# Solar Energy Prospects

Piero Salinari

# 2004 world power consumption: by source

US Energy Information Administration 2006:

**Fossil fuels represented ~ 87% of the total world power (15 TW) in 2004:**

| Source | Power<br>W | % of total | Energy/year<br>J/year |
|---|---|---|---|
| Oil | 5.60E+12 | 37.3% | 1.80E+20 |
| Natural gas | 3.50E+12 | 23.3% | 1.10E+20 |
| Coal | 3.80E+12 | 25.3% | 1.20E+20 |
| Hydroelectric | 9.00E+11 | 6.0% | 3.00E+19 |
| Nuclear | 9.00E+11 | 6.0% | 3.00E+19 |
| Geothermal, Eolic, Solar, Wood | 1.30E+11 | 0.9% | 4.00E+00 |
| Total | 1.50E+13 | 100.0% | 4.71E+20 |
| | | | |
| World Population 2004 | 6.40E+09 | | 6.80E+09 |
| Power pro capite | 2,344 | | 7.36E+10 |

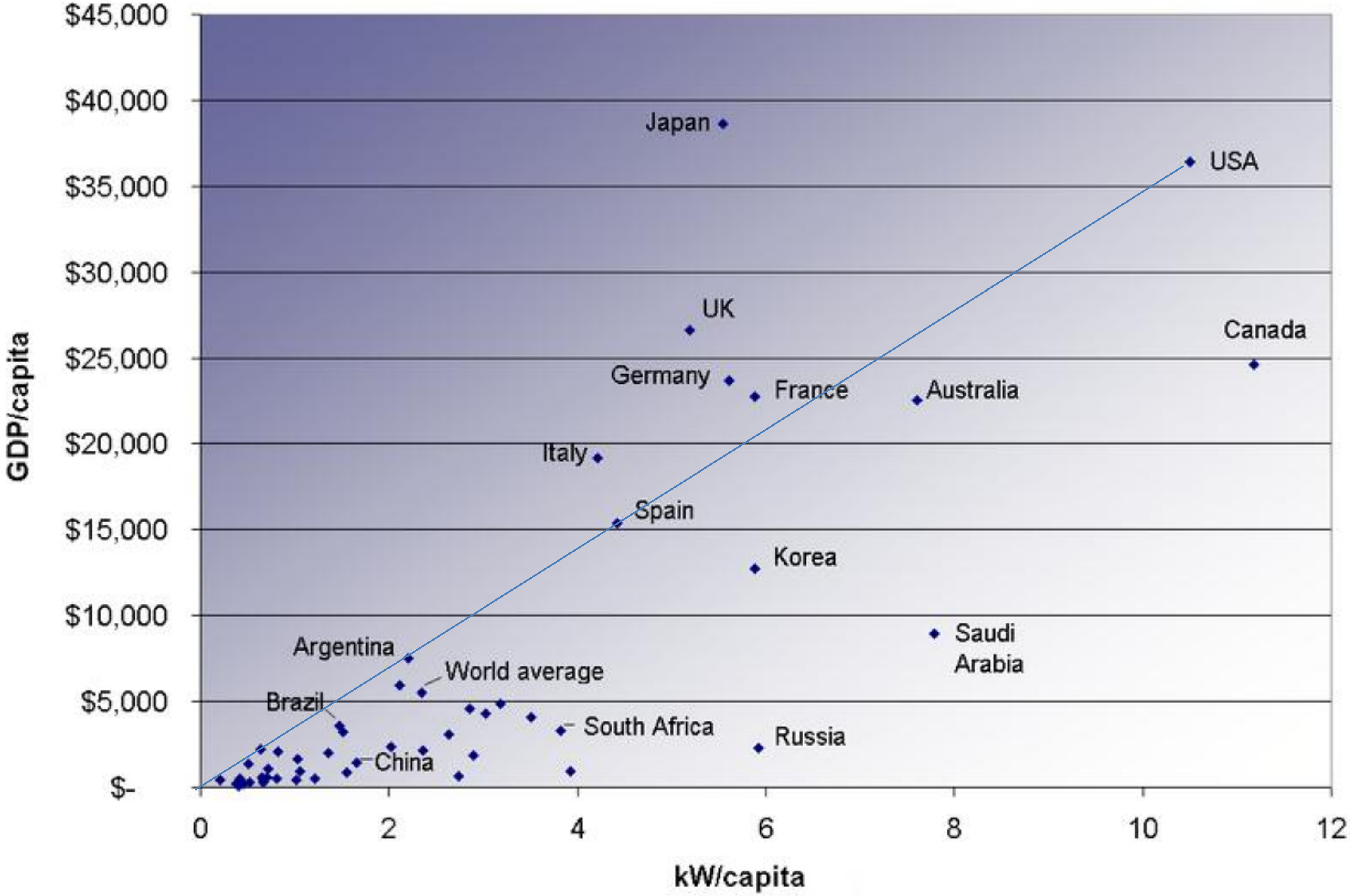
# 2004 world power consumption: by sector

| Use | Fraction of total | In units of human power (100 W) |
|---|---|---|
| Agricolture, mining, manifatture, building | 37% | 8.6 |
| Private and public transportation | 20% | 4.7 |
| Domestic heating, lighting, appliances | 11% | 2.6 |
| Idem for commercial building + water supply | 5% | 1.2 |
| Generation and transportation loss | 27% | 6.3 |
| Total | 100% | 23.4 |

# Individual and social use of power

| Use | Fraction of total | In units of human power (100 W) |
|---|---|---|
| Direct human consumption (food) | | 1 |
| Food and water chain | 12% | 3 |
| Domestic heating, lighting, appliances | 11% | 2.6 |
| Vital individual use | 23% | 5.6 |
| | | |
| Industry | 27% | 6.3 |
| Private and public transportation | 18% | 4.2 |
| Other collective uses | 4% | 0.9 |
| Generation and transportation loss | 27% | 6.3 |
| «Social» use | 76% | 17.7 |

# Energy use and income



# Electric energy use (W per capita)

| World average | 297 W |
|---|---|

| Rich Countries | Average power per capita W | | Poor Countries | Average power per capita W |
|---|---|---|---|---|
| Iceland | 3152 | | Eritrea | 5,91 |
| Norway | 2812 | | Sierra Leone | 4,71 |
| Finland | 1918 | | Haiti | 4,31 |
| Canada | 1910 | | Burkina Faso | 4,14 |
| Qatar | 1757 | | Guinea-Bissau | 4,01 |
| Sweden | 1692 | | Ethiopia | 3,8 |
| Luxembourg | 1549 | | Niger | 3,58 |
| Kuwait | 1540 | | Tanzania | 3,57 |
| United States | 1460 | | Somalia | 3,48 |
| United Arab Emirates | 1335 | | Afghanistan | 3,06 |
| Australia | 1244 | | Central African Republic | 2,86 |
| Bahrain | 1195 | | Cambodia | 1,67 |
| Taiwan (Republic of China) | 1101 | | Chad | 1,03 |
| New Zealand | 1059 | | Gaza Strip | 0,02 |

# Energy use and quality of life

**In average only about 13% of the USED power is Electric Power**
**but**
**taking into account an average Thermal-to-Electric conversion efficiency of ~ 40%**
**The production of Electric Power uses about 1/3 of the total power.**

