Concentrated Solar Thermal Power Technology

Prof. G.R. Tynan

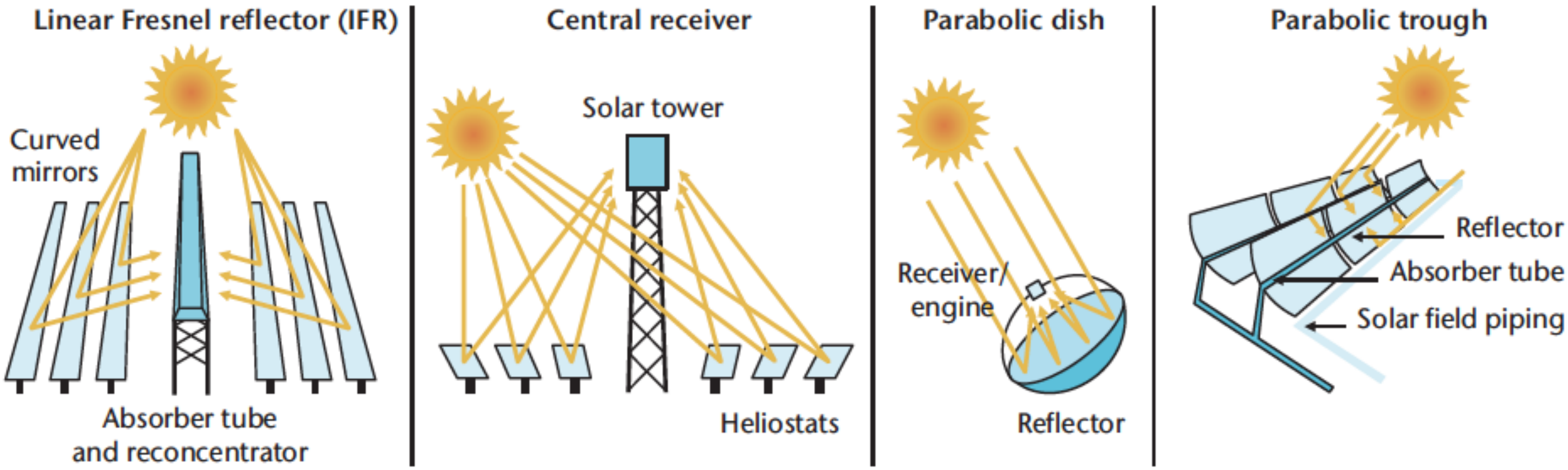
MANY SLIDES ADOPTED FROM
A TALK AT 2005 AAAS MEETING
BY
E. BOES, NREL

And

Professor Carlos Coimbra, UCSD-MAE & CER

Three Main Solar Thermal Electric System Architectures

Figure 3: Main CSP technologies



KEY POINT: Most current CSP plants are based on trough technology, but tower technology is increasing and linear Fresnel installations emerging.

IEA, Solar Thermal Power Technology Roadmap, 2014

Three Main Solar Thermal Electric System Architectures

Trough Technology (Bulk Power)

(a)

Dish/Engine Technology (Distributed Power)

(b)

Power Tower Technology (Bulk Power)

(c)

Utility Scale Central Plants

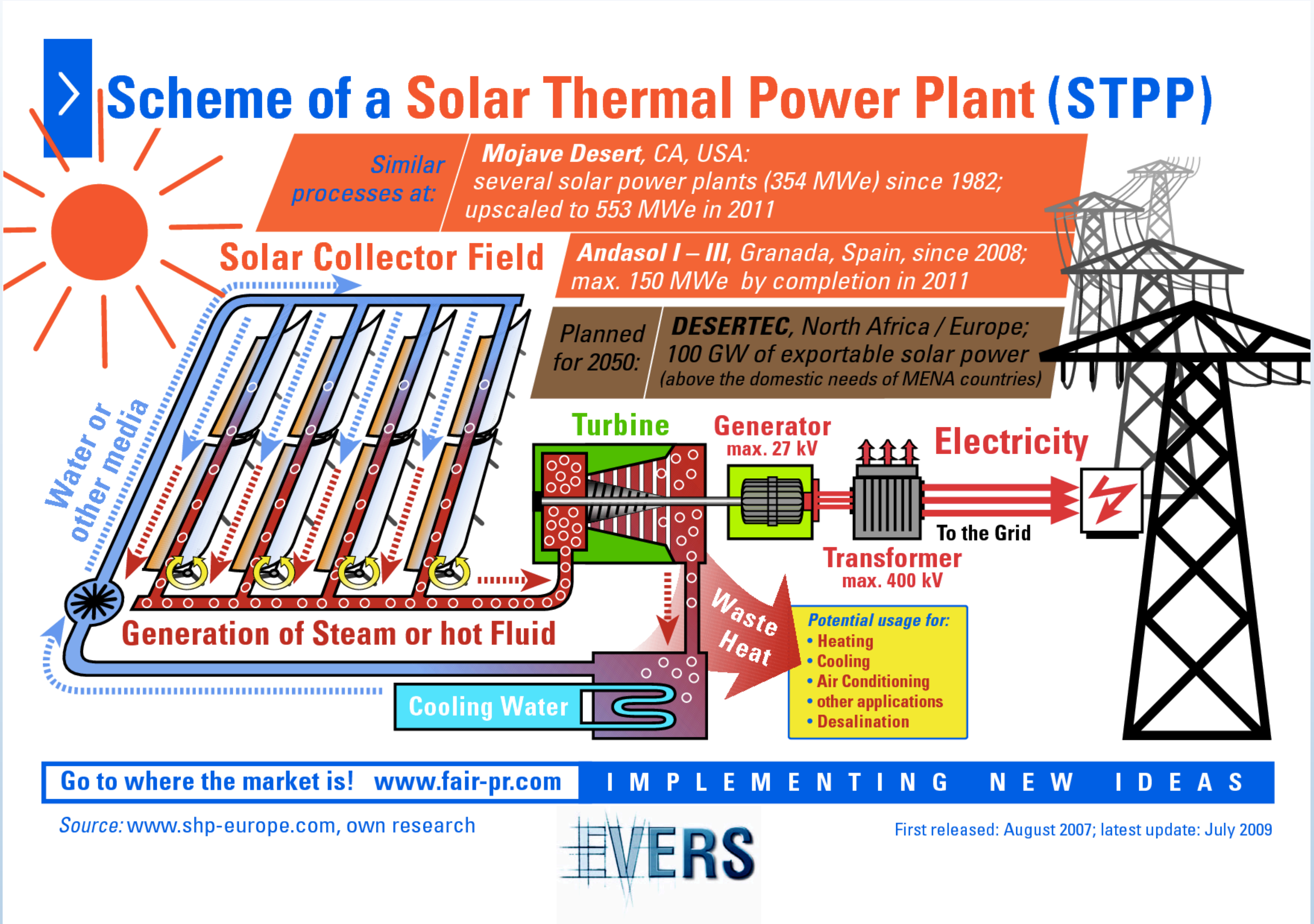
California Valley Solar Ranch, 250 MW Single-Axis Tracking

Concentrating Parabolic Trough Technology

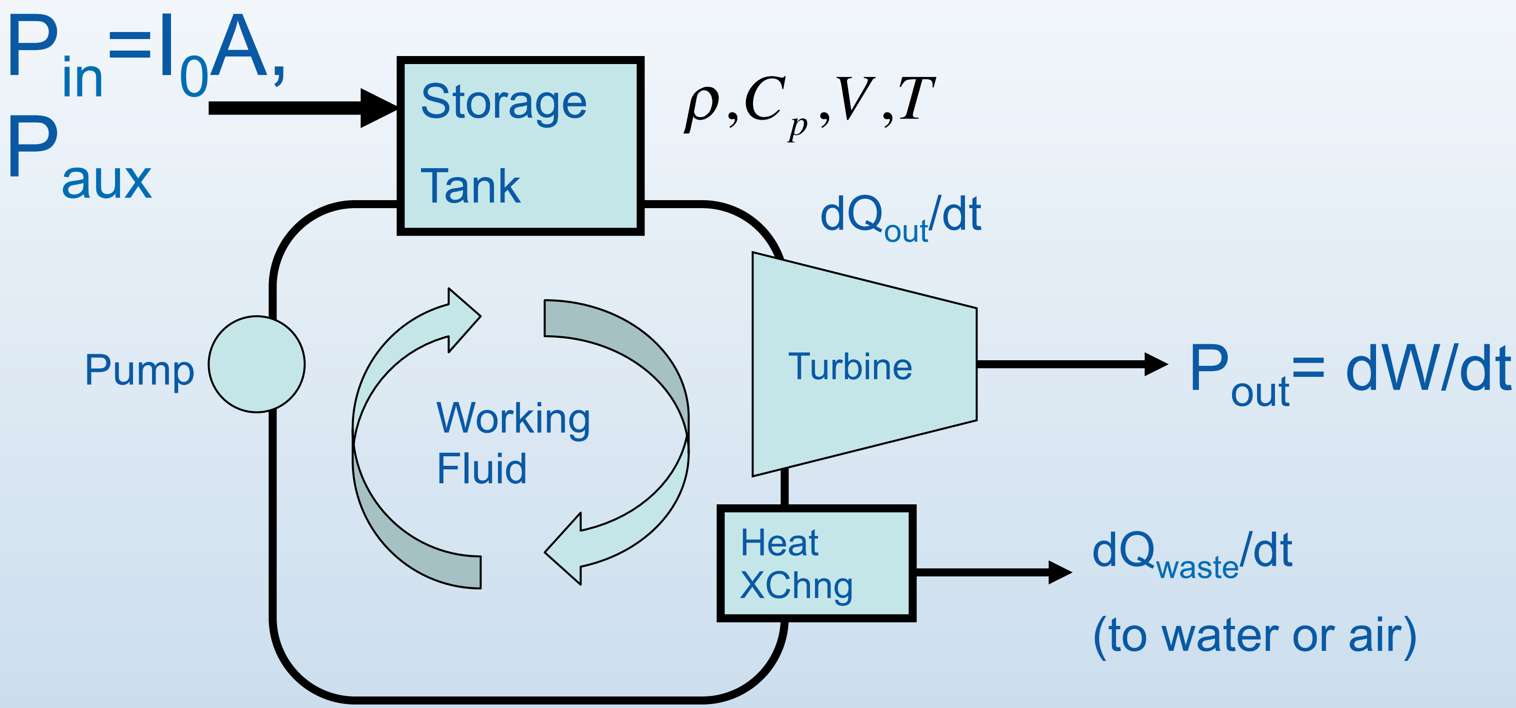
Heliostat Array & Power Tower

Ivanpah Solar Electric Generation System,
www.brightsourceenergy.com

System schematic



Schematic of Solar Thermal Plant w/ Thermal Storage



Energy Balance at Storage Tank Gives

$$\rho C_p V \frac{\partial T}{\partial t} = P_{in} + P_{aux} - \frac{dQ_{out}}{dt}$$

Energy Balance at Turbine Gives

$$\frac{dQ_{out}}{dt} = \frac{dW}{dt} + \frac{dQ_{waste}}{dt}$$

Analysis of Solar Thermal Heat Balance-Steady-state Day Operation

Add two together & use def'n of P_{out}

$$\frac{dQ_{out}}{dt} = P_{out} + \frac{dQ_{waste}}{dt}; \quad P_{out} = dW/dt; W = \eta_{th} Q_{out}$$

thus

$$\rho C_p V \frac{\partial T}{\partial t} = P_{in} + P_{aux} - \frac{1}{\eta_{th}} P_{out}$$

With Solar Input Only Then Have

$$\rho C_p V \frac{\partial T}{\partial t} = P_{in} + \cancel{P_{aux}} - \frac{1}{\eta_{th}} \frac{dW}{dt} \Rightarrow P_{in} = \frac{1}{\eta_{th}} \frac{dW}{dt} \ \ in\ S.S.$$

Steady-state!

