Solar Thermal Technology
for
Climate Change Mitigation

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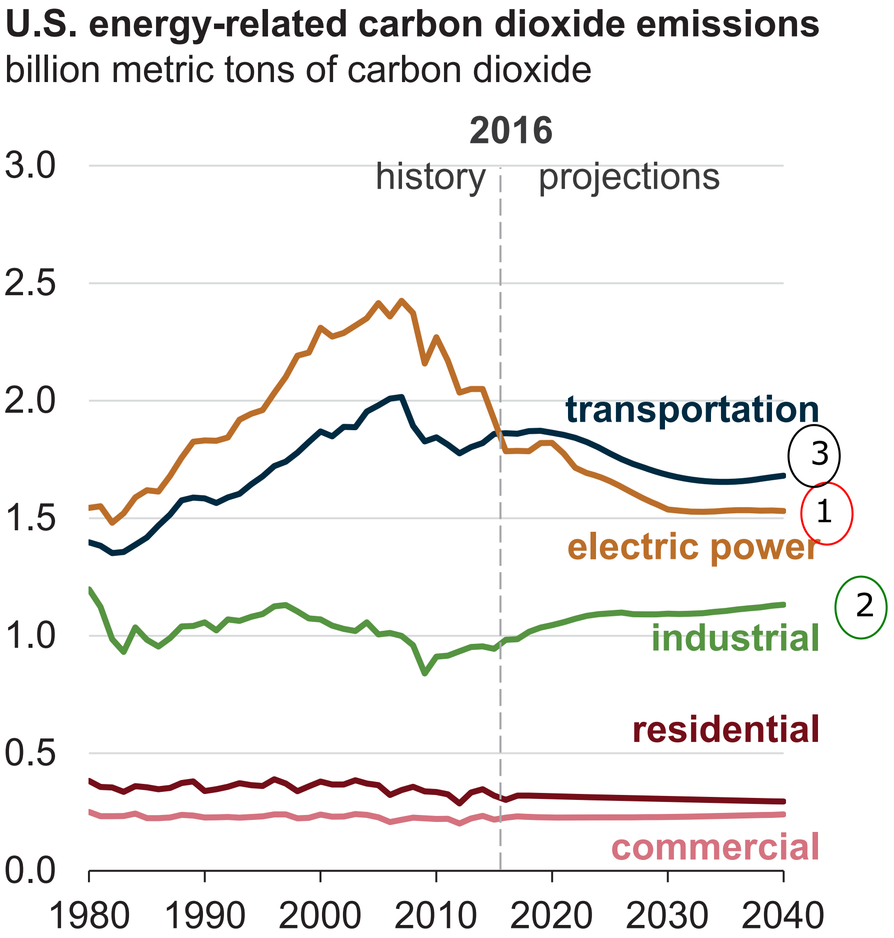
**Don Fuqua Eminent Scholar Chair Professor Emeritus*