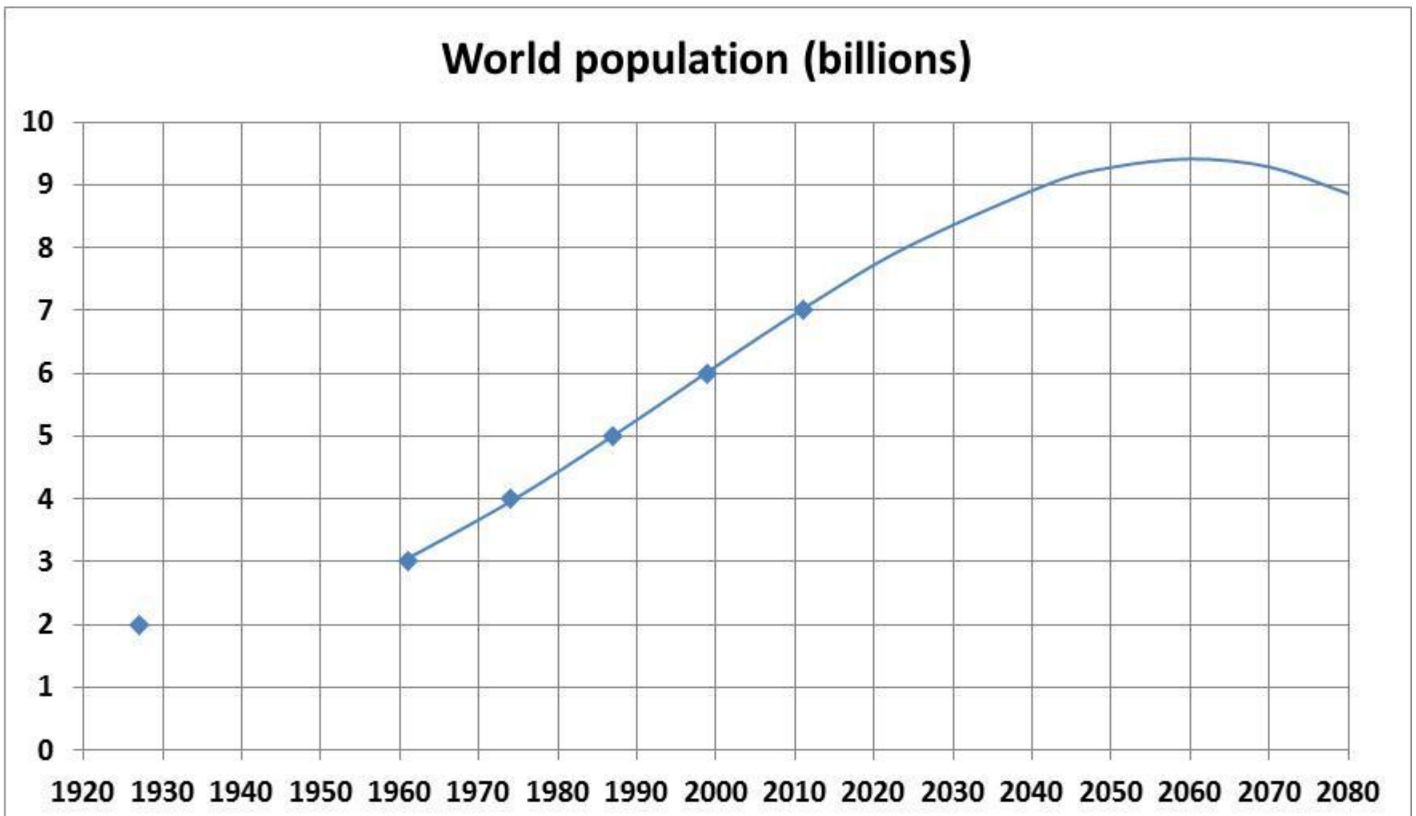
**Electric Power use is**
**STRONGLY correlated with quality of life**
**(and in many applications represents an OVERALL saving of power)**
**BUT**
**is not (yet) suitable for some applications**
**(e.g. air and sea transportation)**

**Transferring MOST of the power uses to Electricity**
**is a must for renewable energies**
**due to their variable spatial and temporal distribution**

**But this is also DESIRABLE!**

# How much power will be needed in future?

**We will need much more power than we currently use**
**to allow for development of underdeveloped areas**
**and to cope with the forseen**
**increase of the world population**
**from ~ $6,5 \times 10^9$ (2005)**
**to ~ $9,5 \times 10^9$ (2060)**

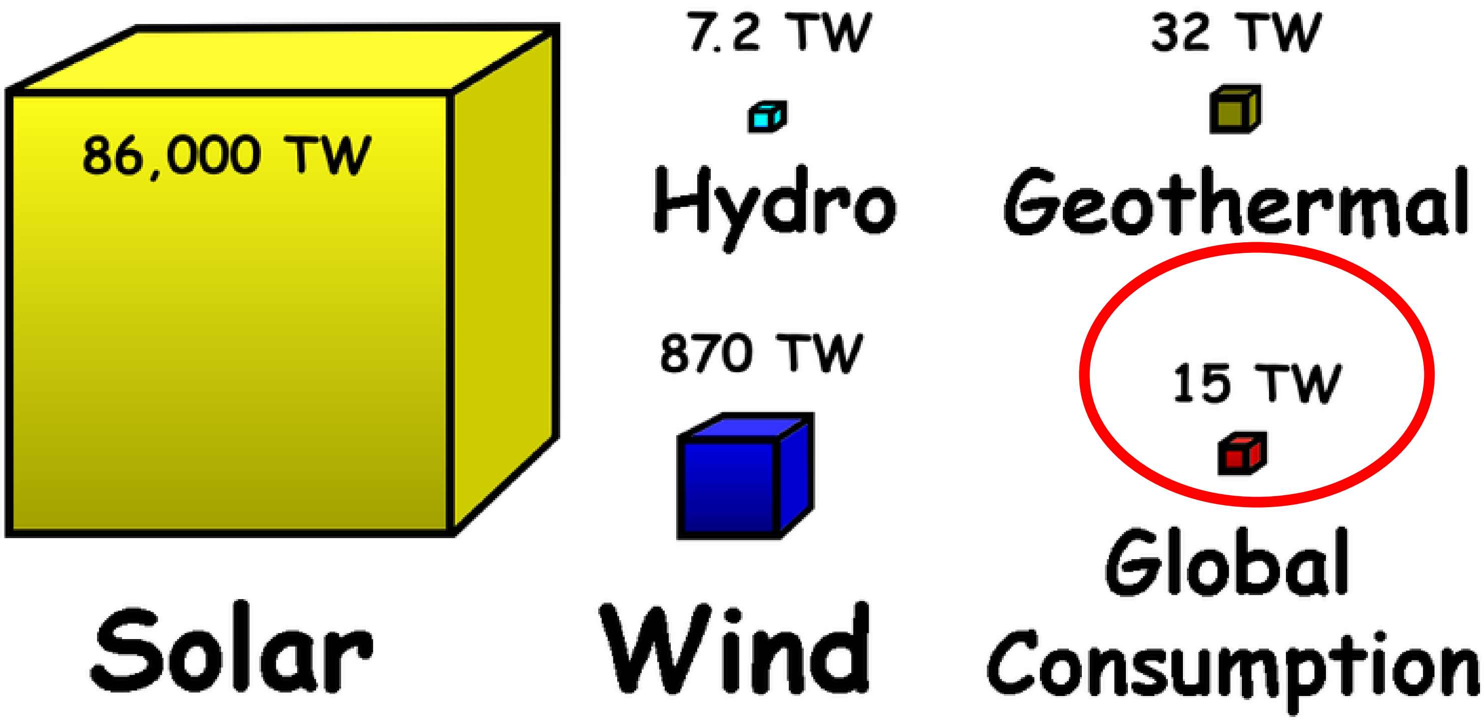


# Potential of different renewable energy sources

**Suppose we will need 50 TW of Electric Power**
**We should use the following fractions of:**

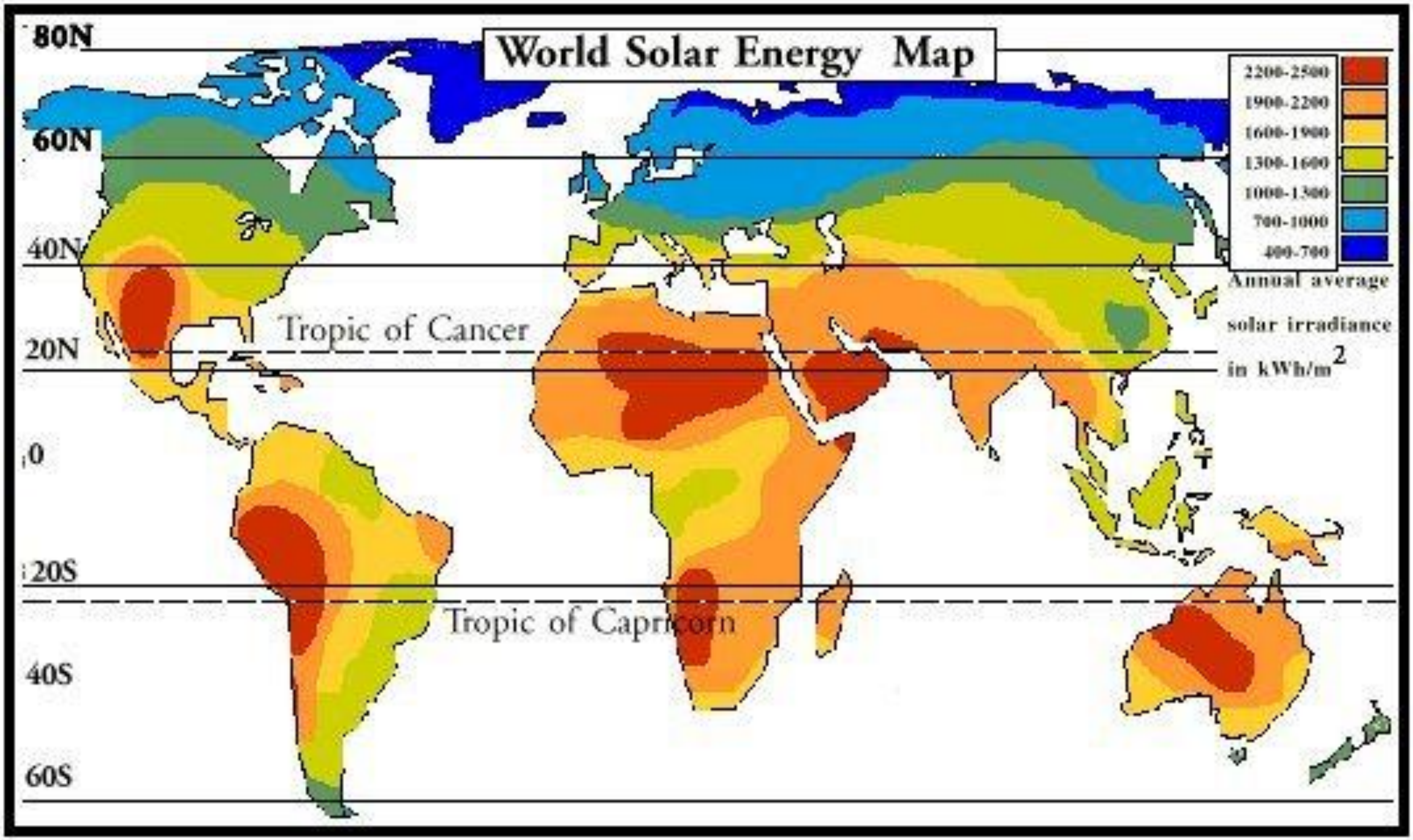
**0.06%** of available SOLAR Energy
**6 %** of available WIND Energy
**156%** of available Geothermal Energy