Analysis of Solar Thermal Heat Balance-Transient Night Operation

At Night Have No Power Input

$$P_{in} = 0 \; \& \; P_{aux} = 0$$

Transient Heat Balance Gives

$$\rho C_p V \frac{\partial T}{\partial t} = -\frac{1}{\eta_{th}} \frac{dW}{dt}$$

If Have Expontial Like Decay, T~$e^{-t/\tau}$

$$\rho C_p V \left(-\frac{T}{\tau} \right) = -\frac{1}{\eta_{th}} \frac{dW}{dt} \Rightarrow \quad \tau = \frac{\rho C_p V T \eta_{th}}{dW / dt}$$

Transient Night Operation of Solar Thermal Plant

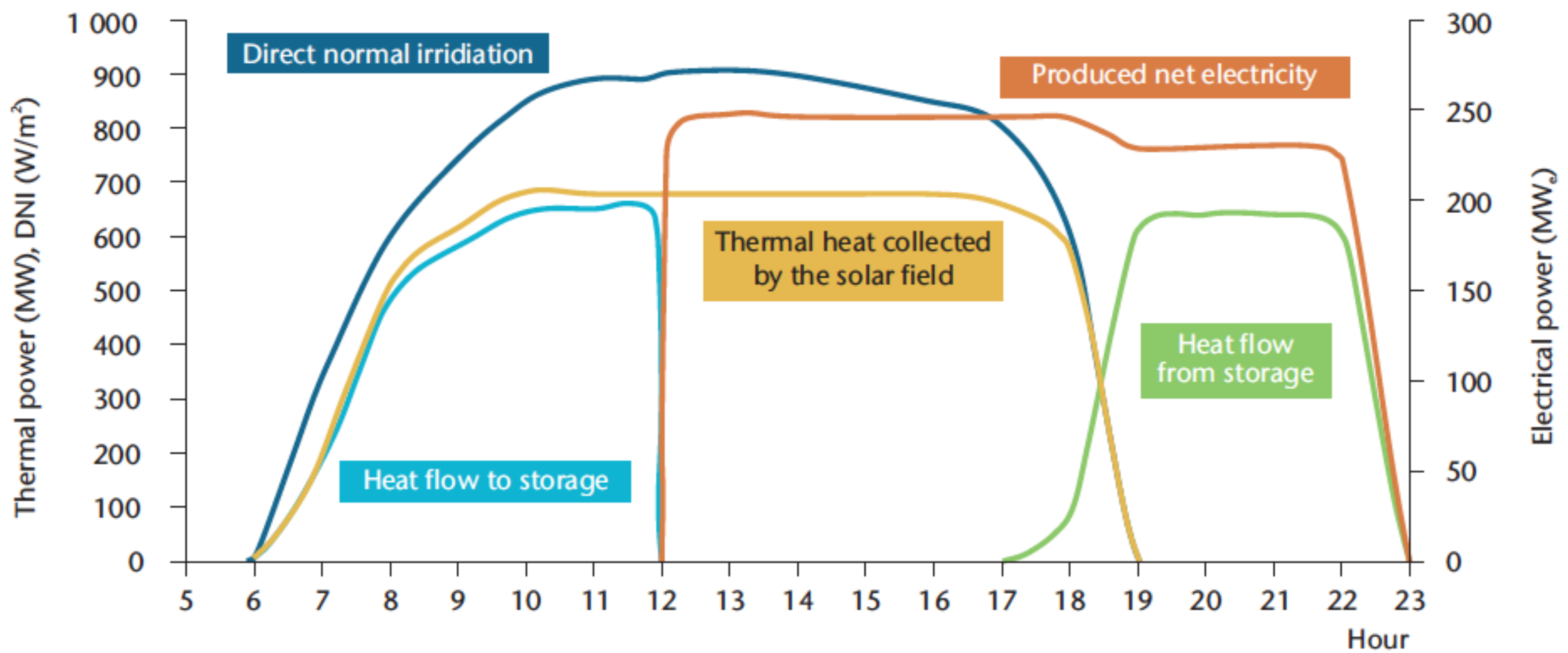
Key Conclusion: Can make Power at Night
IF V large enough and/or dW/dt Small Enough

$$\tau = \frac{\rho C_p V T \eta_{th}}{dW / dt} > 24\,hours$$

Adding P_{aux} (e.g. from Gas Fired Heat Input) Allows Additional Backup Capability

Thermal Storage Enables Dispatchability; Load Shifting

Figure 4: Use of storage for shifting production to cover evening peaks



Notes: the graph shows on left scale the DNIR and the flows of thermal exchanges between solar field, storage and power block, and on the right scale electricity generation of a 250-MW (net) CSP plant with storage. Courtesy of ACS Cobra.

KEY POINT: Thermal storage uncouples electricity generation from solar energy collection.

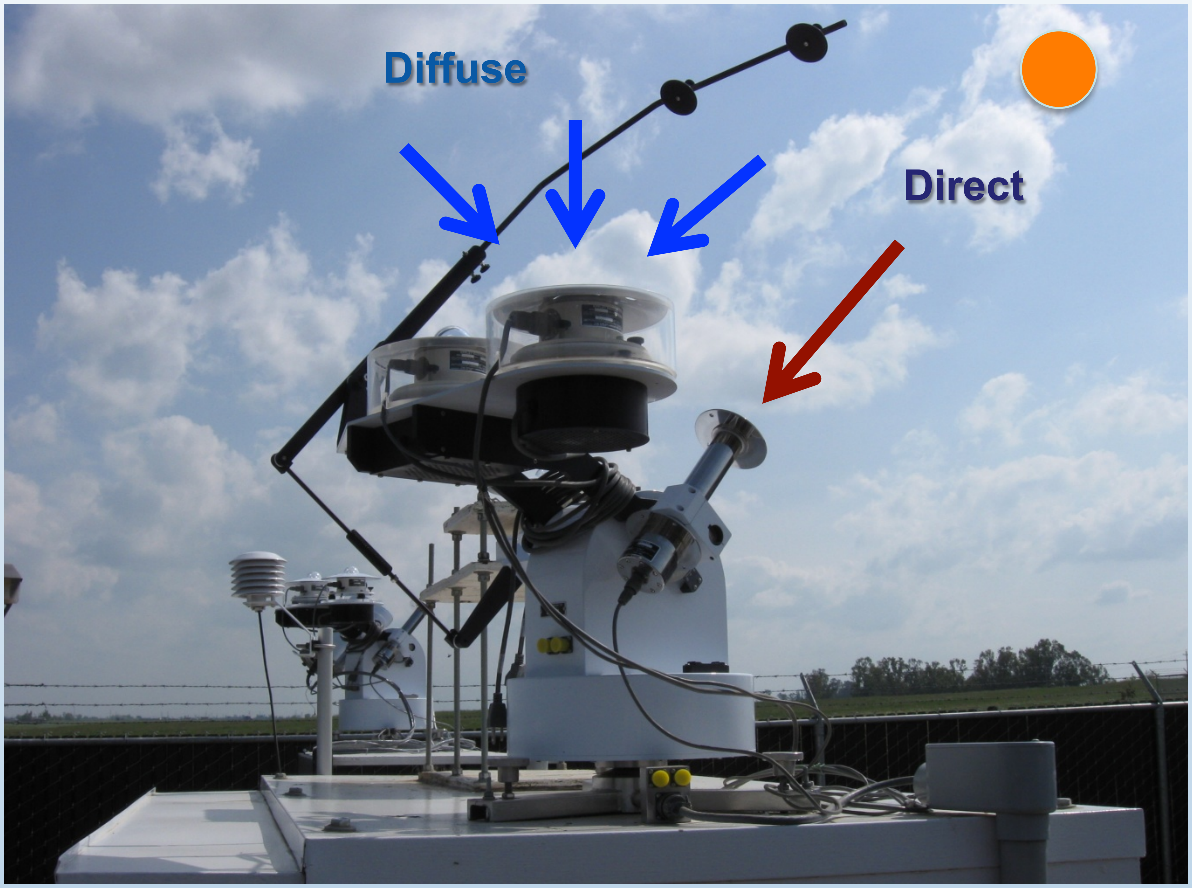
IEA, Solar Thermal Power Technology Roadmap, 2014

Three types of solar irradiation

- **Direct normal incidence (DNI)**: intensity of unscattered light coming directly from sun, normal to a surface
- **Diffusive horizontal incidence (DHI)**: intensity of scattered irradiation incident on a horizonal surface
- **Global horizontal irradiance (GHI)**: DHI + direct irradiance to a horizontal surface

Difference between direct normal irradiance (DNI) and global horizontal irradiance (GHI)

Zenith angle q_z

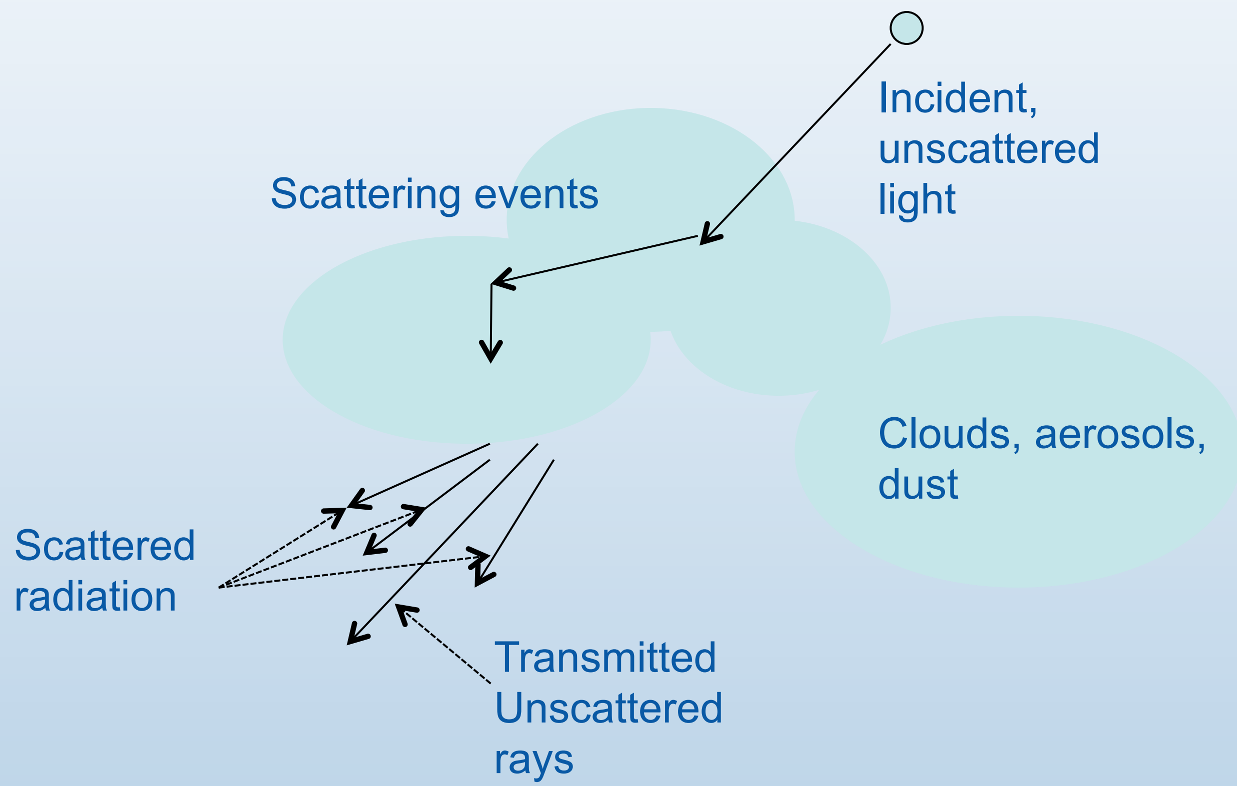


GHI ~ Direct*cos q_z + Diffuse

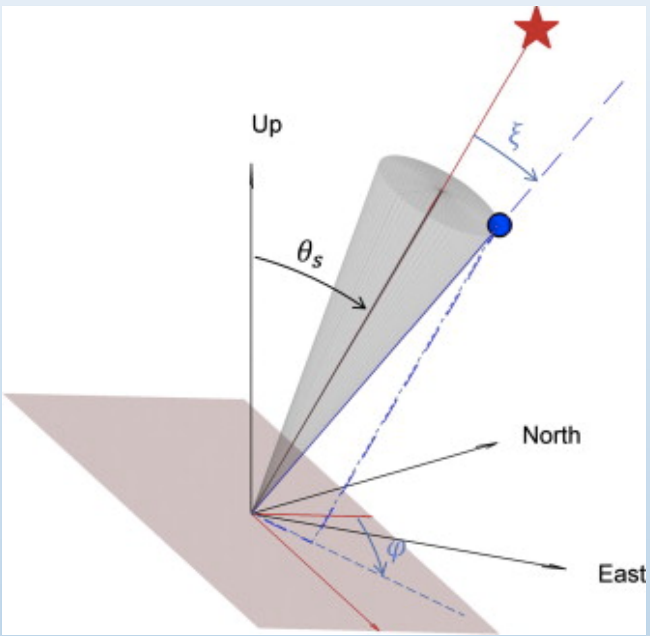
Concentrated Solar Power (CSP)