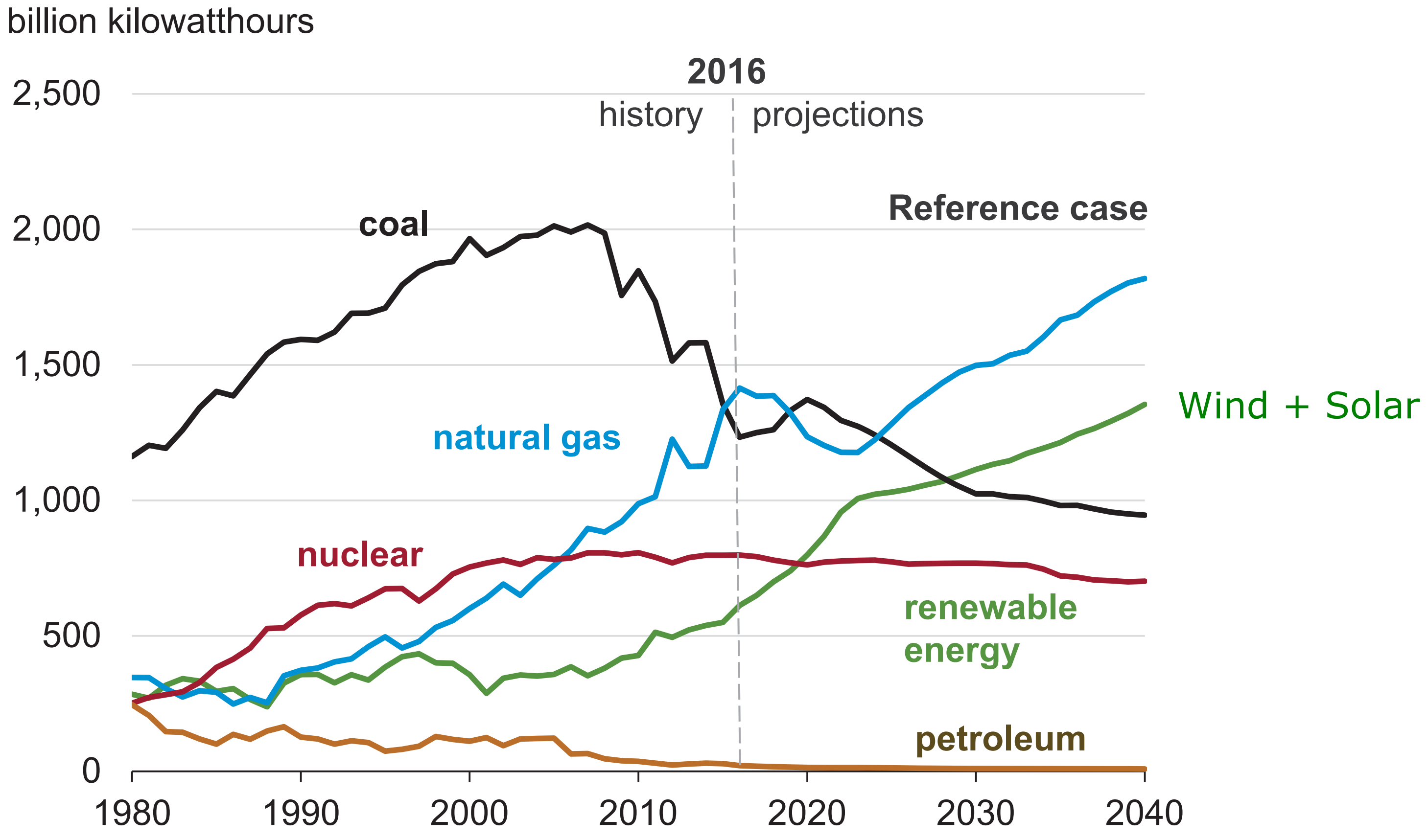
CO_2 Emissions



Can Solar Thermal Technologies play a role in Climate Change Mitigation!