**This is why Solar Energy is crucial!**

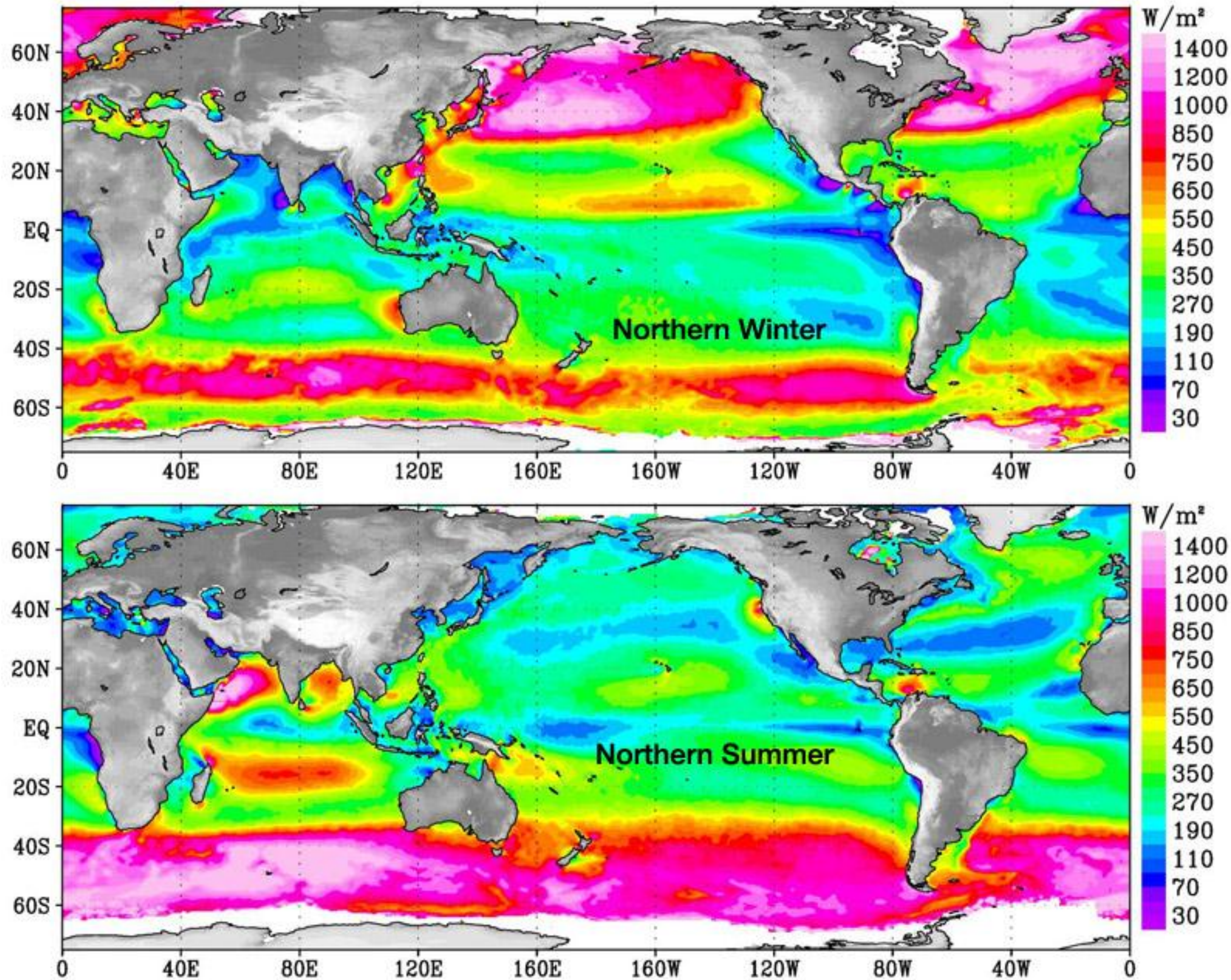


# Distribution of Sun power

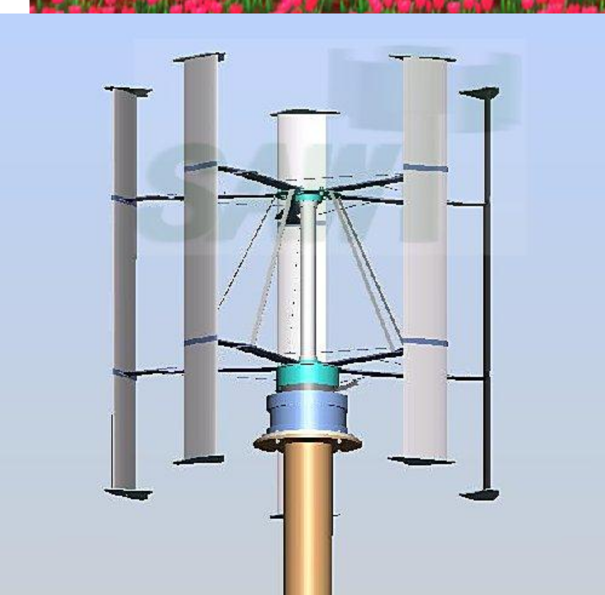
**This is "Global" irradiance over an horizontal surface and takes sky cover into account**



# Distribution of Wind Power



# Wind (where/when available)): a mature technology



**Already competitive**
**High transformation efficiency**
**(~ 50% of ½$\rho V^3$ )**

**BUT:**

- **Highly variable in time**
- **Only available in restricted areas**

# Where are the problems for exploiting solar energy?

**Not in availability**

**not in power density (see graph)**

**not in geographical distribution (available in all continents)**

**not in time variability (storage + extended electric grid)**

**THE MAIN PROBLEM IS ECONOMIC: «LEVELIZED ENERGY COST»**

# Levelized (electric) Energy Costs (LEC) 2009

| Plant Type | Capacity Factor (%) | Levelized Capital Cost | Fixed O&M | Variable O&M (incl. fuel) | Transm. Investm. | Total Levelized Cost $/MWh |
|---|---|---|---|---|---|---|
| Adv. Combined Cycle | **87** | **22.4** | **1.5** | **52.3** | **3.7** | **79.9** |
| Convent. Combined Cycle | 87 | 23 | 1.6 | 55.7 | 3.7 | 83.9 |
| Conventional Coal | 85 | 64.5 | 3.7 | 23 | 3.5 | 94.6 |
| Advanced Coal | 85 | 75.6 | 5.2 | 19.3 | 3.5 | 103.5 |
| Advanced Nuclear | 90 | 84.2 | 11.4 | 8.7 | 3 | 107.3 |
| Biomass | 83 | 71.7 | 8.9 | 23 | 3.9 | 107.4 |
| Geothermal | 90 | 86 | 20.7 | 0 | 4.8 | 111.5 |
| Hydro | 52 | 97.2 | 3.3 | 6.1 | 5.6 | 114.1 |
| Adv. CC with CCS | 87 | 43.6 | 2.6 | 65.8 | 3.7 | 115.7 |
| Adv. Coal with CCS | 85 | 87.4 | 6.2 | 25.2 | 3.8 | 122.6 |
| Adv. Combustion Turbine | 30 | 38.5 | 4 | 71.2 | 10.7 | 124.3 |
| Conv. Combustion Turbine | 30 | 41.3 | 4.6 | 83.6 | 10.7 | 140.2 |
| Wind | 35.1 | 122.7 | 10.3 | 0 | 8.5 | 141.5 |
| **Wind-Offshore** | 33.4 | 193.6 | 27.5 | 0 | 8.6 | **229.6** |
| **Solar Thermal** | **31.2** | **232.1** | **21.3** | **0** | **10.3** | **263.7** |
| **Solar PV** | **21.7** | **376.6** | **6.2** | **0** | **12.9** | **395.7** |