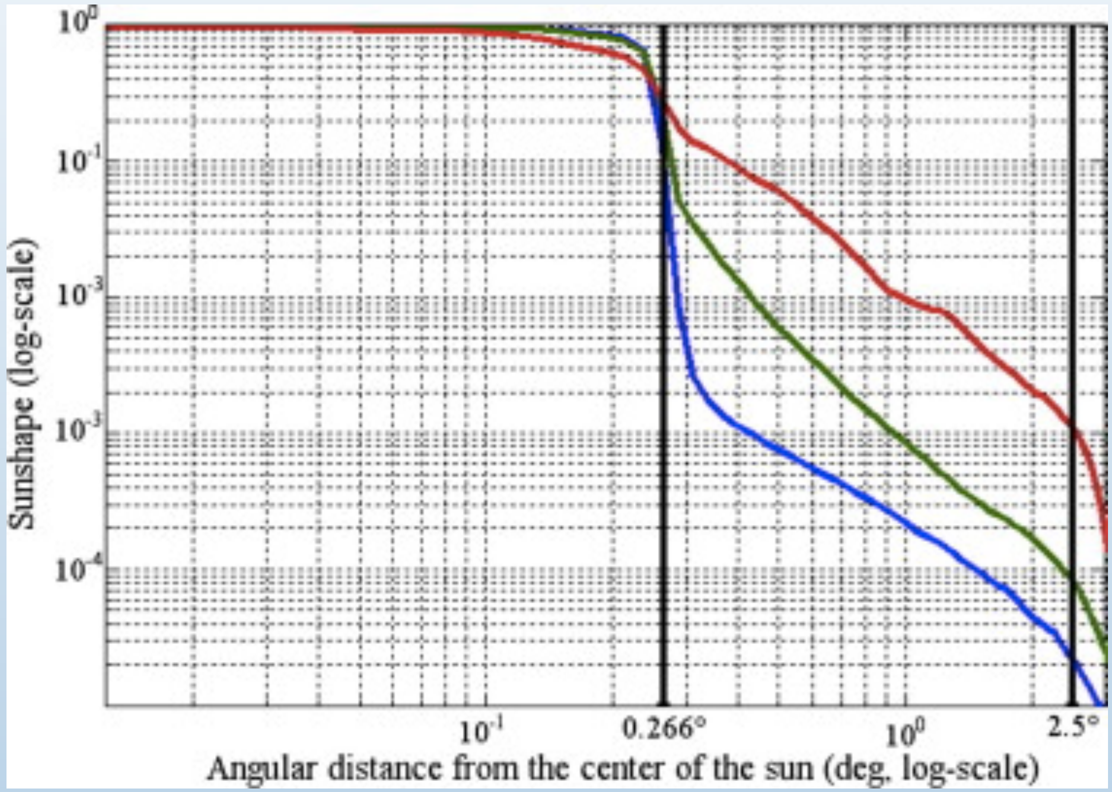
- **Requires direct-beam solar radiation (more in a moment)**
- Uses familiar components & technologies – glass, steel, gears, heat exchangers, turbines
- Can provide dispatchable power IF:
  - Thermal storage is incorporated, or
  - Hybridized with natural gas

Clouds, Dust & Aerosols Act to Scatter Solar Radiation ➔ Reduced DNI

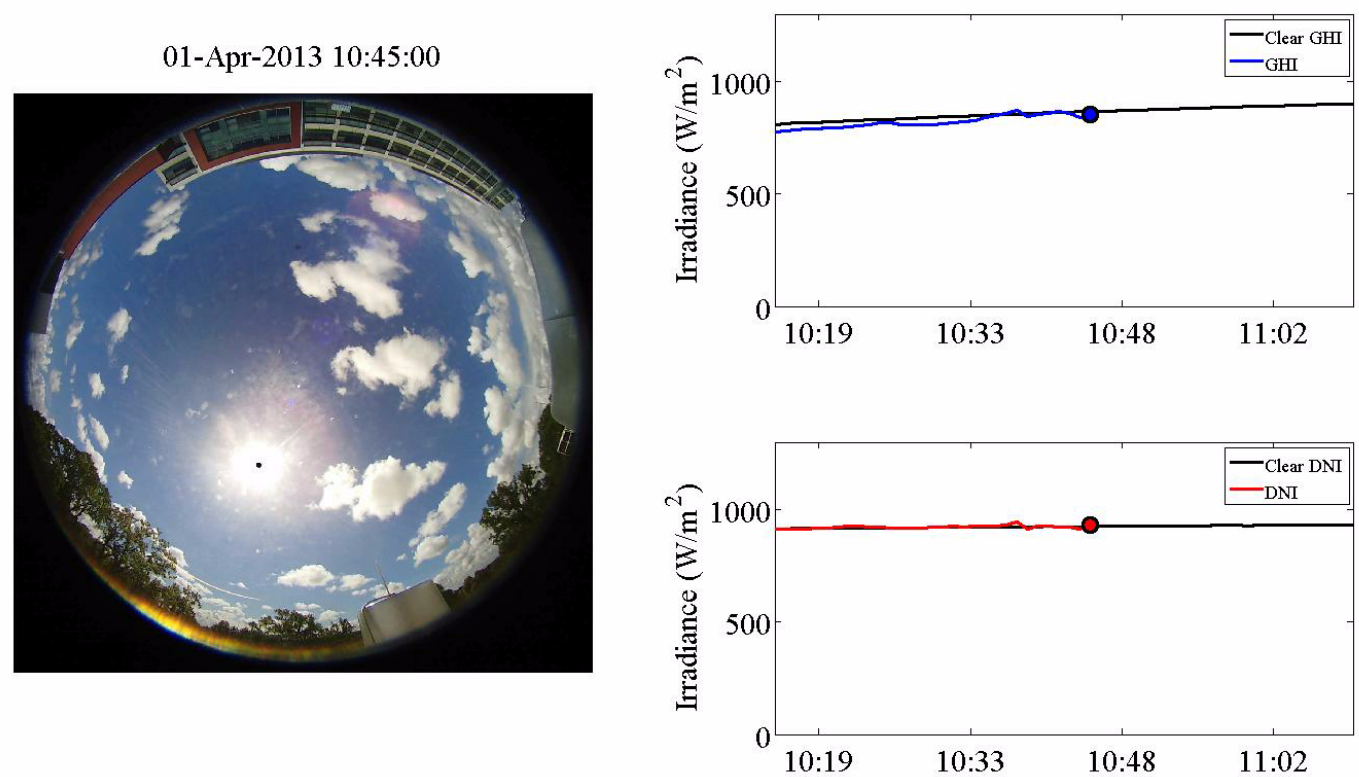


Clouds, Dust & Aerosols Act to Scatter Solar Radiation ➔ Reduced DNI



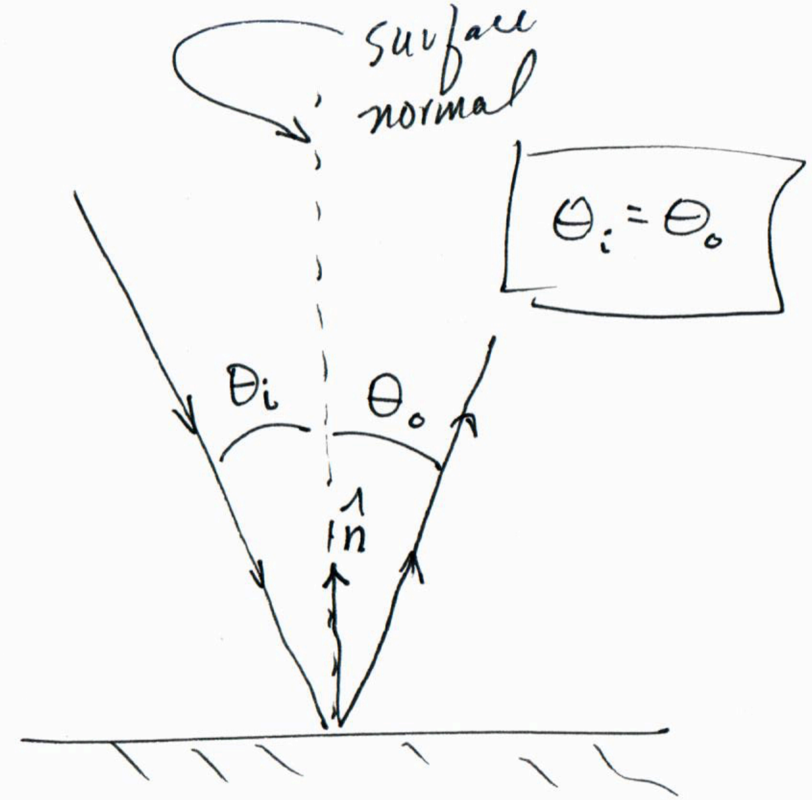


Effect of clouds on solar irradiance at the ground level

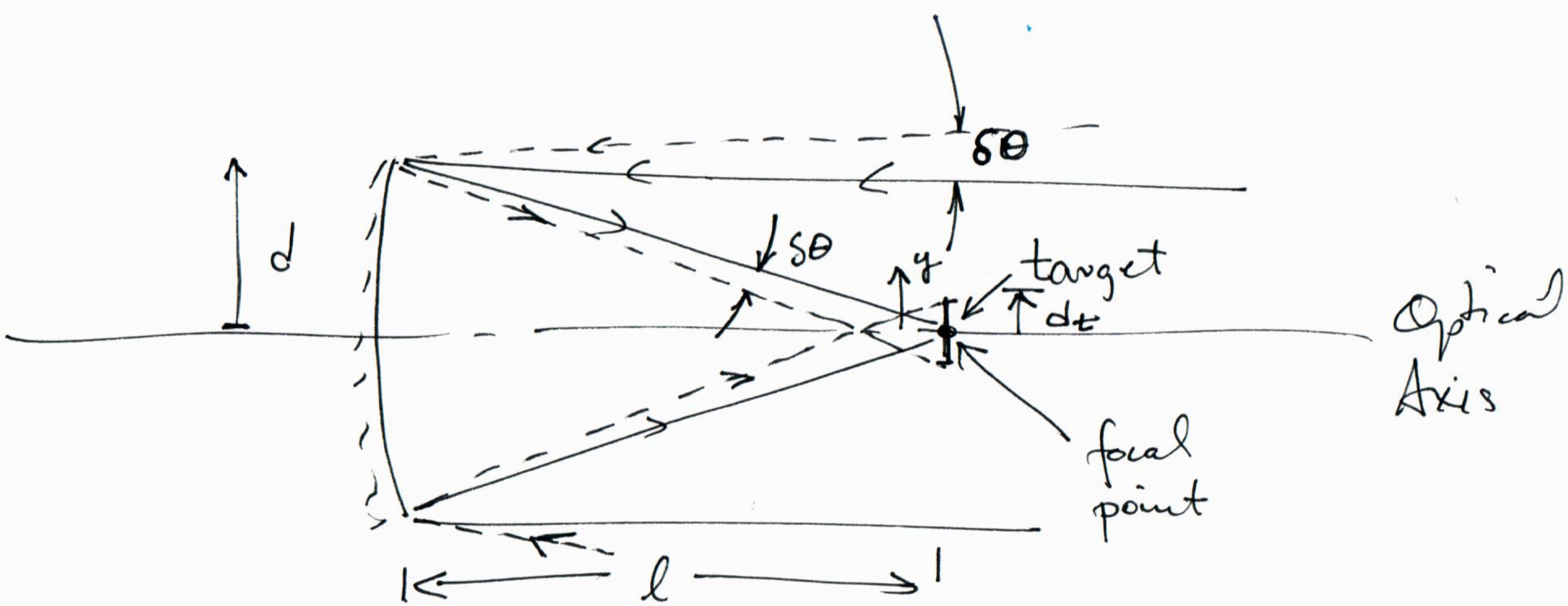


Review Specular Reflection, Focusing Optics Acceptance Angle and Radiation Scattering