Source: EIA

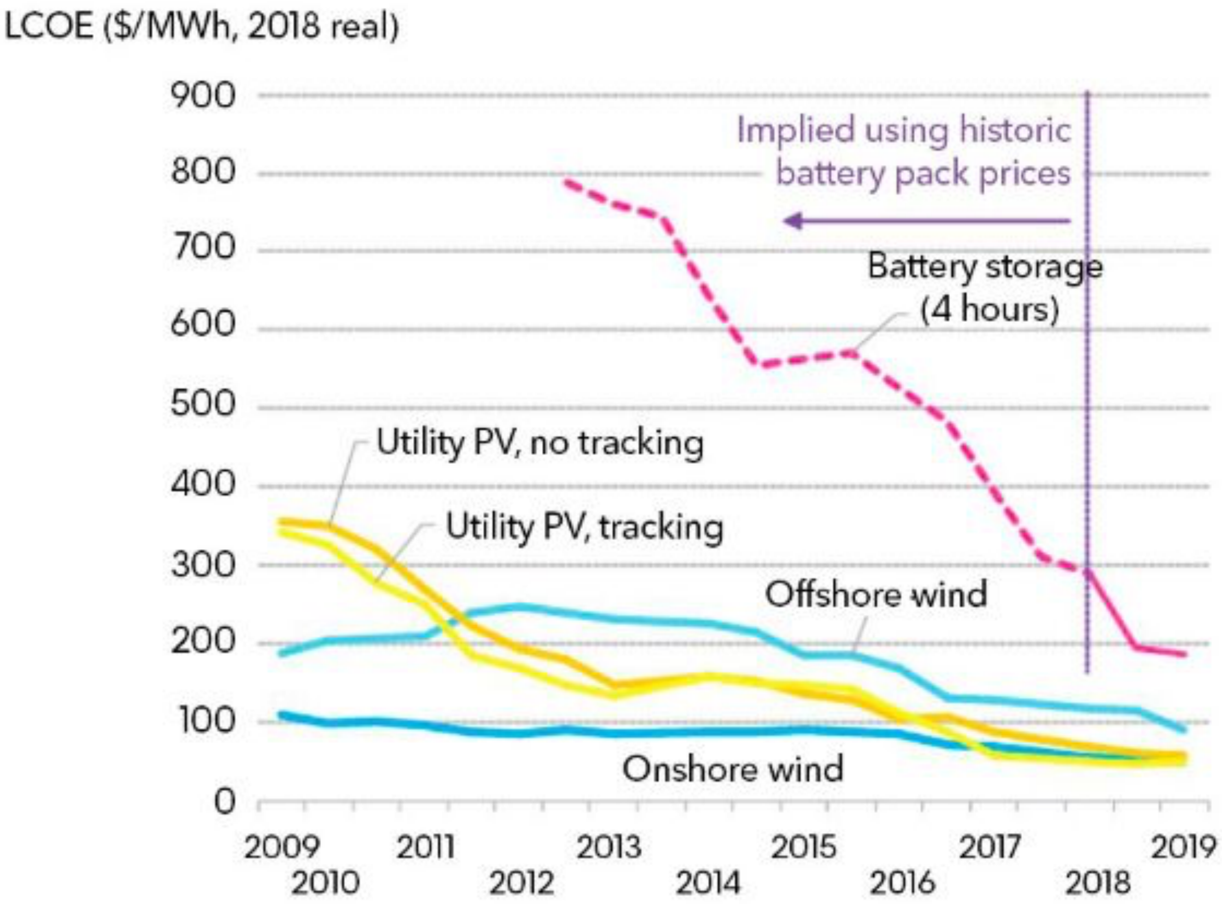
US Net Electricity Production



Source: EIA

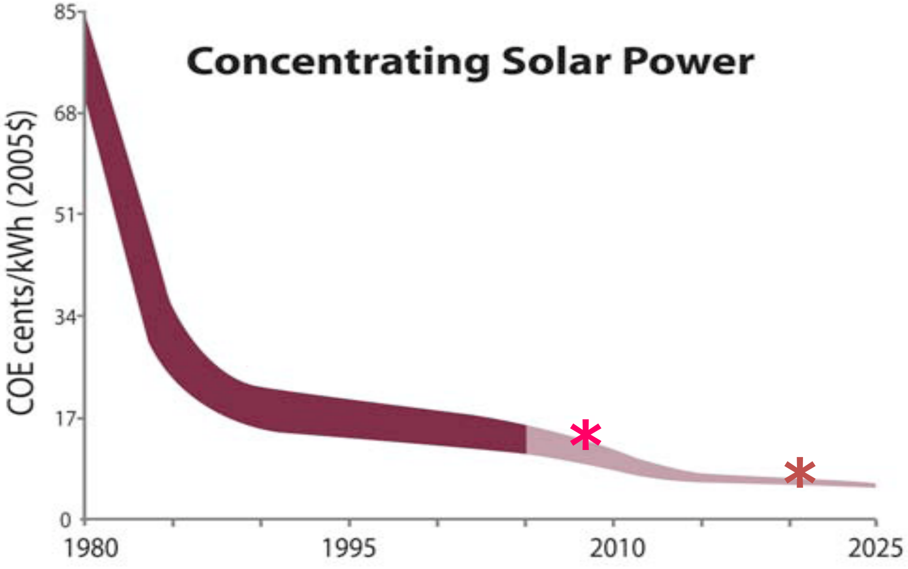
Battery Storage - Load Leveling, Peak Shaving

Renewable Electricity Cost



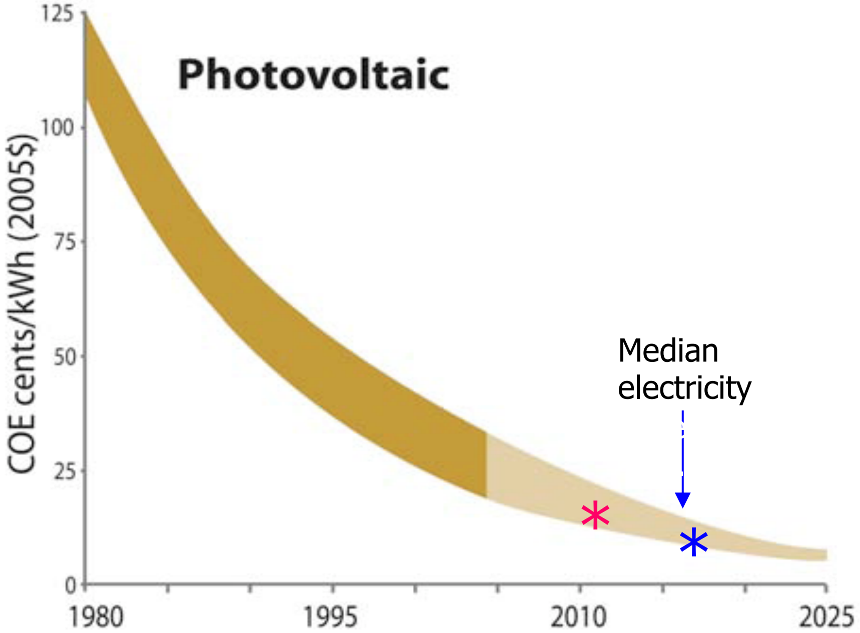
Source: BloombergNEF. Note: The global benmark is a country weighed-average using the latest annual capacity additions. The storage LCOE is reflective of a utility-scale Li-ion battery storage system running at a daily cycle and includes charging costs assumed to be 60% of whole sale base power price in each country.