Source: Energy Information Administration, Annual Energy Outlook 2009 (revised), **April 2009**, SR-OIAF/2009-03, http://www.eia.doe.gov/oiaf/servicerpt/stimulus/index.html

**Hydro, Biomass, Geothermal and Wind power**
**(the last at a LEC of ~140 $/MWh),**
**Are already exploited wherever available . . .**
**then**
**Solar Power needs to reach a similar LEC ratio to CC than Wind:**

**LEC(Wind)/LEC(Advanced Combined Cycle) =1,75**

**to become**
**economically attractive**
**i.e.**
**Solar Thermal should reduce its LEC by a factor of 2**
**Photovoltaics should reduce its LEC by a factor of 3**

**(or fuel cost must go up by a larger factor . . .)**

# (Silicon) Photovoltaics: Simple, can go everywhere

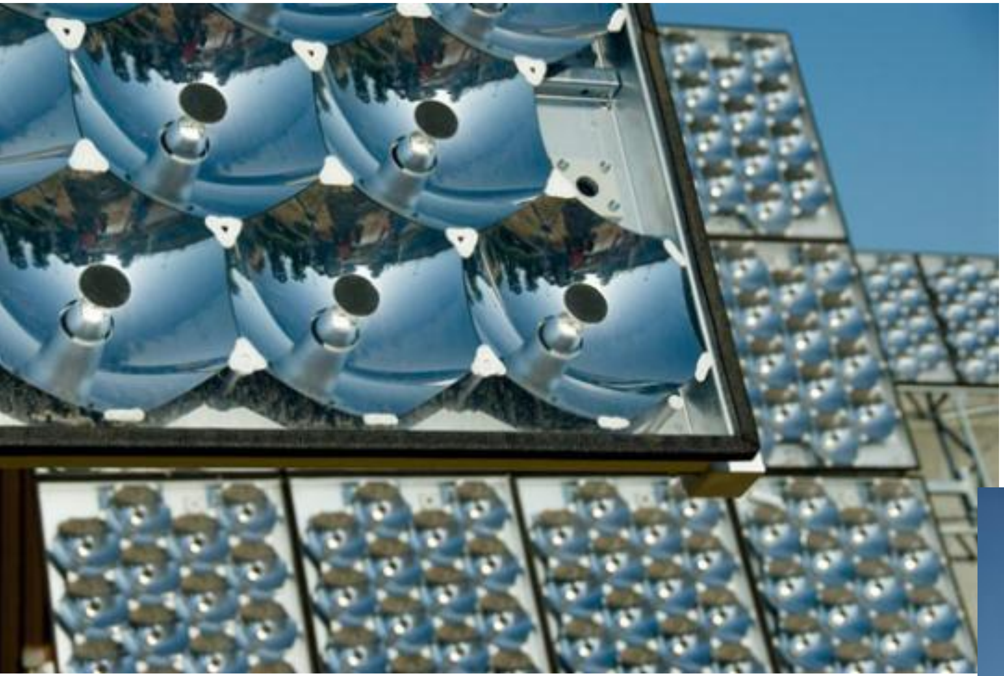
Exploits direct AND diffused sunlight
But over a reduced wavelength range
And with poor overall efficiency (15%)

Well suited to niche applications

Most of the cost is in the production of high quality Silicon.

There are attempts to use much lower cost materials (even at a lower efficiency) To reduce LEC

# Concentrated Photovoltaics (CPV): new and more efficient!



- Solar-to- electric efficiency can be > 30%
- Cell cost greatly reduced by concentration

But

- requires cooling and tracking
- Requires rare materials (Ga, In, Ge . .)

The certified availability
of the necessary rare elements
Is currently sufficient only
for, at most, a few TW

## Where is the problem with CSP?

The current Combined Cycle Plants
(Gas Turbine followed by a Steam Turbine)
have a
Net Thermal-to-Electric Efficiency
> 55%

while
most CSP cycles
have a
"Net Solar-to-Electric Efficiency"
~ 15%
(the exception is the "Solar Dish",
where Solar-Electric efficiency is ~ 30%
but the cost of the converter is very high)

## How can we obtain a higher Solar-to-Electric efficiency?

**A. By increasing the solar field thermal efficiency**

- **Collecting ALL the sun light from sunrise to sunset**
  (=avoiding Mirror Shadowing)
- **Collecting it at a moderate angle of incidence**
  (=reducing mirror area by reducing “cosine effect”)
- **Concentrating it in the smallest possible receiver**
  (=reducing radiation losses!)

**B. By increasing Thermal-to-Electric conversion efficiency**

- **Using higher temperature cycles**
  (i.e. higher concentration of Solar Energy)
- **In large enough plants to allow for high cycle efficiency**
  (i.e. power >1 MWt)

## Solar Dish

The problems here are:
- Small unitary power (<100kWt)
- Shadowing at low sun elevation
- High cost (many small Stirling engines)

BUT
The concentration
and the collector efficiency
can be very high.
Solar to electric efficiencies
of ～30%
Have been attained

## Parabolic Trough

**Have obvious problems in:**

- Concentration !! (< 100 suns)
- Collection efficiency at low Sun elevation

**BUT**

- Can have essentially unlimited power
- Can use Thermal Storage


# Efficiency Factors for Parabolic Trough (@390 °C)

| | Base-line | SunLab Forecast | | |
|---|---|---|---|---|
| Case | | Near Term | Mid Term | Long Term |
| Project | SEGS VI | Trough 100 | Trough 150 | Trough 400 |
| Year In Service | 1989 | 2004 | 2010 | 2020 |
| Project | SEGS VI | Trough 100 | Trough 150 | Trough 400 |
| Year In Service | 1989 | 2004 | 2010 | 2020 |
| Solar Field Optical Efficiency | 53.30% | 56.70% | 59.80% | 60.20% |
| Receiver Thermal Losses | 72.90% | 86.00% | 85.20% | 85.30% |
| EPGS Efficiency | 35.00% | 37.00% | 40.00% | 40.00% |
| Electric Parasitic Load | 82.70% | 88.40% | 92.20% | 92.80% |
| Net power generator efficiency | 28.95% | 32.71% | 36.88% | 37.12% |
| Parziale | **11.25%** | **15.95%** | **18.79%** | **19.06%** |
| Piping Thermal Losses | 96.10% | 96.50% | 96.70% | 96.80% |
| Storage Thermal Losses | NA | 99.10% | 99.60% | 99.60% |
| Power Plant Availability | 98.00% | 94.00% | 94.00% | 94.00% |
| Parziale | **94.18%** | **89.89%** | **90.53%** | **90.63%** |
| | | | | |
| Annual Solar-to-Electric Efficiency | **10.60%** | **14.30%** | **17.00%** | **17.20%** |