Remember Basic Concept of Specular Reflection



Consider focusing optics based system:



d ~ radius of primary optical element

ℓ ~ focal length

d_t ~ radius of target

$\delta\theta$ ~ deviation of rays from parallel to optical axis define the so-called f-number of the optics as

$$f \equiv l/d \sim \text{ratio of focal length / optical element size}$$

from geometry, the rays defined by the dashed line are displaced away from the focal point. This distance is given by

$$\delta y = l \tan \delta\theta .$$

for small $\delta\theta \ll 1$,

$$\delta y \simeq l\,\delta\theta$$

Now... if $\delta y > d_t$ then the collected light misses the target! Thus we require

$$d_t \geq \delta y$$

or

$$d_t \geq l\,\delta\theta$$

Solving for maximum allowable $\delta\theta$:

$$\delta\theta \leq \frac{d_t}{l}$$

An important parameter is the concentration ratio, C

$$C \equiv d/d_t \gg 1$$

← usually

Solving for d_t gives $d_t = \frac{d}{C}$

and so we can write

$$\delta\theta \lesssim \frac{1}{C}\frac{d}{\ell}$$

or

$$\delta\theta \lesssim \frac{1}{C}\frac{1}{f}$$

Consider two main types of system geometry

Trough: $d \sim$ few m $\quad \ell \sim d \rightarrow f \sim 1$

$C \sim 10^2$ or so... $\longrightarrow \delta\theta \lesssim \frac{1}{10^2}\frac{1}{1} \sim 10^{-2}$ radian

Power Tower

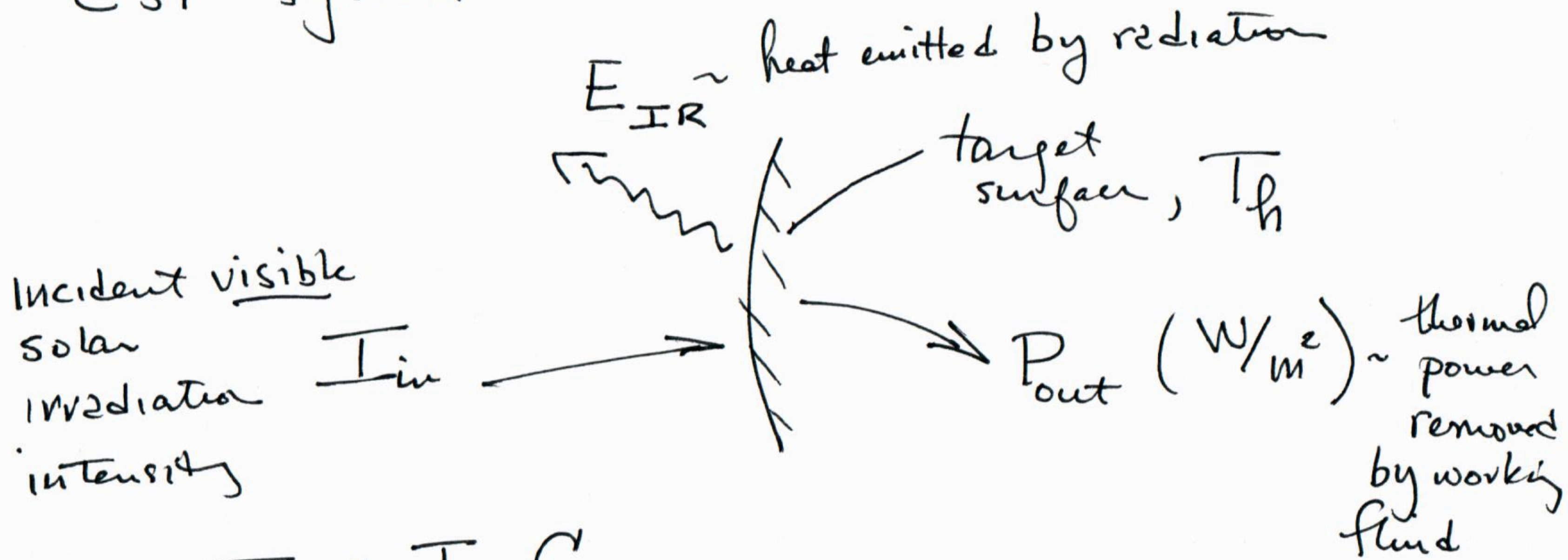
$d \sim 100-1000$ m

$\ell \sim d \sim 100-1000$ m $\rightarrow f \sim 1 \quad C \sim 10^2-10^3$

$$\delta\theta \lesssim \frac{1}{10^2}-\frac{1}{10^{-3}} \sim 10^{-3} \rightarrow 10^{-2} \text{ radian}$$

<u>What value of C do we want</u>?

Consider power balance at target of the CSP system



$$I_{in} = I_o C$$

I_o ← solar insolation [~~intensity~~ W/unit area] within acceptance angle of system power balance gives:

$$I_{in} = E_{IR} + P_{out} \; ; \quad \text{w/ } E_{IR} = \sigma T_h^4$$

$$I_{in} = I_0 C$$

$$I_0 C = \sigma T_h^4 + P_{out}$$

we wish to make T_h as high as possible (with materials limits) to maximum η_{th}

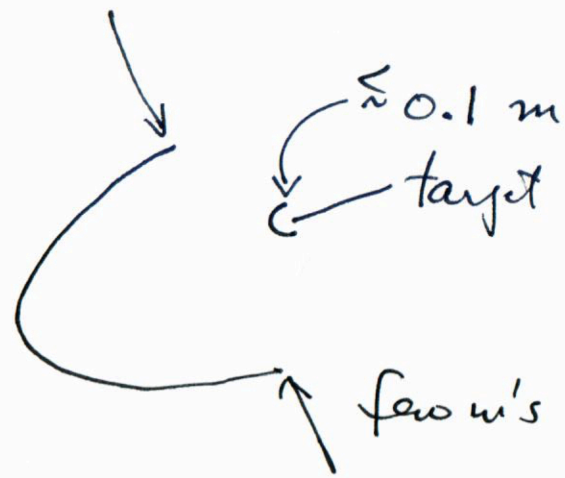
Solve for T_h

$$T_h = \sqrt[4]{\frac{1}{\sigma}\left(I_0 C - P_{out}\right)}$$

for a given P_{out}, I_0 $\Longrightarrow$ Maximize C!

look at typ systems:

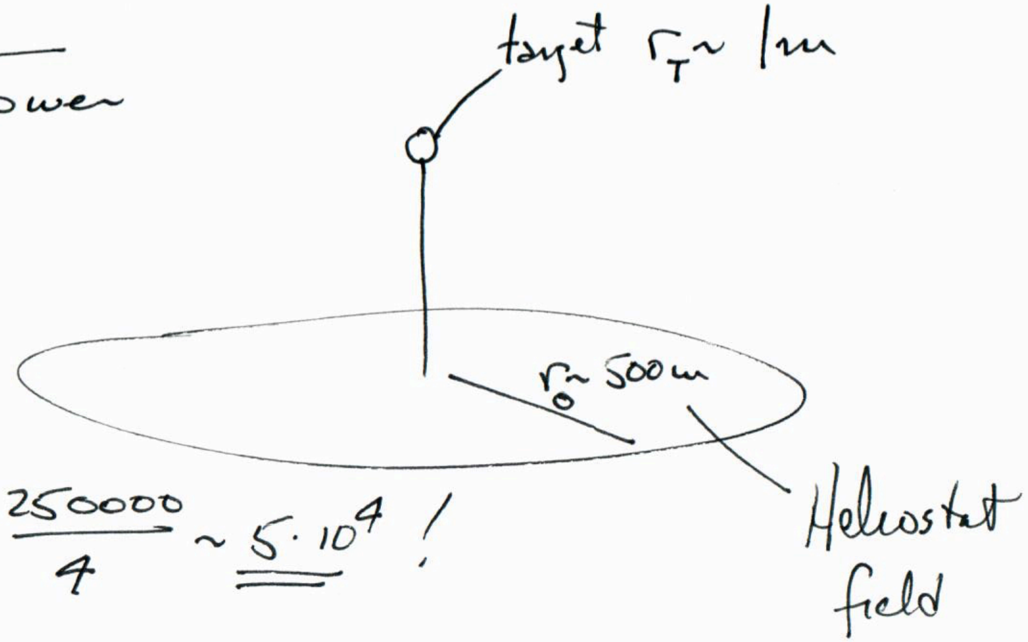
Trough System



$$C \sim \frac{3\text{-}5\,m}{0.05\text{-}.1\,m}$$

$$\sim \underline{\underline{30-100}}$$

Power Tower



$$C \sim \frac{\not{4}\pi r_0^2}{4\pi r_T^2}$$

$$\sim \frac{500^2}{4 \cdot 1^2} \simeq \frac{250000}{4} \sim \underline{\underline{5 \cdot 10^4}}\,!$$

Estimate T_h :

$$\sigma \sim 6 \times 10^{-8}\ W/m^2 K^4$$

thermal power in one tower at Ivanpah ~ 300 MW

$$P = 300\ 10^6\ W / A_t \sim 3\ 10^8 / 4 \cdot \pi \cdot 2^2 \sim 10^7\ W/m^2$$

Heliostat area $A \sim \pi r_0^2 \sim 3 \cdot 5^2 \cdot 10^4 \sim 75 \cdot 10^4 \sim 10^6\ m^2$

$$I_0 \sim 400\ W/m^2$$

$$C \sim 5\ 10^4$$

~~$\therefore T_h = \sqrt{\frac{1}{6\,10^{-8}} (4\,10^2 \cdot 5\,10^4 - 3\,10}$~~

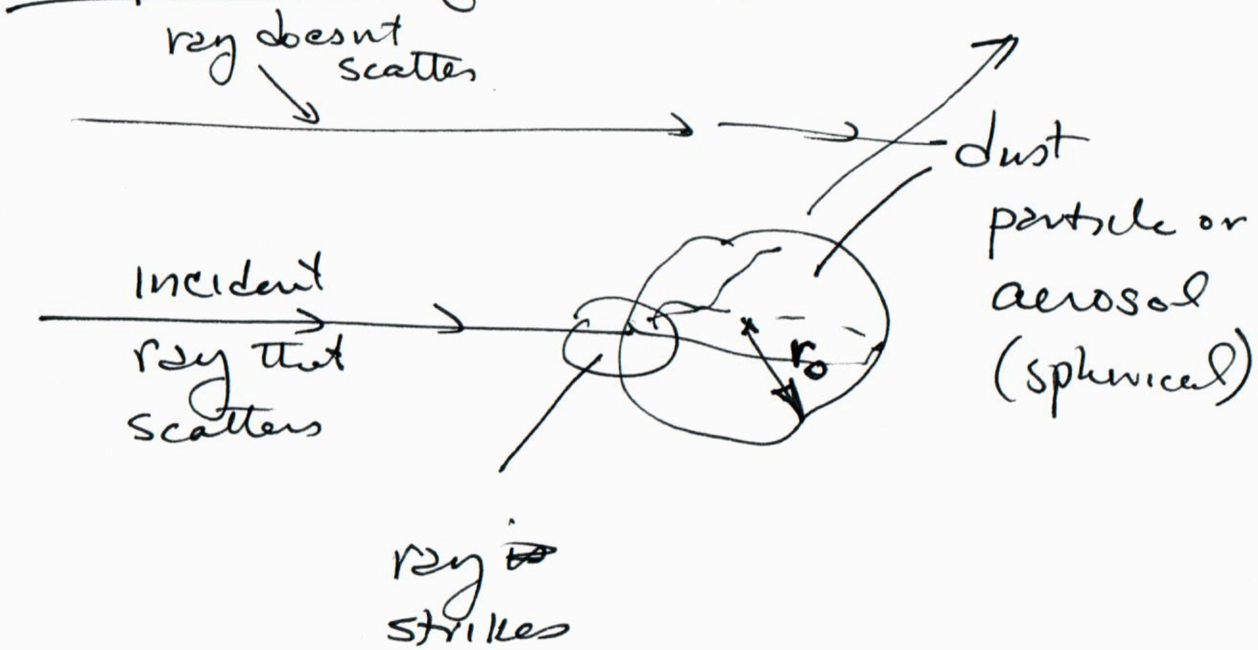
$$T_h = \sqrt[4]{\frac{1}{6\,10^{-8}} \left(4\,10^2 \cdot 5\,10^4 - 10^7\right)} = \sqrt[4]{\frac{10^{15}}{6}} \approx \sqrt[4]{10^{14}}$$

