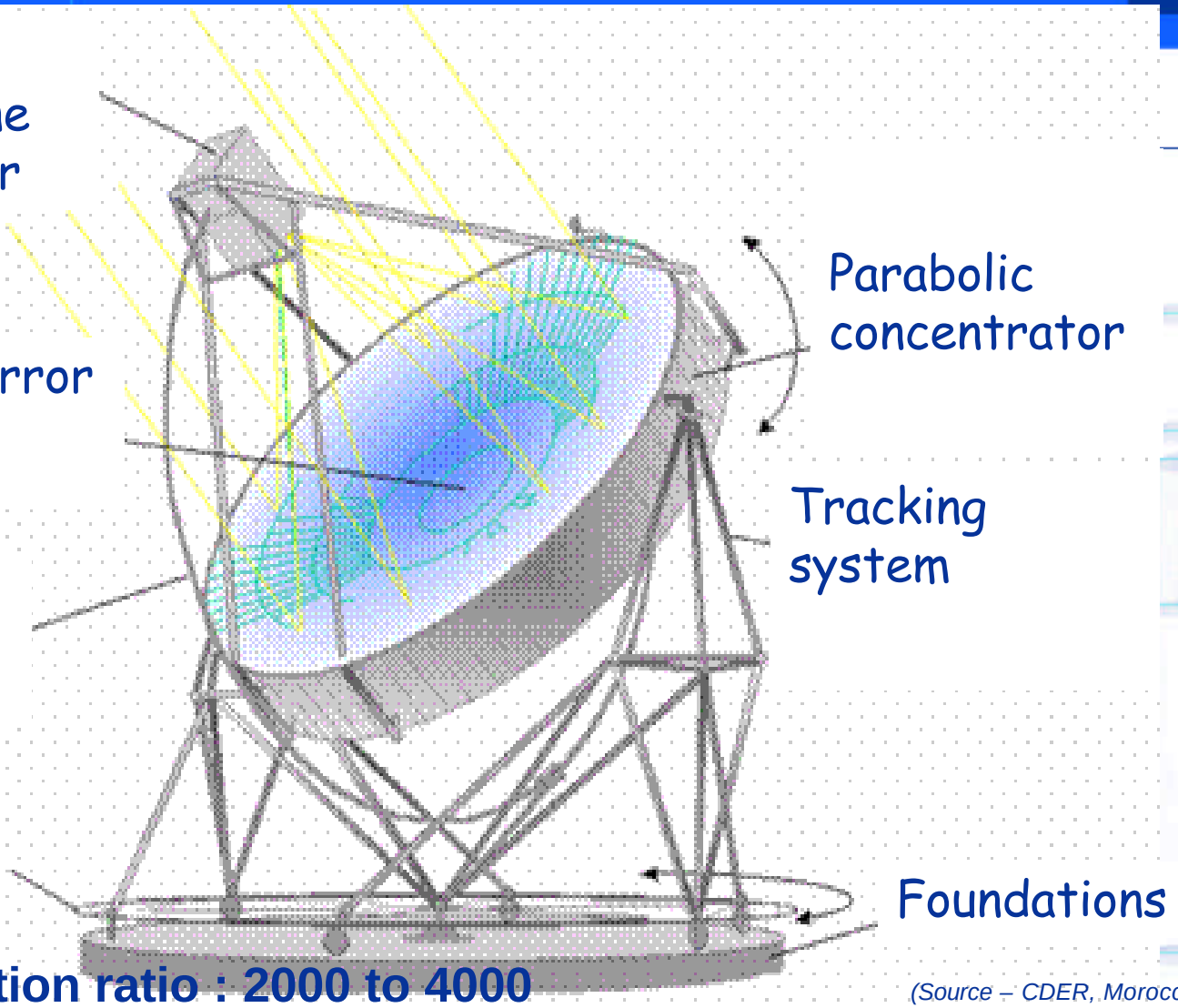
Objective for the future : facilitate commercialisation

- **Solar towers : less mature than PT plants**

- **Increase of the size of plants and of availability**
  - *from 10 MWe (Solar2, PS10) up to 150-200 MWe*
  - *Increase capacity factor up to 75%*

- **Focus research on :**
  - *Reduction of the cost of components*
    - Increase of the heliostat size
    - Autonomy of héliostats
  - *Simplification of O&M procedures*
  - *Development of innovative receivers (air)*
  - *Multi-towers concept*

Dish-Stirling systems



- **Concentration ratio : 2000 to 4000**
  - *A HTF (hydrogen or helium) transfers its energy to a small Stirling engine*

(Source – CDER, Morocco)

SES 25 kWe System

Design McDonnell Douglas

Concentrator
87,7 m² (diam. 10,5 m), made of 82 mirror facets 1m x 0,80m and thickness 0,7 mm.
Réflectivity > 91%

Moteur **United Stirling 4-95 Mark II using hydrogen working at 720°C.**
therm. Eff. : 42%

Generator **480 V 3-ph, 50/60 Hz**

dish-stirling System
- Height : 15 m
- 25 kWe for 1000W/m²
- Availabie when > 200 W/m²
- Peak eff. 29%
-average eff. : 24%
Annual production in Las Vegas : 54,5 MWh/an