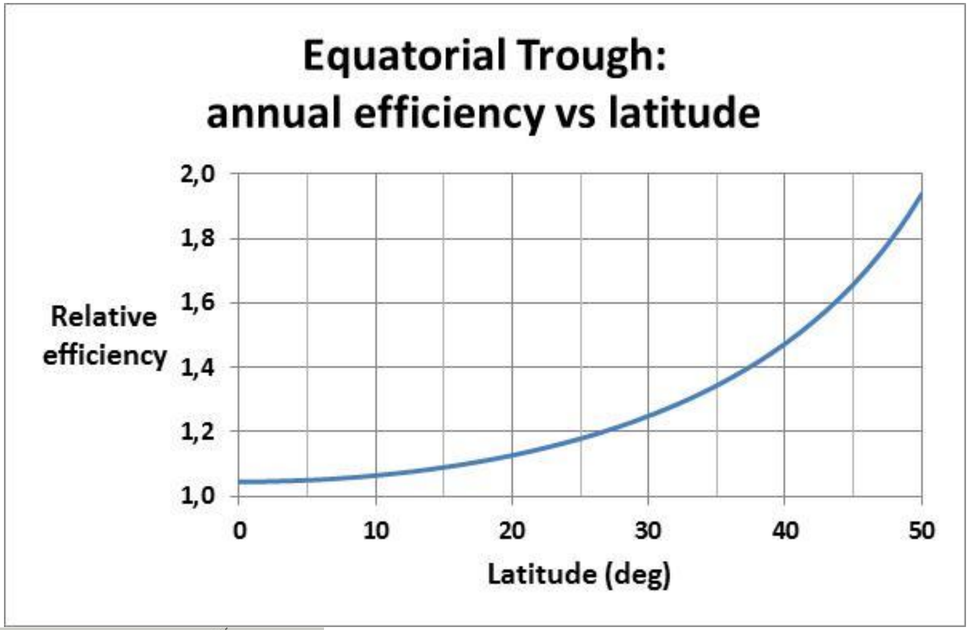
October 2003 • NREL/SR-550-34440

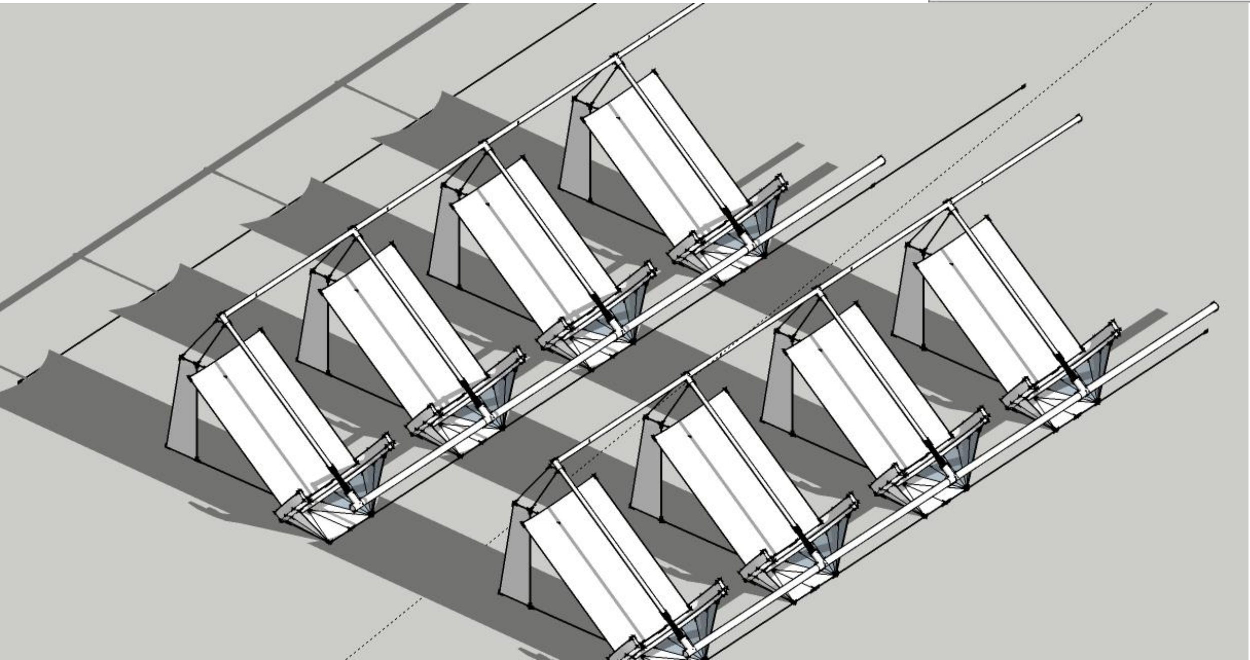
# Improvements for Though Fields

## «**Equatorial Tracking**»

removes the seasonal change of angle of incidence

- Annual average «geometrical collection efficiency» ≥95% (at all latitudes!)
- Single mirror optical efficiency of collector ~95%
- **Mean collector efficiency ~ 90%**



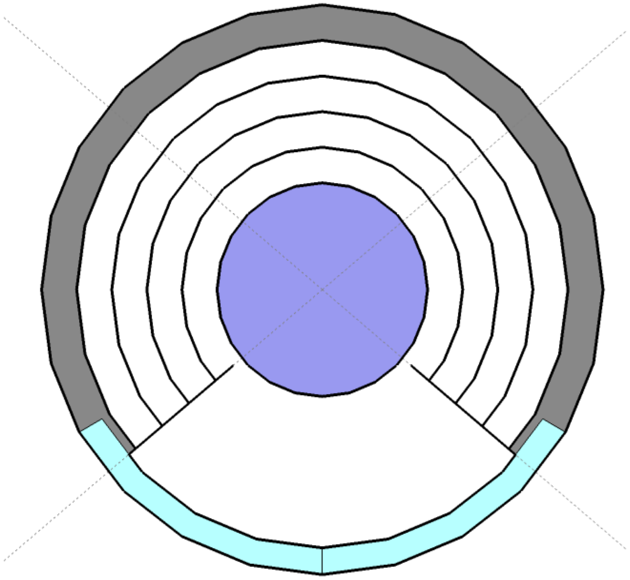



**This geometry**

- **Improves thermal efficiency**
- **Expands the latitude range**
- **Allows use of inclined terrains**
- **Reduces pumping power**

**At no extra cost/m² of the field**

# Plus an «advanced receiver»



**With**

- **FIXED fluid pipe**
- **Radiation shields**
- **Correcting  window**
- **Low pressure Xenon insulation**
- **Appropriate coatings on pipe and windows**

**Can achieve a receiver efficiency:**

**~ 90% @ T=600 ºC!!**

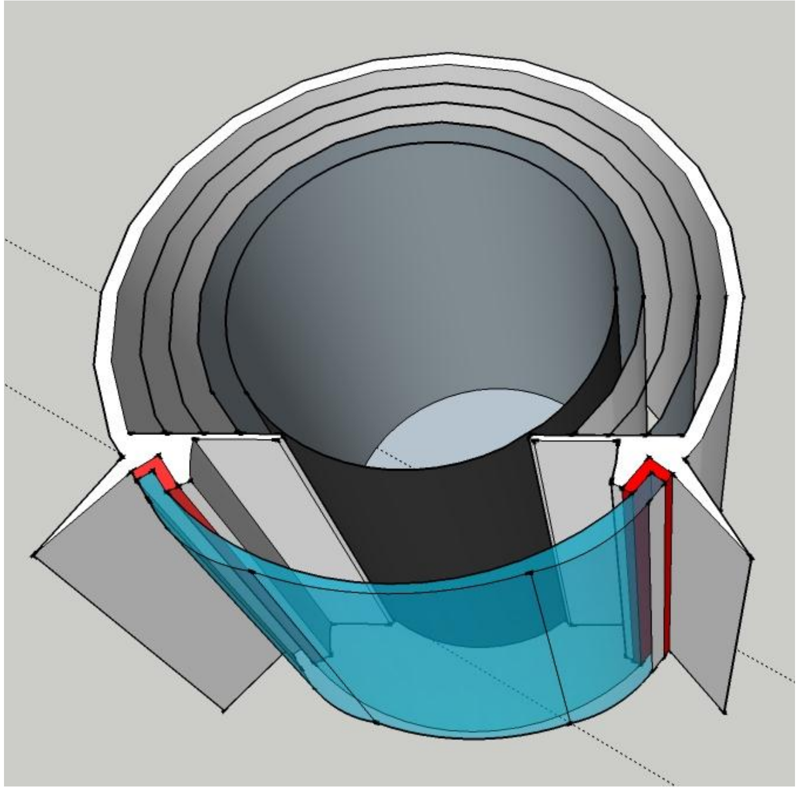
**(~ 85% @ T=800 ºC!!!!)**

**(vs 85% @ 390 ºC)**

So the total thermal efficiency
can reach ~81% @ **600 ºC**

(assuming 46% eff. for the EPGS @ T=600 ºC)
**a total solar to electric efficiency**
**of 37% can be obtained**