(arrow: $\rightarrow 10^7$)

$$= \sqrt{10^7} \sim \underline{\underline{3000\,^\circ K}}\,!$$

What determines $\delta\Theta$? Radiation Scattering by air (small effect), dust, aerosols, (**BIGGER** effect

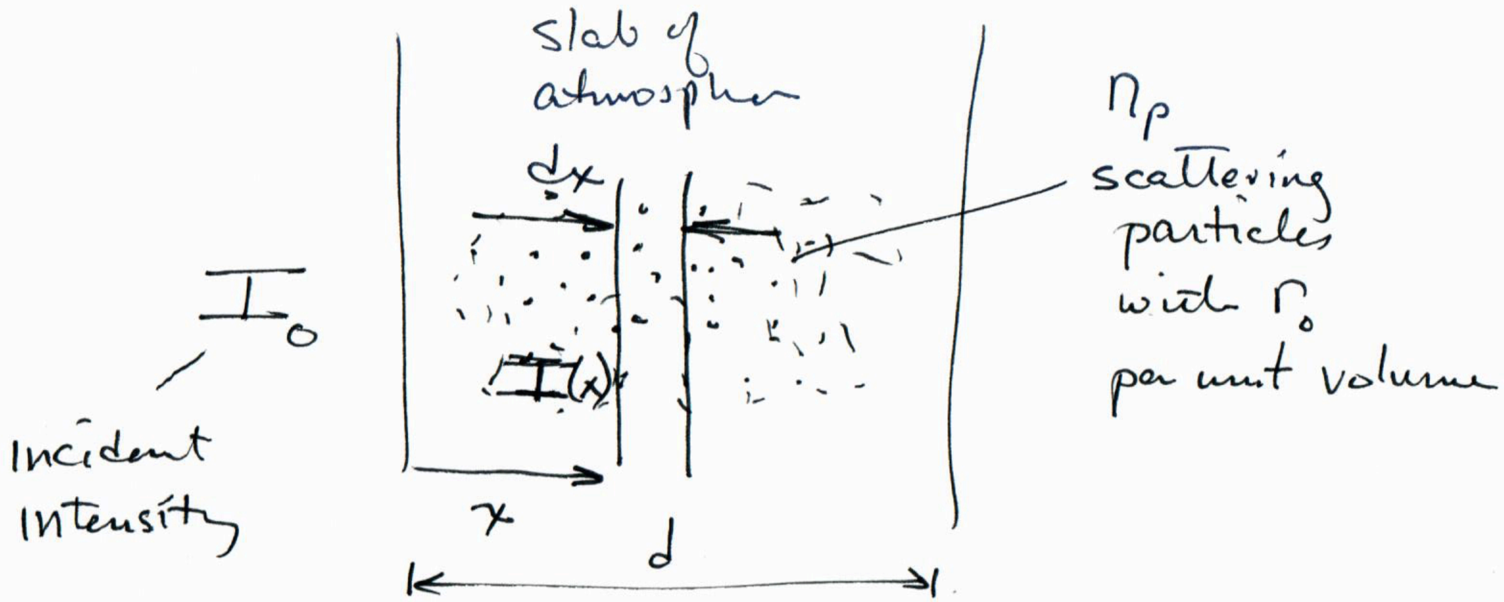
<u>Simple model of scattering:</u>



suppose projected area of particle, $A_{part} = \pi r_0^2$

& there are n_p particles/volume.

Q: How does unscattered radiation behave with r_0, n_p?



$I(x)$ ~ <u>Unscattered</u> intensity at position x

$$dI(x) \propto -I(x)\, n_p\, dx$$

$$dI(x) = -\sigma_{scatt}\, I(x)\, n_p\, dx$$

← take $\sigma_{scatt} \simeq \pi r_0^2$

$\therefore \quad I(x) = I_0 \exp(-x/L_{scatt})$

where $L_{scatt} = (n_p \sigma_{scatt})^{-1}$

$= (n_p \pi r_0^2)^{-1}$

L_{scatt} is the mean-free path for light to travel in a dusty atmosphere

Some numbers:

$r_0 \sim 10\ \mu m = 10^{-5}\ m$

$n_p \sim 10/m^3$ $\quad L_{scatt} \sim [10 \cdot 3 \cdot (10^{-5})^2]^{-1} = (3\,10^{-9})^{-1}$ $\simeq 3\times10^{10}$ m!

$100/m^3$

$10^3/m \rightsquigarrow L_{scatt}\ 3\times10^7\ m = 3\times10^4$ km!

Atmosphere Aerosol size & density can vary. Typ. Values:

$$r_0 \lesssim 1\,\mu m \text{ or so}$$

$$n_p \sim 10^2/cm^3 = 10^8/m^3$$

$\therefore$

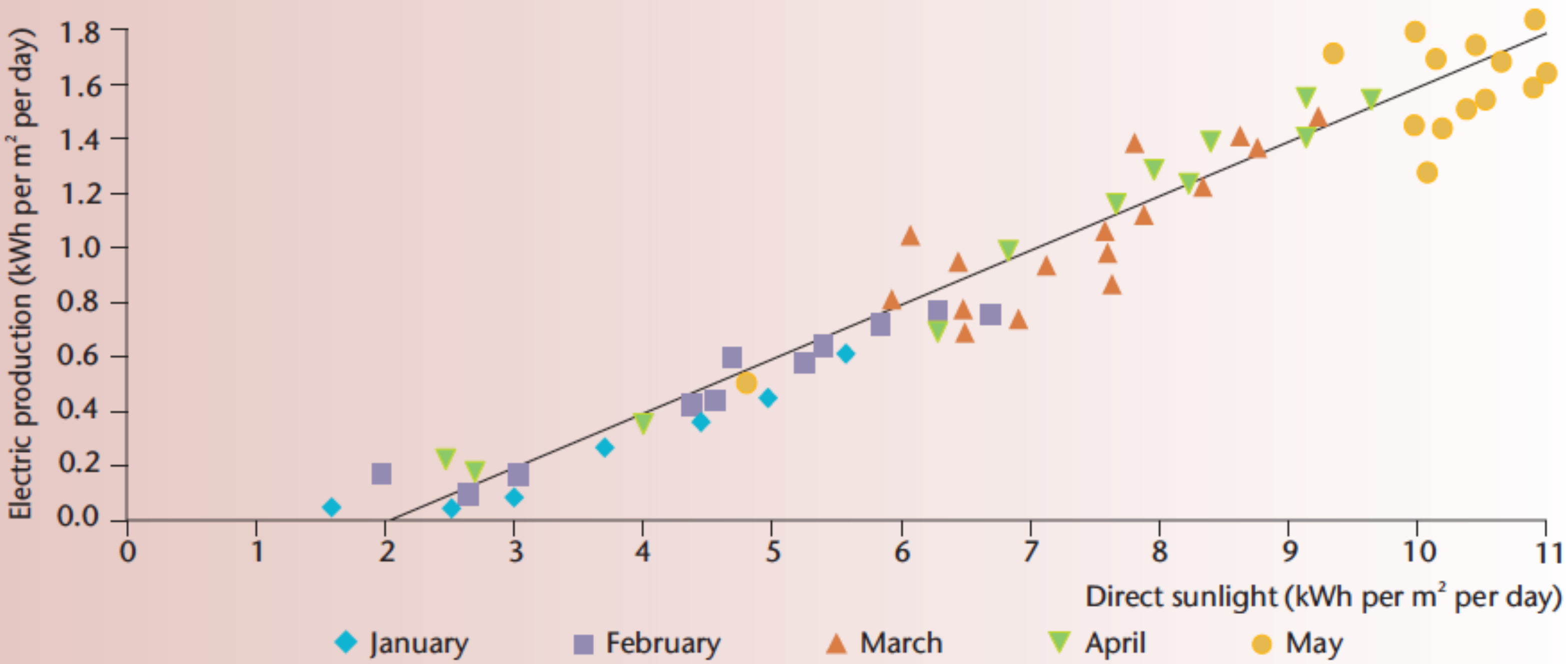
$$L_{scatt} \sim \frac{1}{n_p \pi r_0^2} \sim \frac{1}{10^8 \cdot 3 \cdot 10^{-12}} \sim \frac{10^4}{3} \sim \underline{\underline{300\,m.}}$$

<u>Implication</u>: DNI will be reduced by scattering
DHI " " increased " "

$$DNI \sim I_0 \exp\left(-d/L_{scatt}\right) ; \; d \sim \text{effective thickness of aerosol layer}$$

Require adequate DNI for CSP

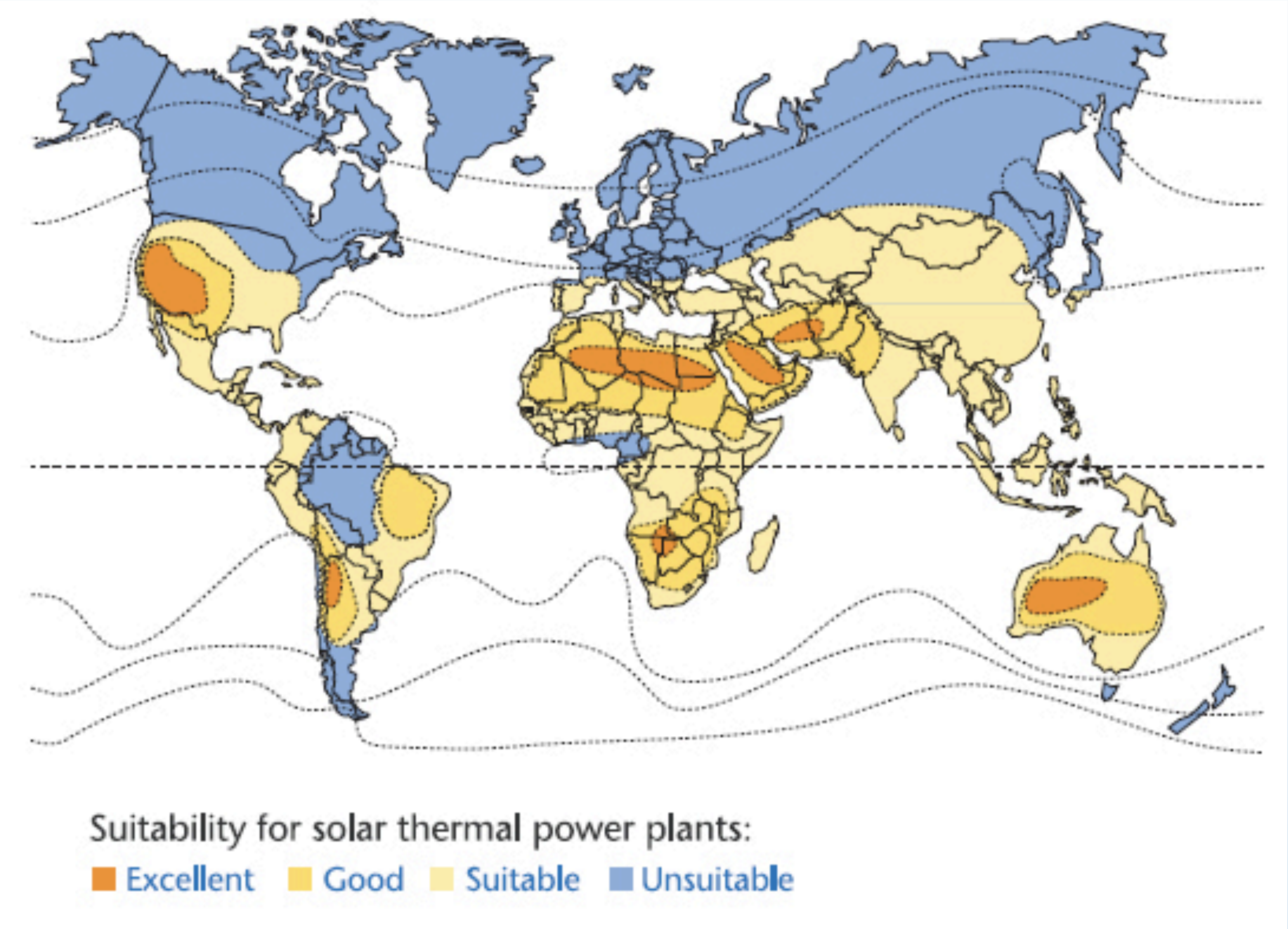
Figure 2: Output of an early CSP plant in California as a function of daily DNI