EuroDish System

10 kWe

- ✓ **Concentrator**
  Diameter 8,5 m, made of 12 segments of reinforced glass fiber connected to a shell whose surface is covered of thin mirrors
- ✓ **Engine** Stirling SOLO 161.
  Te gas used is helium heated up to 650°C under 15 MPa
- ✓ **Dish-stirling system**
  Peak eff. : 21%
- ✓ **Annual production at PSA** :
  18 à 20 MWh/an

Costs and performances

Performances et coûts	2005 10-25 kWe	2010 1 MWe	2020 > 1 MWe
Stockage	non		
Rendement net	12-25%		
Disponibilité solaire	25%		
Coût d'investissement	10-14 €/We	7 €/We	1,5 €/We
Coût de production zone aride (2700 kWh/m²/an) France (1850 kWh/m²/an)	 200-250 €/MWh 290-365 €/MWh	 150 €/MWh 215 €/MWh	 ?
O&M	?	?	?

Perspectives

- **Compared to the two other technologies :**
  - *Higher efficiency (30 %)*
  - *Higher modularity (Distributed or decentralised applications are possible)*
  - *More autonomous operation*
  - *Hybridation with fossil fuels is possible*

- **But a technology still at the stage of R&D …**
  - *2 axes tracking : complexity in terms of O&M in isolated sites*
  - *Systems must be protected in case of high winds (v>16 m/s)*
  - *No Stirling industry at the moment, and reliability problems*

- **Research**
  - *Tests of systems under operation*
  - *Multi-mégawatt plants*

Market development

Three main drivers

- **Feed-in tarriff in Spain**
  - *216 €/MWh for 25 yrs (pool between 20 and 80€/MWh)*
  - *Limitation : 150 MW*
  - *Installation of 200 MW is planned within 2010*
- **USA : RPS and political will**
  - *RPS Arizona : 1,1% RE with 60% solar*
  - *Western states Governors : 1000 MW*
- **Interest of development banks**
  - *200 M$ granted by World Bank to projects in Egypt, India, Morocco and Mexico (ISCCS)*

	Projet	Puissance nette (MWe)	Part solaire (MWe)	Cycle	Technologie	Etat du projet	Mise en service	Promoteurs	financement
Brésil	?	?	?	?	NC	4	?	?	GEF
Inde	Mathania	140	35	ISCCS	Cylindro-parab.	2	2006	RSPC	GEF, KfW, Inde
Algérie	?	140	35	ISCCS	NC	3	2006	NEAL	
Maroc	Ain Beni Mathar	230	30-50	ISCCS	Tour ou Cylindro-parab.	3	2006	ONE	GEF (50 M$)
Egypte	Kuraymat : « HSTF » (Hybrid Solar Thermal Fossil)	120-140	30	ISCCS	Tour ou Cylindro-parab.	3	2007	NREA + secteur privé	GEF (50 M$)
Jordanie	?	100-150		?	?	4	?		GEF
Israël	?	100	100	SEGS	Cylindro-parab.	3	2005	Ministère SOLEL	Gouvernement
Italie	?	40	40	Vapeur	?	4		ENEA	
Espagne	Province de Grenade : « Andasol-1 et 2 »	2 x 50	2 x 50	SEGS 6h de stockage	Cylindro-parab.	2	2006	Solar Millenium	Tarif espagnol Subv. FP5 (UE)
	Province de Navarre : « EuroSEGS »	15	15	SEGS	Cylindro-parab.	2		EHN Solargenix	Tarif espagnol
	Sanlucar (Seville) : « PS10 »	10	10	Récepteur à vapeur 50min stockage	Tour	1	2006	Inabensa	
	Province de Cordoba : « Solar Tres »	15	15	Sel fondu, 16 h de stockage	Tour	4	?	Ghersa, Boeing, Nexant	
Iran	Désert de Yazd	370	70	ISCCS	Cylindro-parab.	4	?		GEF
Mexique	Baja California Norte	300	30	ISCCS		3			GEF
USA	Boulder, Nevada	50	50	SEGS	Cylindro-parab.	2		Solargenix	
	Arizona	1	1	SEGS	Cylindro-parab.	1	2006	APS, Solargenix	
	Etats de l'ouest		1000	?	?	4	?		
Australie	New South Wales	1440	35	Compact linear Fresnel	NC			Austa Energy & Stanwell Corp	Gouv. Australien
Grêce	Crête : « Theseus »	52	52	SEGS	Cylindro-parab.	4	?		
Afrique du sud	?	100	100	Sel fondu 8h de stockage.	Tour	3	?	Eskom	

Etat du projet : 1 = en construction ; 2 = projet en développement ; 3 = étude de faisabilité en cours ; 4 = intention

Environmental issues

Little impact on environment

- **Land occupation**
  - *2-4 ha/MW without thermal storage*
  - *3 to 10 fois more in case of storage (i.e. 6 à 40 ha/MW)*
- **Water needs**
  - *2 to 4 m^3 of water per MWh generated*
  - *dish-stirling systems don't need water*
- **No GHG emitted by the solar part of the plant**
  - *Possibility of green certificate in solar mode*
- **ACV**
  - *20 kg eqCO_2/MWh*
  - *Energetic payback time : 6 months*