**This is already a factor of two better than current performances**



# Solar Towers

**Have obvious problems in:**

- Collection efficiency at low Sun elevation
- Concentration

**BUT**

- Can have high power (many MWt)
- Can use Thermal Storage



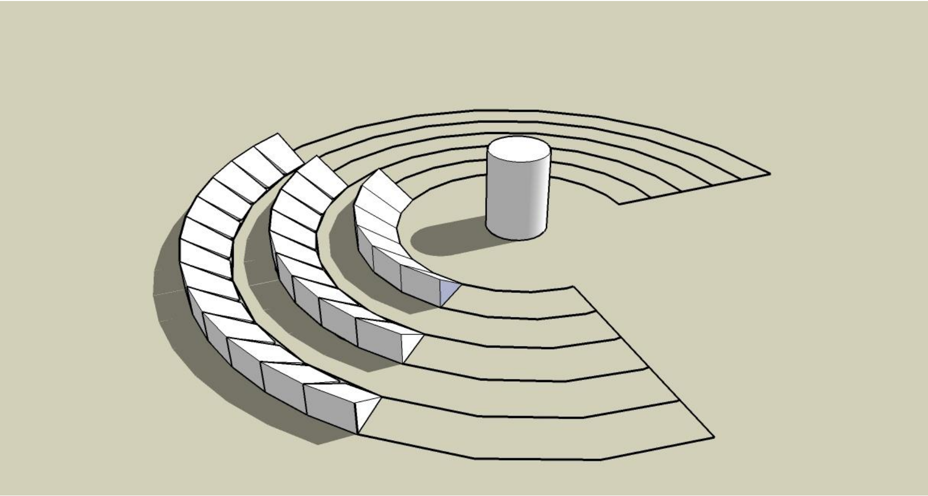
# Efficiency factors for Solar Towers

| | Baseline | SunLab forecast | | |
|---|---|---|---|---|
| | | Near Term | Mid-Term | Long Term |
| | 1996 | 2004 | 2008 | 2020 |
| | Solar Two | Solar Tres | Solar 100 | Solar 220 |
| **Collector Efficiency** | 50.30% | 56.00% | 56.30% | 57.00% |
| **Receiver Efficiency** | 76.00% | 78.30% | 83.10% | 82.00% |
| **Gross Cycle Efficiency** | 31.70% | 40.50% | 42.00% | 46.30% |
| **Parasitic** | 73.00% | 86.40% | 90.00% | 90.00% |
| **Net Generator efficiency** | 23.14% | 34.99% | 37.80% | 41.67% |
| **Partial** | **8.85%** | **15.34%** | **17.68%** | **19.48%** |
| **Thermal Storage** | 97.00% | 98.30% | 99.50% | 99.50% |
| **Piping** | 99.00% | 99.50% | 99.90% | 99.90% |
| **Availability** | 90.00% | 92.00% | 94.00% | 94.00% |
| **Partial** | **63.09%** | **77.75%** | **84.09%** | **84.09%** |
| | | | | |
| **Annual Solar-to-Electric Efficiency** | **7.60%** | **13.70%** | **16.60%** | **18.10%** |

October 2003 • NREL/SR-550-34440

# Possible improvements:

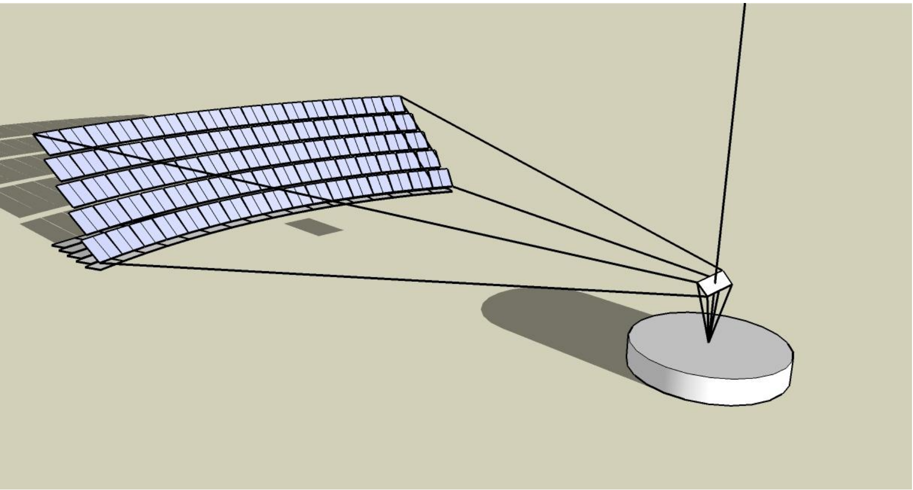
# First of all by changing field geometry!



**Simply grouping the mirrors and moving them in Azimuth on common rails improves dramatically the mirror collection efficiency.**

The annual average of the daily azimuth angle variation is 180 deg, while for elevation this is (at most, at the Equator) 90 deg.

Removing the Az component therefore greatly reduces the average incidence angle on the mirrors, increasing the effective collecting area.

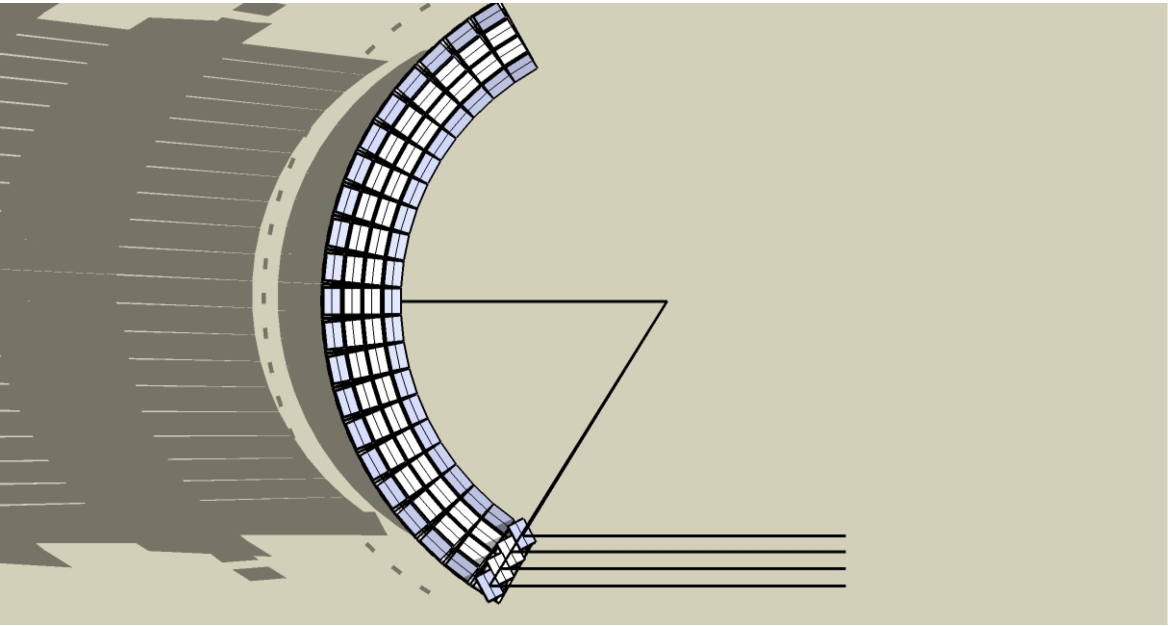


**One can do even better by placing the mirrors at different height on a common radius.**

This

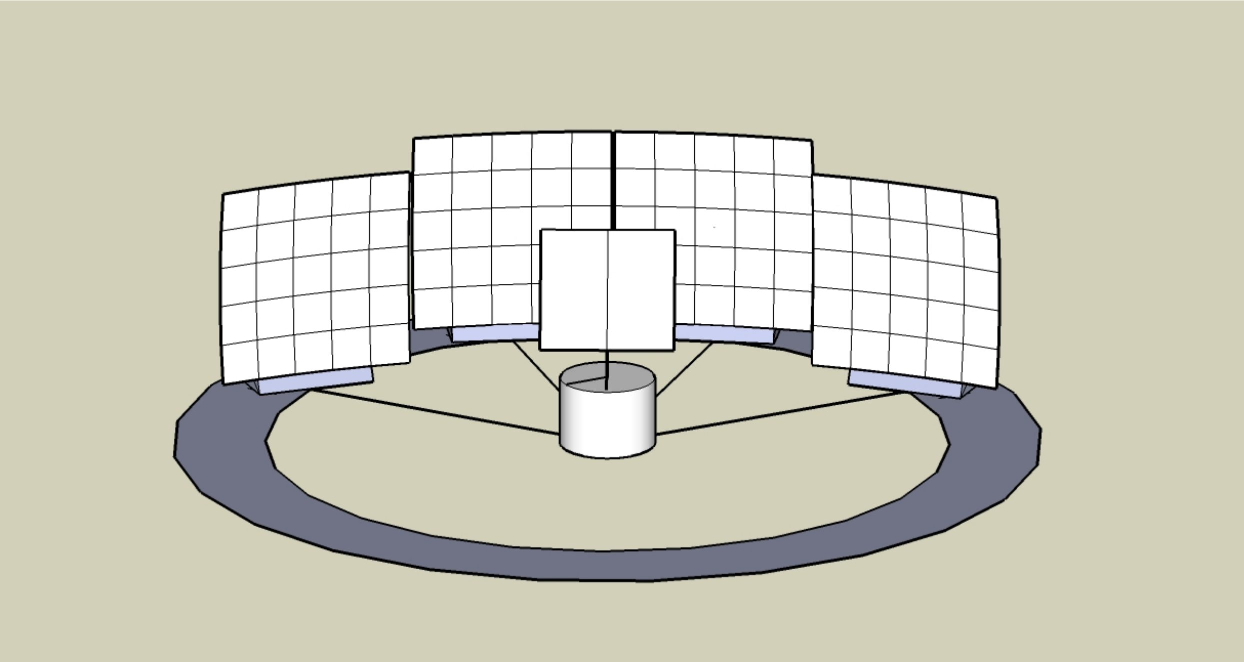
- removes mirror shadowing
- reduces the spread in Sun image size
- reduces the impact on land
- allows mirror cleaning every night