Source: Pharabod, F. and C. Philibert (1992), *Luz solar power plants*, DLR for IEA-SSPS.

IEA, Solar Thermal Power Technology Roadmap, 2014

CSP Systems only use DNI
➔Only some regions are suitable



Q: Where are the good sites? Where are the demand centers?

Sample Locations in the CONUS

Merced, California

Latitude: 37.36

Longitude: -120.43

Altitude: 65m

San Diego, California

Latitude: 32.88

Longitude: -117.23

Altitude: 104m

Las Cruces, New Mexico

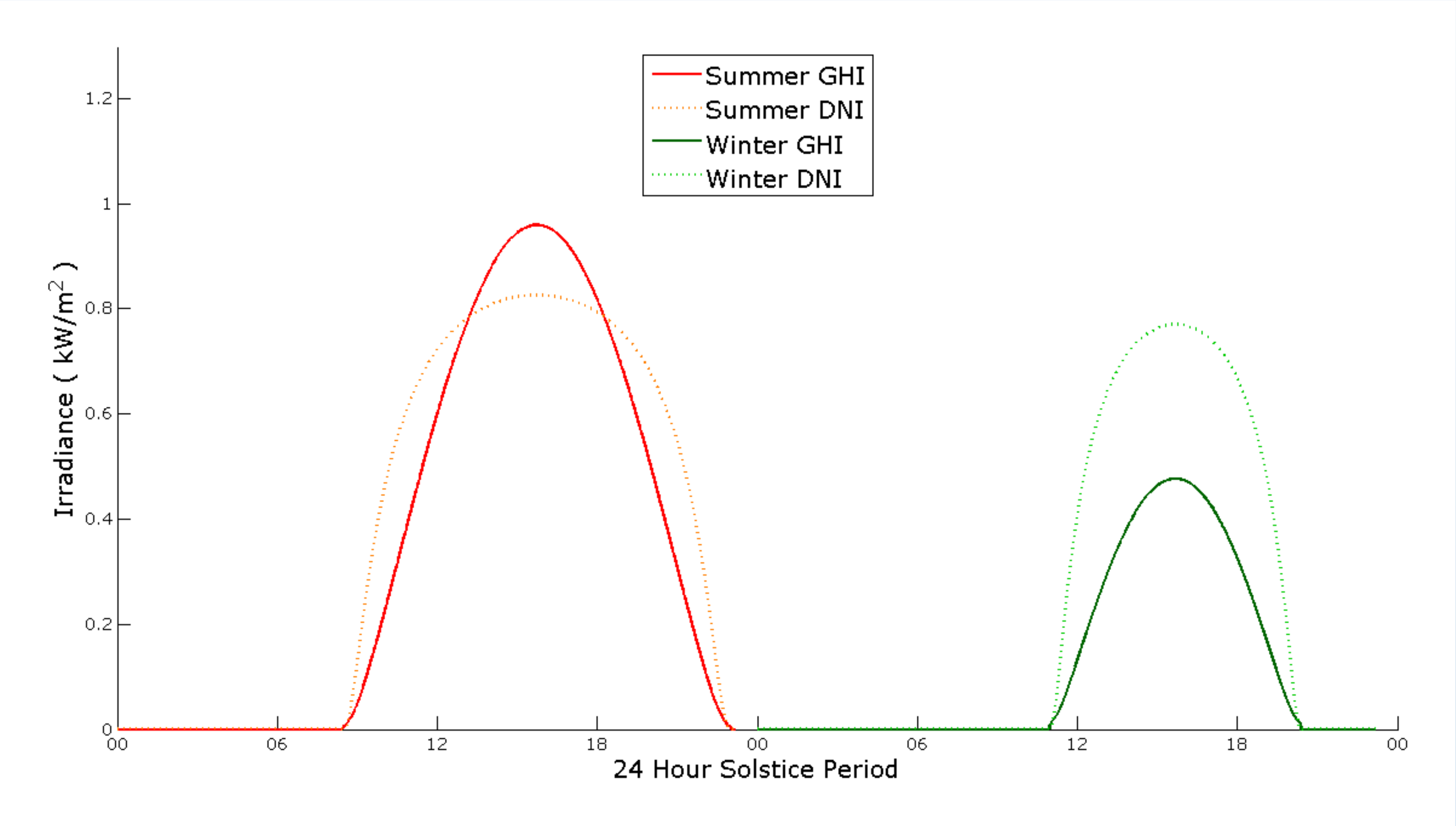
Latitude: 32.32

Longitude: -106.77

Altitude: 1219m

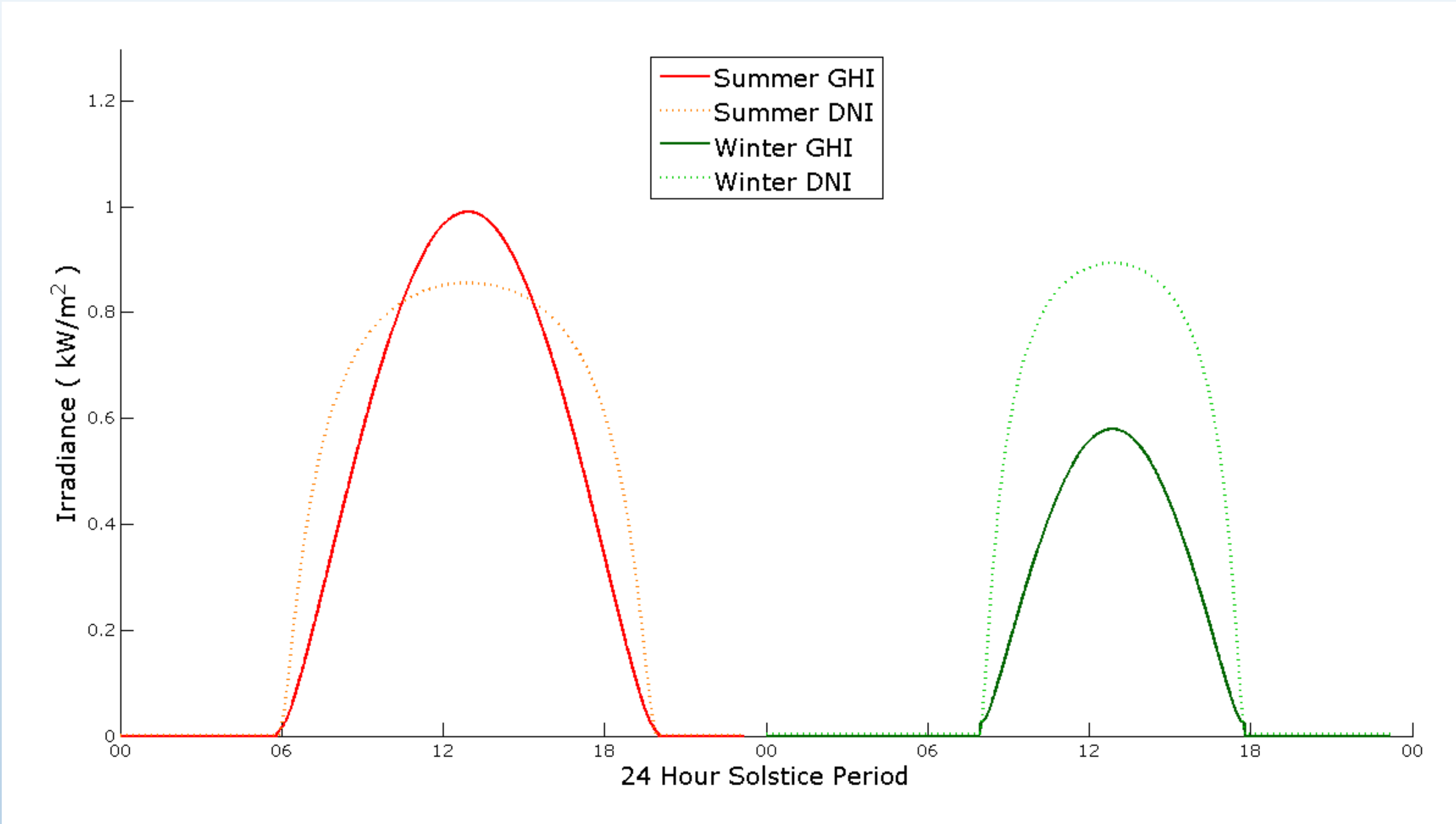
Merced

Summer GHI Maximum	Winter GHI Maximum
0.8262	0.7702



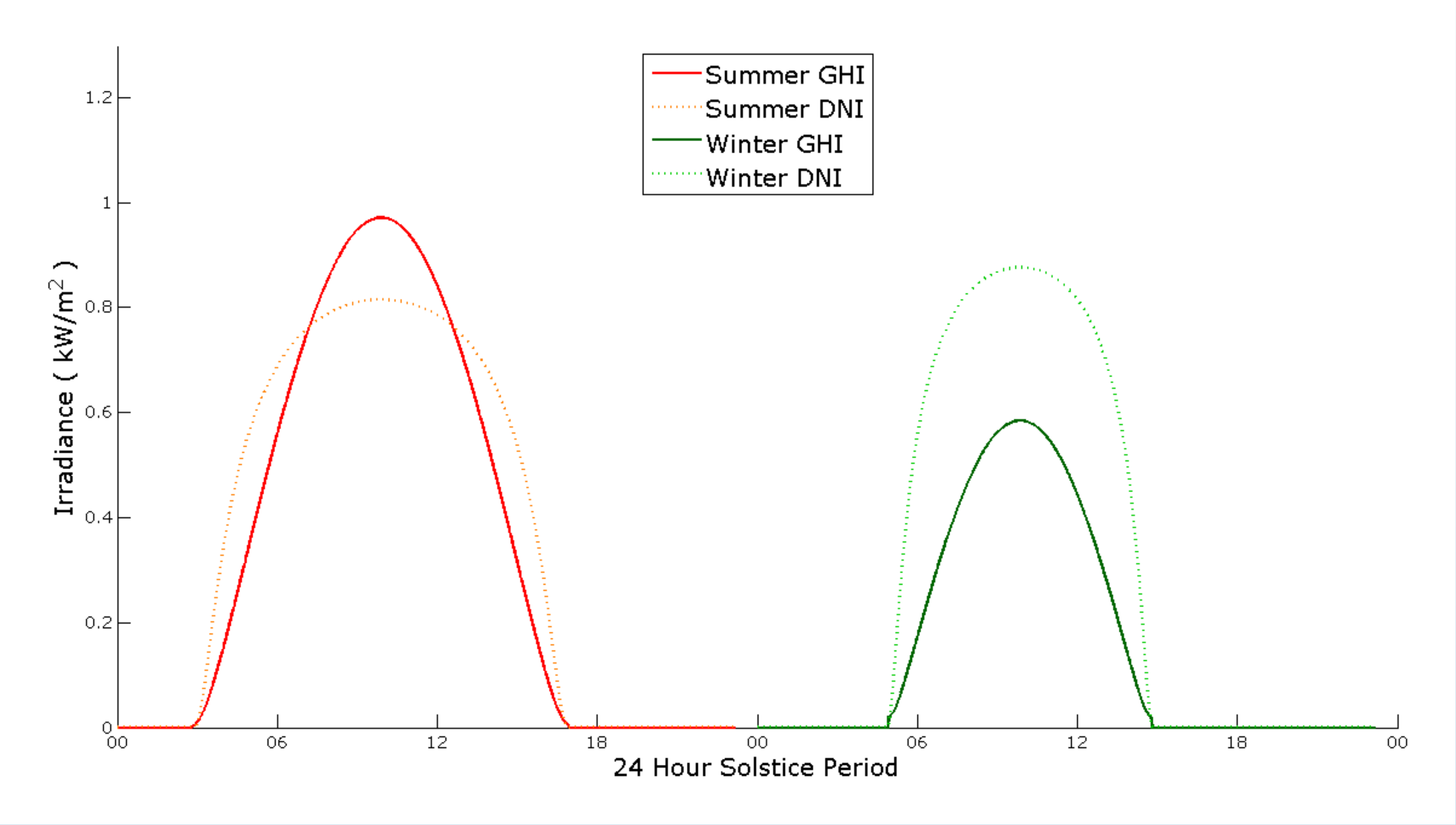
San Diego

Summer GHI Maximum	Winter GHI Maximum
0.8560	0.8936



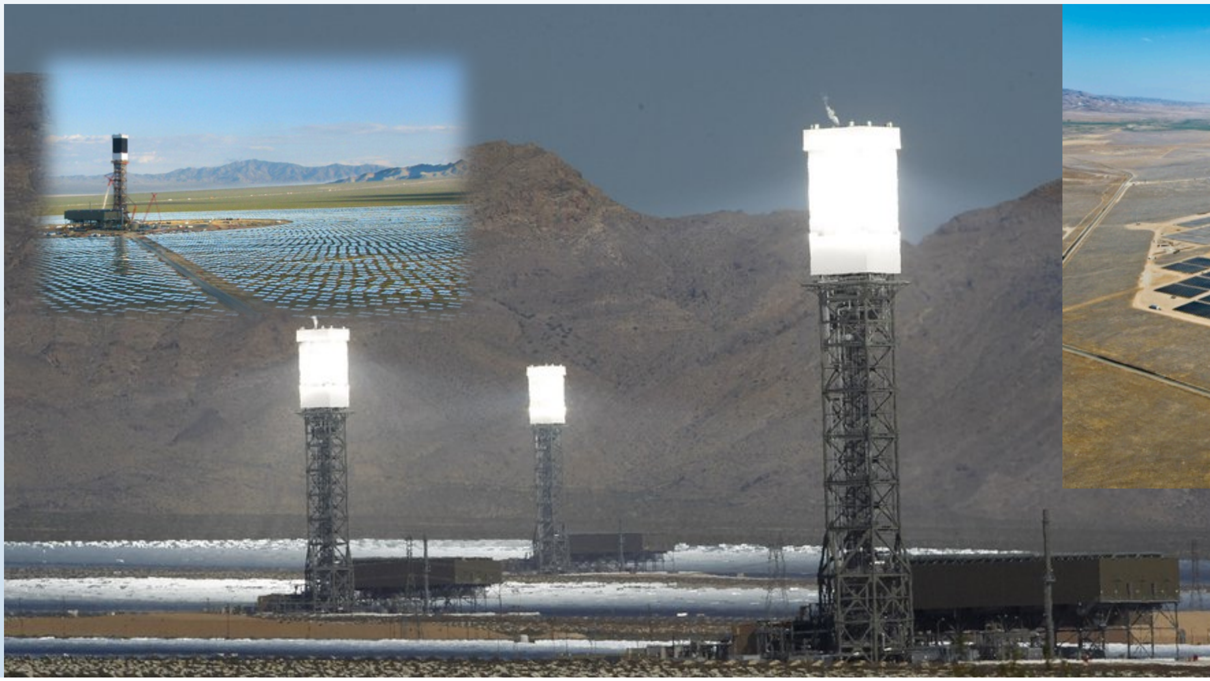
Las Cruces

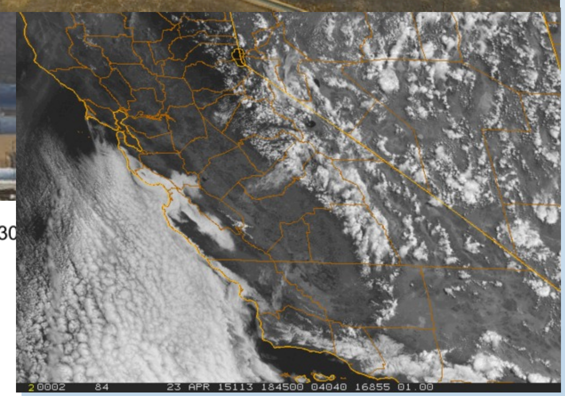
Summer GHI Maximum	Winter GHI Maximum
0.8153	0.8766

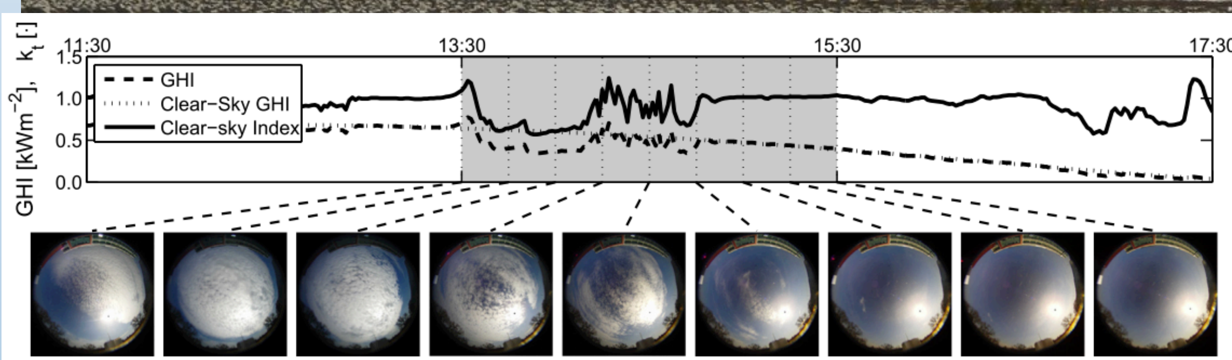


Solar and Wind Forecasting for Large Power Plants

Prof. Carlos F. M. Coimbra UCSD MAE/CER







Ivanpah Project Facts

IVANPAH AT A GLANCE

The world's largest solar thermal project

- Size: 3,600 acres
- Power Production: 370 MW (nominal)
- Homes Served Annually: 140,000
- Customers: PG&E and SCE
- Owners: NRG, Google, BrightSource
- DOE Loan Guarantee: $1.6B
- Project Financing: $2.2B

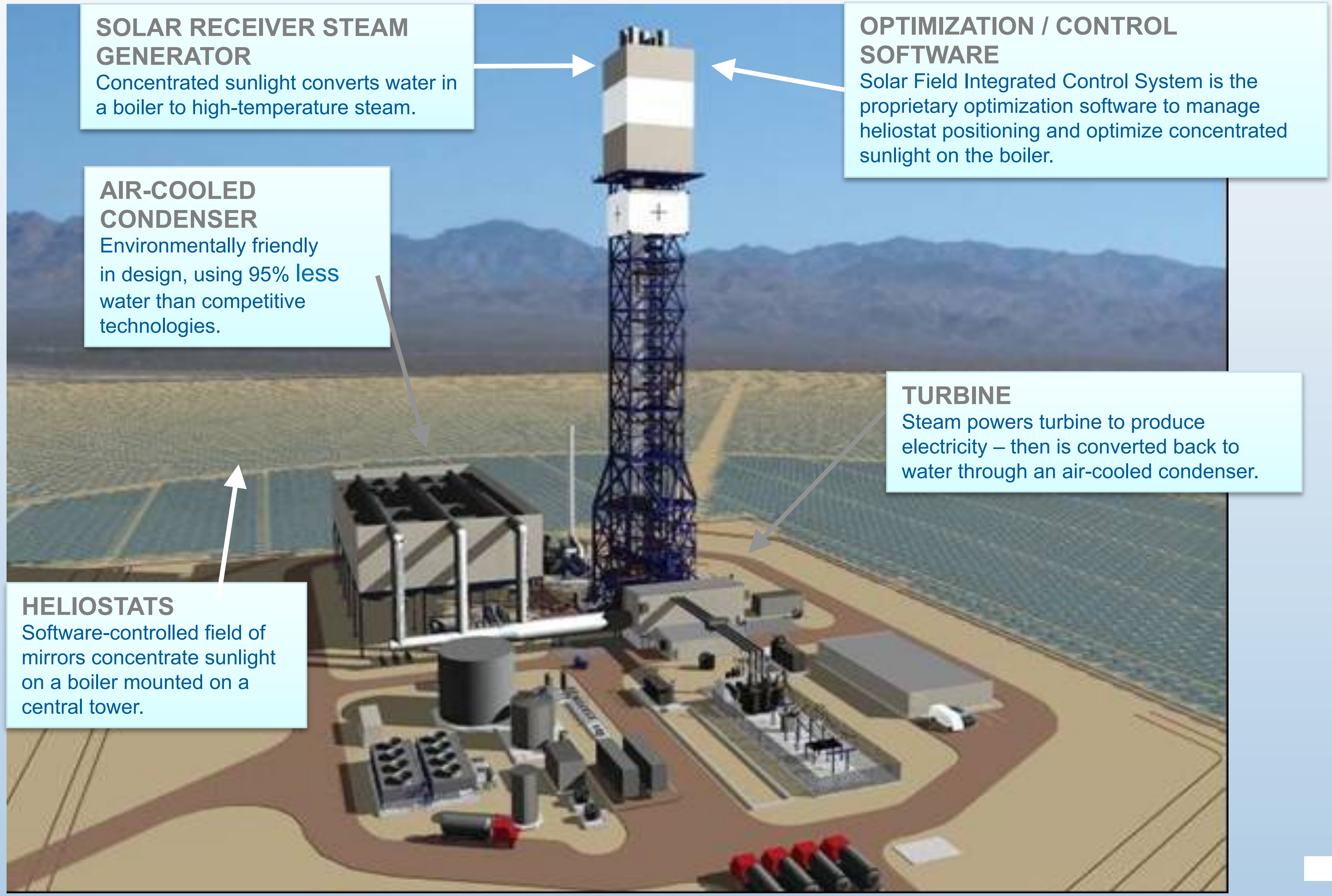
- Construction Commenced: Oct 2010
- Construction Status: **100%**
- Construction workers: 2,000