One can then arrange the individual mirrors in different patterns

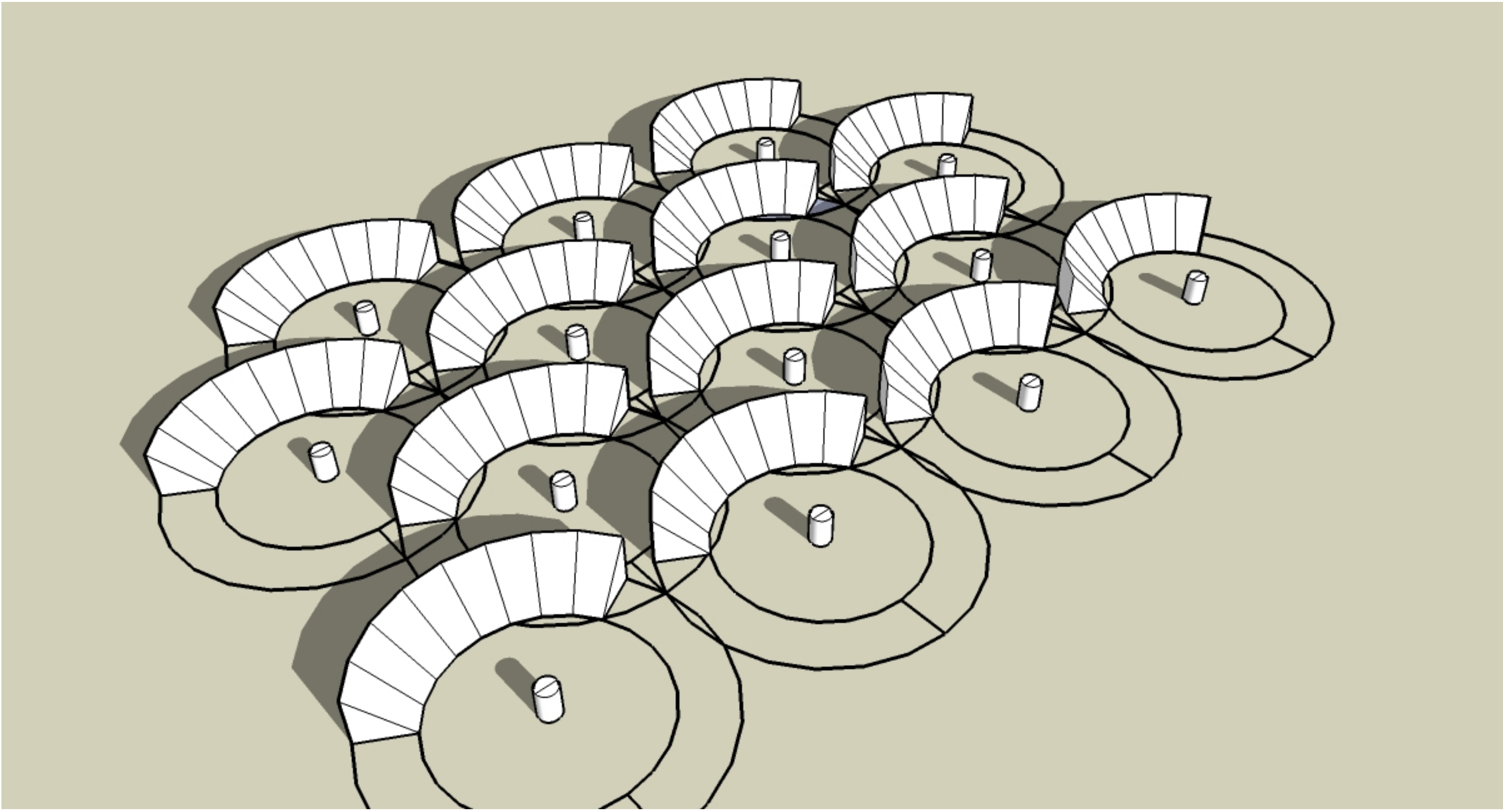


The “Curva Nord” pattern
(with a single rotating support for all the mirrors)

The “multi-array” pattern
(with separate large arrays of mirrors)



# And, if you want a really big field . . .



**You can combine "rotating" mirrors more efficiently than "fixed" ones (look at the shadows and mentally rotate the fields East or West . . .)**

# The "rotating field" can increase the concentration

**A high concentration is certainly VERY desirable, because:**

- **It reduces thermal loss at the receiver (at any temperature)**
- **It allows increasing the operating temperature, i.e. thermoelectric cycle efficiency**

**The concentration of a «Rotating Field» is intrinsically higher than for a conventional Tower because:**

- **The distances between mirrors and receiver are all (nearly) equal**
- **The aberrations are reduced by the much lower off-axis angles**
- **The reduced aberrations can be corrected, if desired, with simple «Active Optics»**

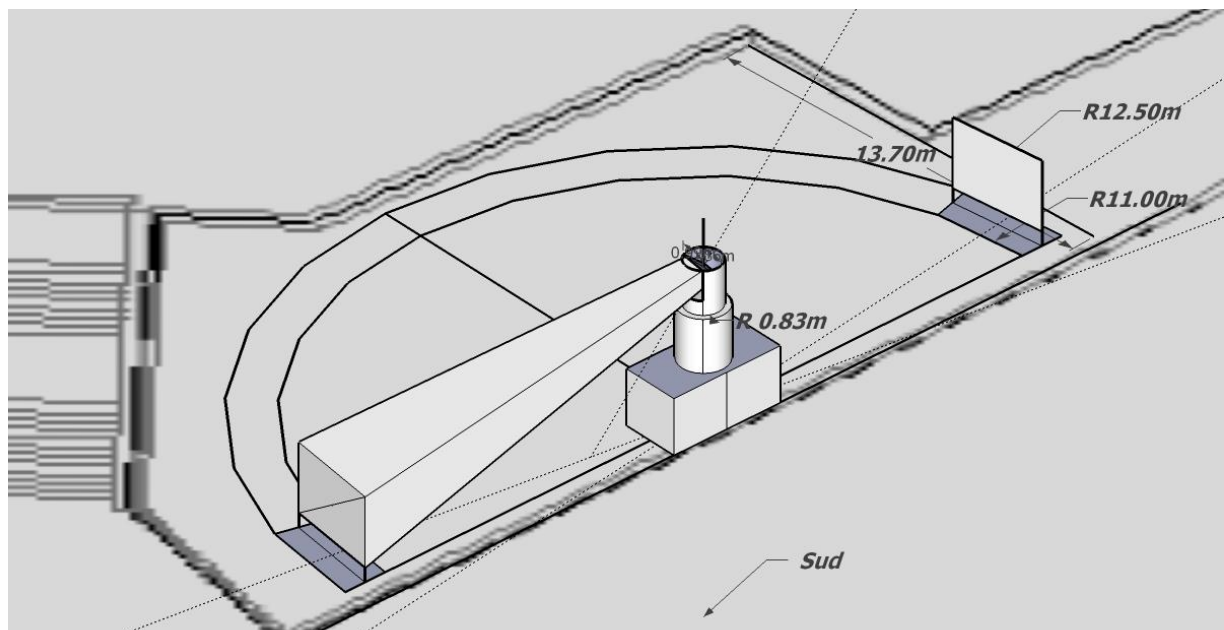
**The net result is that a concentration of > 2000 suns is easily obtainable (vs ~ 500 suns of conventional towers)**

**This allows to increase the operating Temperature from 600 $^{o}$C to > 1000 C**

Solar Tres (Andalusia, Spain)
17 MW
(17.000 $m^2$ of mirrors)
120m high Tower
Operative T of 565 ℃
(operational 2011)

**Versus**

STAR (Arcetri, Tuscany)
0.007 MW
(7 $m^2$ of mirror)
6 m high Tower
@565 ℃
(operational in 2009
for a few months)



# What is the current expectation in terms of Field Efficiency (@565 ℃)?

| NREL annual efficiency factors | Solar Field | |
|---|---|---|
| | Solar Tres | "STAR" Field |
| Mirror Reflectivity | 93,50% | 93,50% |
| Field Optical Efficiency | **64,60%** | **90,00%** |
| Field Availability | 98,50% | 98,50% |
| Mirror Corrosion Avoidance | 100,00% | 100,00% |
| Mirror Cleanliness | **95,00%** | **99,00%** |
| Field High Wind Outage | 99,00% | 99,00% |
| **Annual Heliostat Field efficiency** | **55,96%** | **81,24%** |
| | | |
| Annual Receiver Efficiency (RE) | **78,30%** | **95,00%** |
| Annual Piping Efficiency (PE) | 99,50% | 99,50% |
| Annual Thermal Storage Efficiency (TSE) | 98,30% | 98,30% |
| **Annual thermal efficiency** | **42,85%** | **75,49%** |

**The gain in thermal efficiency is 176%**

## Is “thermal” efficiency the only possible gain?

**NO!**

**An international UE study**
**(“SOLGATE” 2003)**
**“Solar hybrid gas turbine electric power system”**
**Has shown**
**EXPERIMENTALY**
**That a gas turbine can use directly concentrated Sun Power**
**(at concentration >1000)**
**This means that the high efficiency of a CC (55%) can be obtained**
**With a «Rotating Field»**
**This is another potential gain of**
**55/40=1,37**