Connected to Power Grid Since 2014

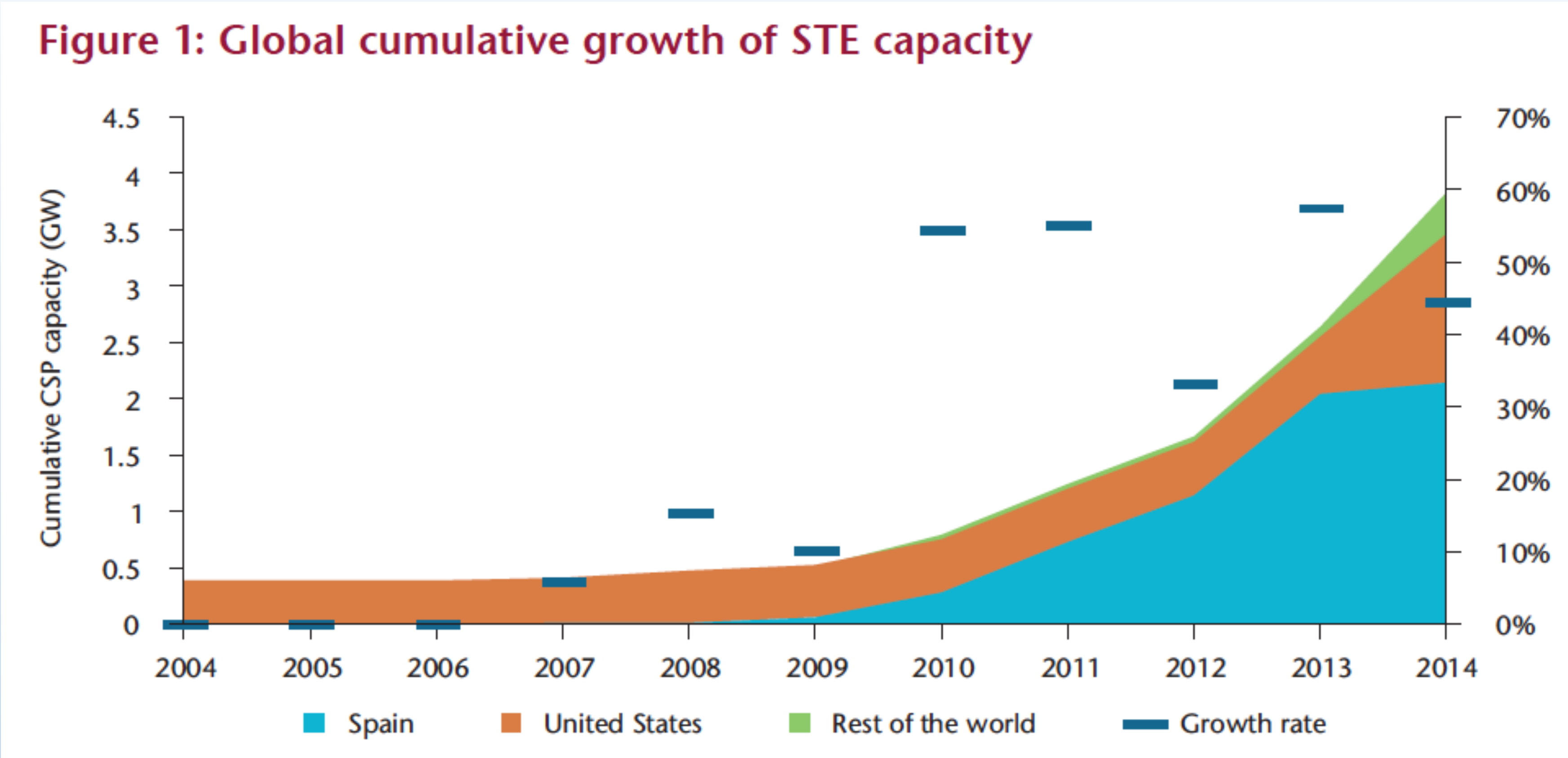
Utility Scale Central Plants

Ivanpah Solar Energy Generation Systems, 392 MW

Concentrated Solar Towers

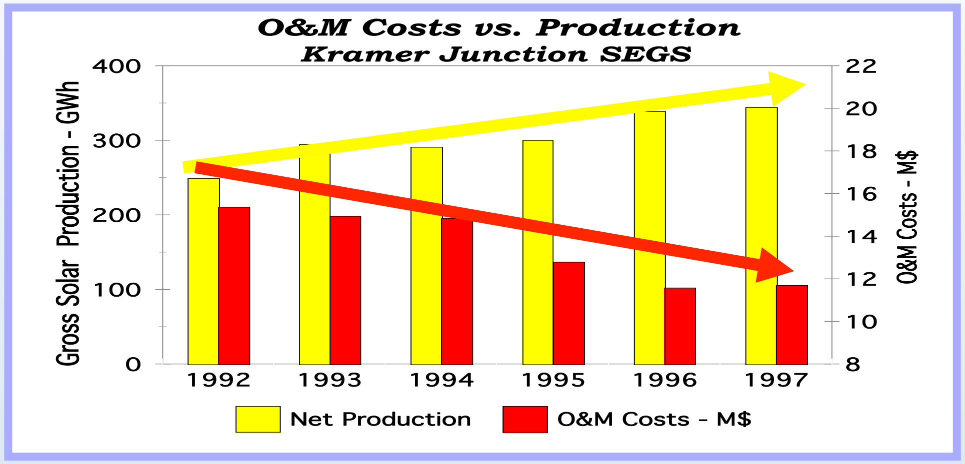


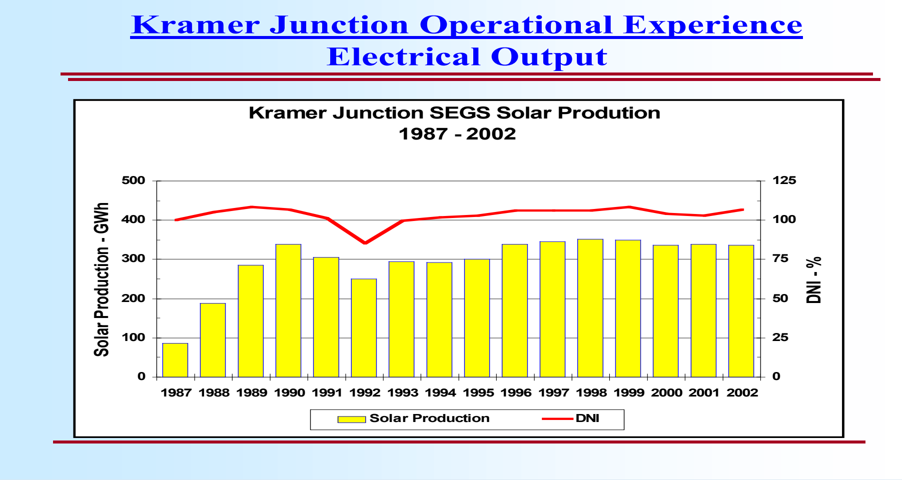
Evolution of Installed Base - CSP



IEA, Solar Thermal Power Technology Roadmap, 2014

SEGS Plant Experience (KJ)



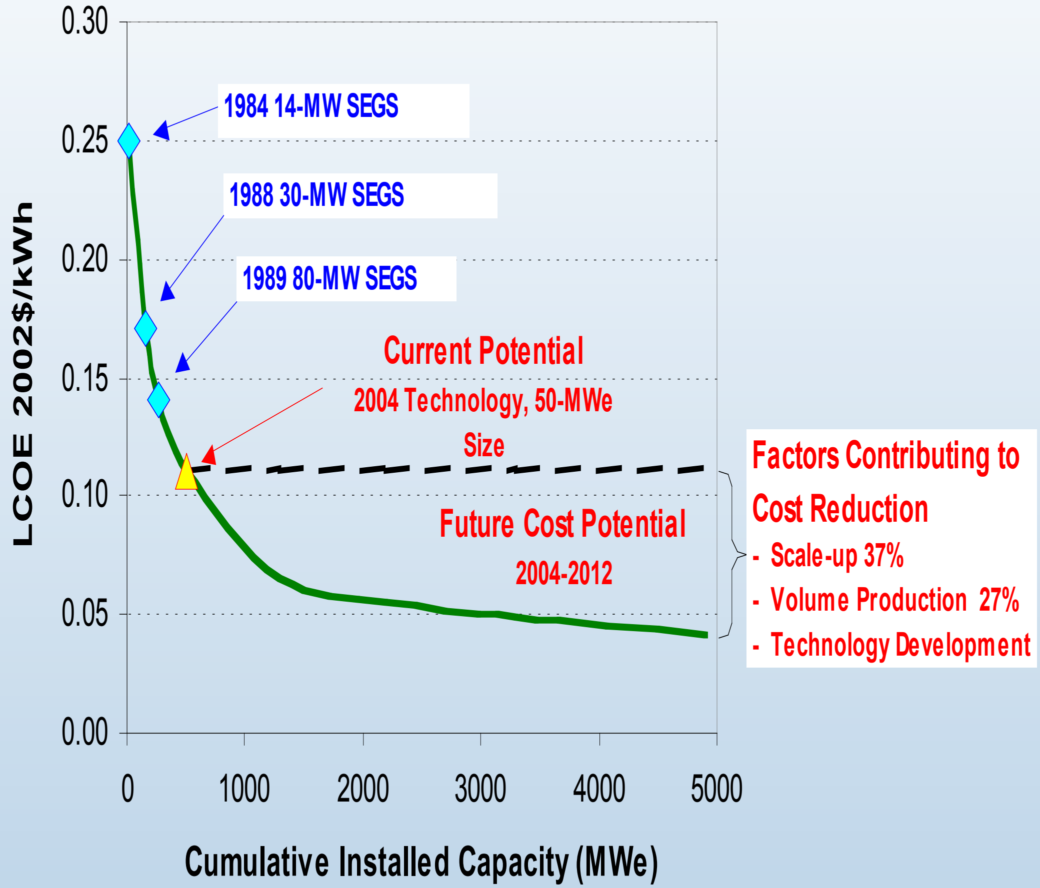


- O&M costs have dropped sharply over time, coincident with performance gains.
- These plants, placed in operation from 1987 through 1989, set many performance records in the 1990s.
- Using 25% energy input from natural gas via a supplemental boiler, capacity factors during SCE on-peak operation have exceeded100% for more than a decade (with >85% from solar operation).

Sargent & Lundy Cost Analysis

Cost reductions from

- **Plant Scale Up**
- **Technology Development**
- **Volume Production**



* Sargent and Lundy (2003). Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Impacts. http://www.nrel.gov/docs/fy04osti/34440.pdf

Solar Thermal Power System Plans

- ·Mojave Solar Park, USA California, 553MW, parabolic trough design[2]
- ·Pisgah, USA California near Pisgah north of I-40, 500MW, dish design[3]
- ·Ivanpah Solar, USA California, 400MW, power tower design[4]
- ·Unnamed, USA Florida, 300MW, Fresnel reflector design[5]
- ·Imperial Valley, USA California, 300MW, dish design[6]
- ·Solana, USA Arizona southwest of Phoenix, 280MW, parabolic trough design[7]
- ·Negev Desert, Israel, 250MW, design will be known after tender[8]
- ·Carrizo Energy Solar Farm, USA California near San Luis Obispo, 177MW, Fresnel reflector design[9]·
- Uppington, South Africa, 100MW, power tower design[10]
- ·Shams, Abu Dhabi Madinat Zayad, 100MW, parabolic through design[11]
- ·Yazd Plant, Iran, 67MW steam input for hybrid gas plant, technology unknown.[12]
- ·Barstow, USA California, 59MW with heat storage and back-up, parabolic trough design[13]
- ·Victorville 2 Hybrid Power Project, 50MW steam input for hybrid gas plant, parabolic trough design[14]
- ·Kuraymat Plant, Egypt, 40MW steam input for a gas powered plant, parabolic trough design[15][16]
- ·Beni Mathar Plant, Morocco, 30MW steam input for a gas powered plant, technology unknown[17]
- ·Hassi R'mel, Algeria, 25MW steam input for gas powered plant, parabolic trough design[18]
- ·Cloncurry solar power station, Australia, 10MW with heat storage, power tower design[19]

Source: http://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations#Operational

Solar Thermal Power Technology

Achievements and Status

- 350 MW of parabolic trough plants built around 1990 still operating well
- Several power tower demonstration plants have established technology viability.
- Several dish systems have also operated successfully
- Engineering cost analyses indicate 5 cents/kWh achievable

Likely Advances

- There are major opportunities for technology advances, in
  - Collectors
  - Power conversion
  - Thermal storage
- Several new systems will be built within 5 years
- Their success should catalyze manufacturing advances, commercialization