**Therefore the total gain in solar-electric efficiency could be**
**1,37 x 1,76 = 2,42**

**SOLGATE solar hybrid gas turbine electric power system**

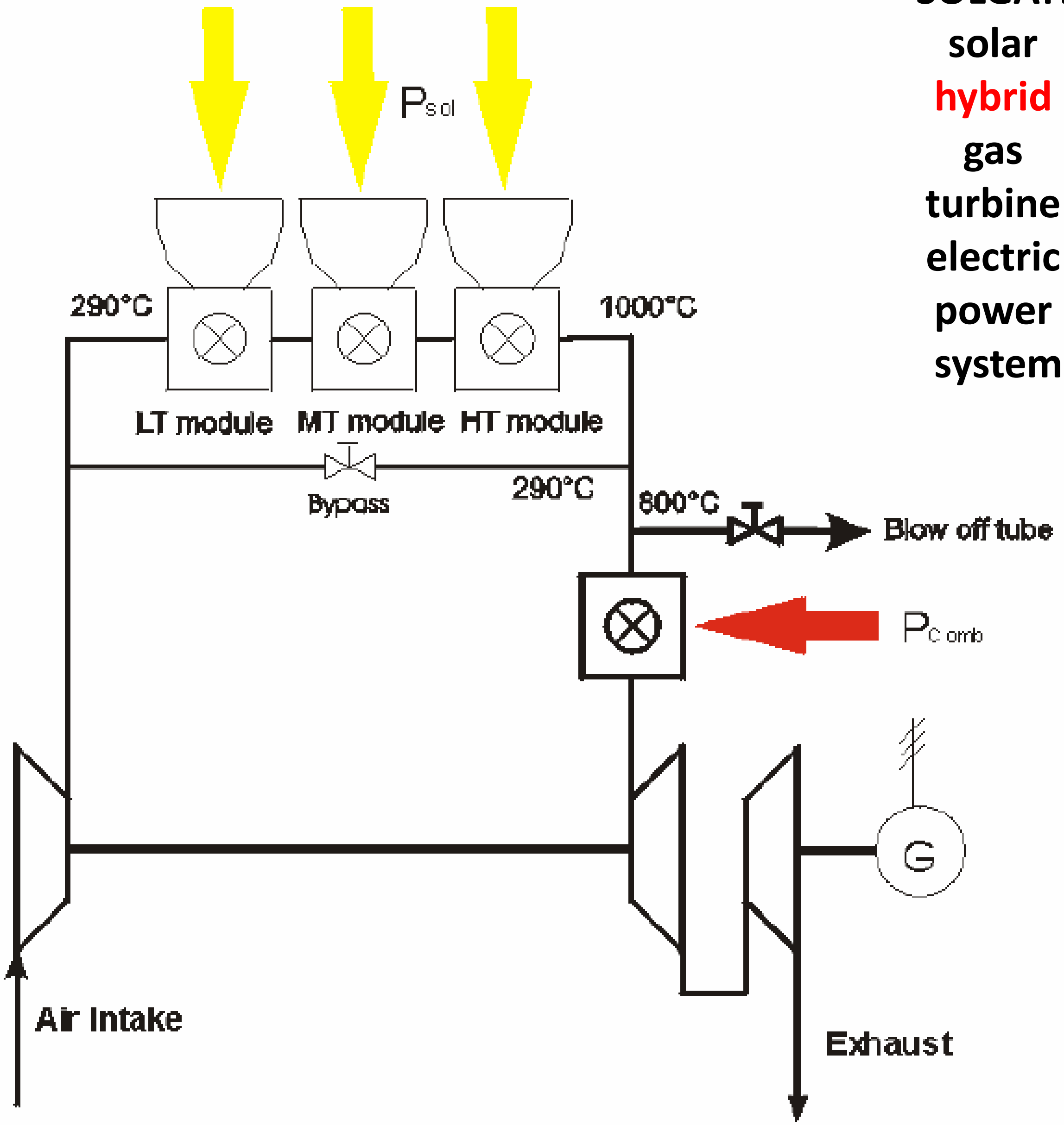


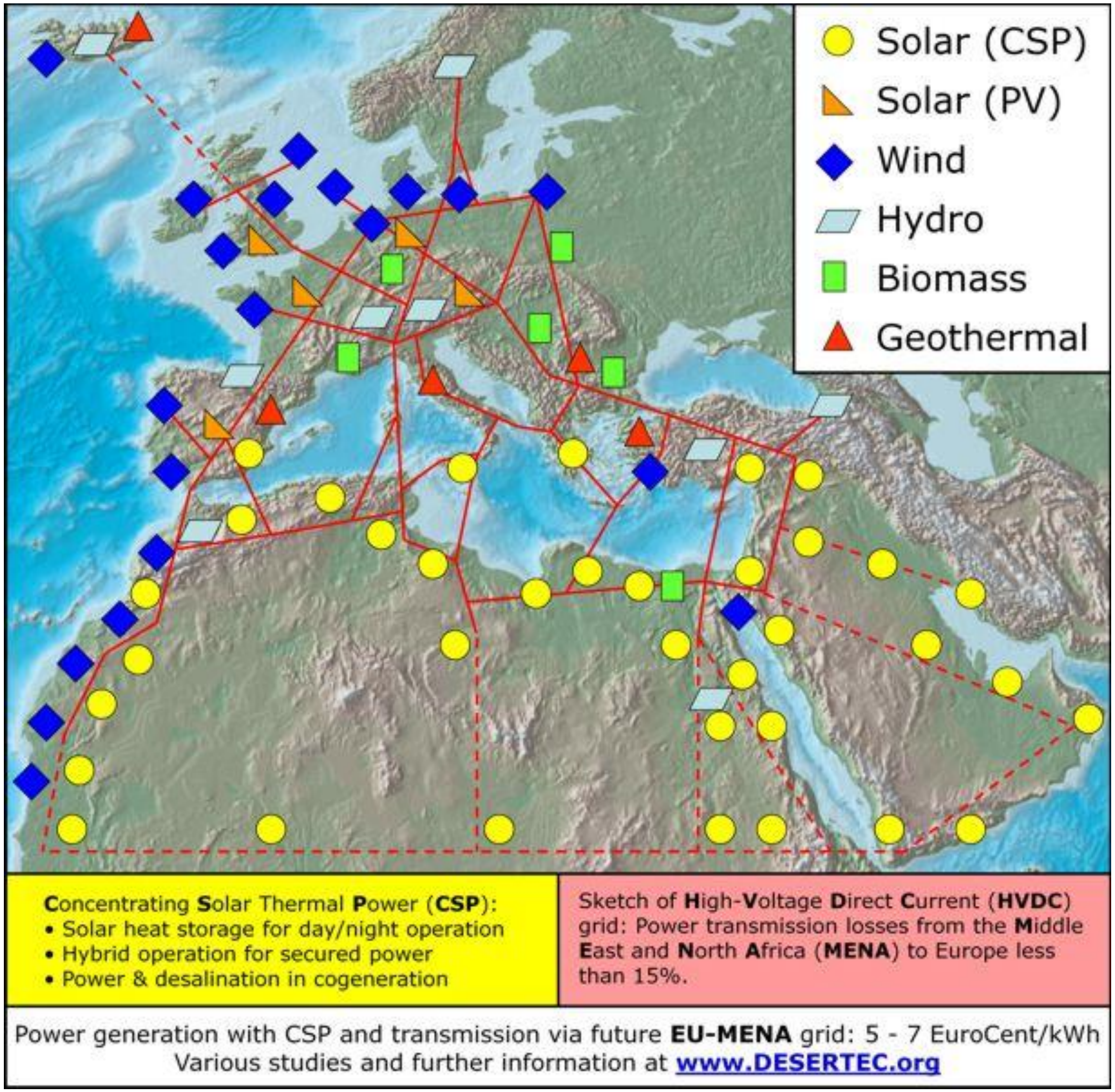

Fig. 3: Scheme of the SOLGATE test system

**In SOLGATE**
**The basic idea is**
**to inject DIRECTLY**
**Concentrated solar light**
**In the first stage**
**(gas turbine)**
**of a Combined Cycle plant**

**This is done using**
**A three stage**
**Heat exchanger in the**
**Turbine**
**(after compression,**
**Before the combustion**
**chamber)**

**The system is therefore**
**HYBRID**
**(and doesn't need**
**Thermal storage)**

# Putting it all together: Desertec




Loan of 400 G€ over 40 Years
granted by Deutsche Bank
to a EU consortium
headed by Siemens

Aims at producing
30% of EU power
By 2050

Uses current solar technology
Covers ~75° in latitude (5 hours)
Uses Thermal and Hydro storage
Plus hybridization
To provide uninterrupted power

i.e.
Even the HIGH LEC
solar technology
Starts to be taken seriously
By serious investors!

Thank you for your attention!