Solar Electricity Costs

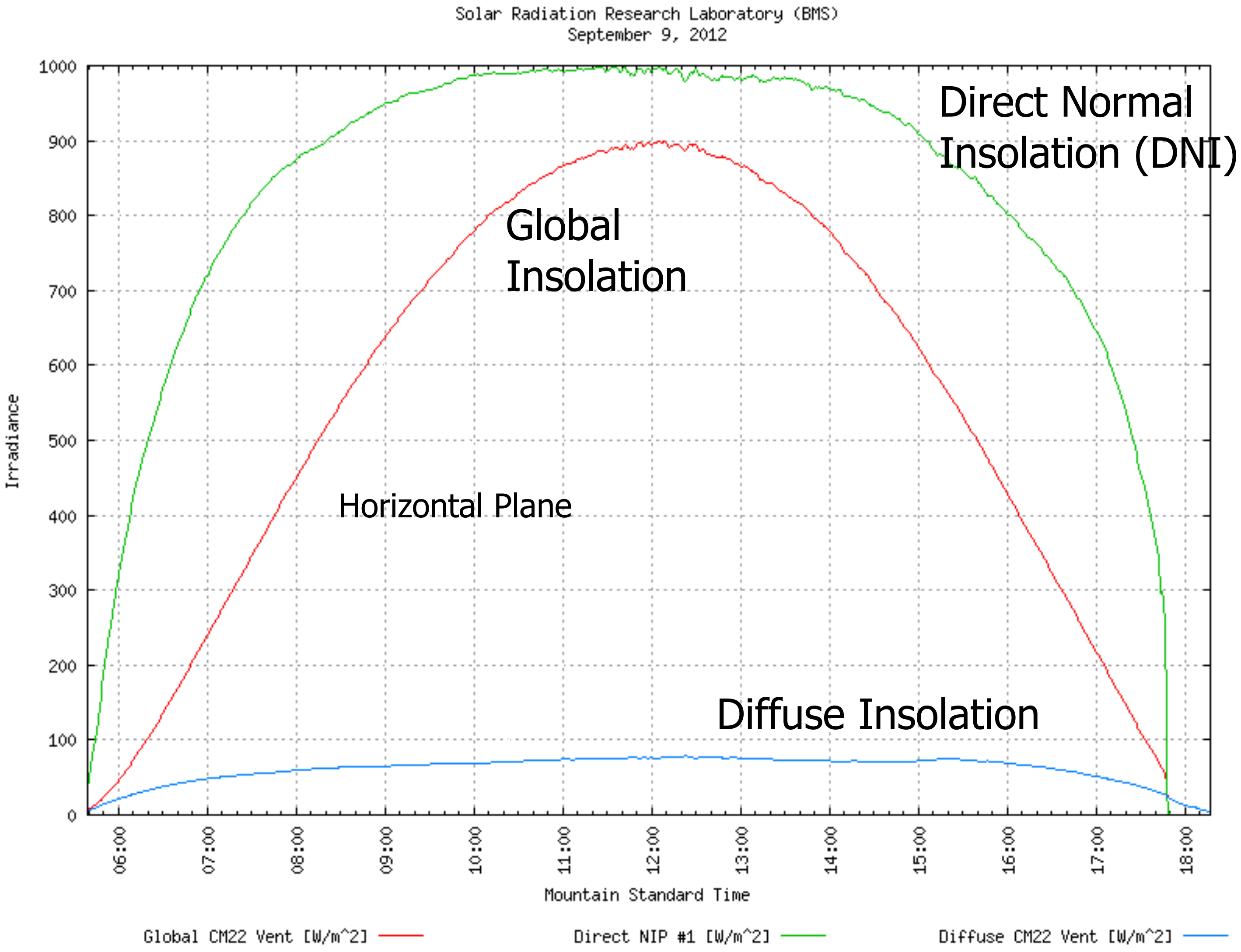


Typical Cost per kWh: $0.07 – 0.12

Typical Cost per kWh: $0.07



Solar Irradiance on Earth



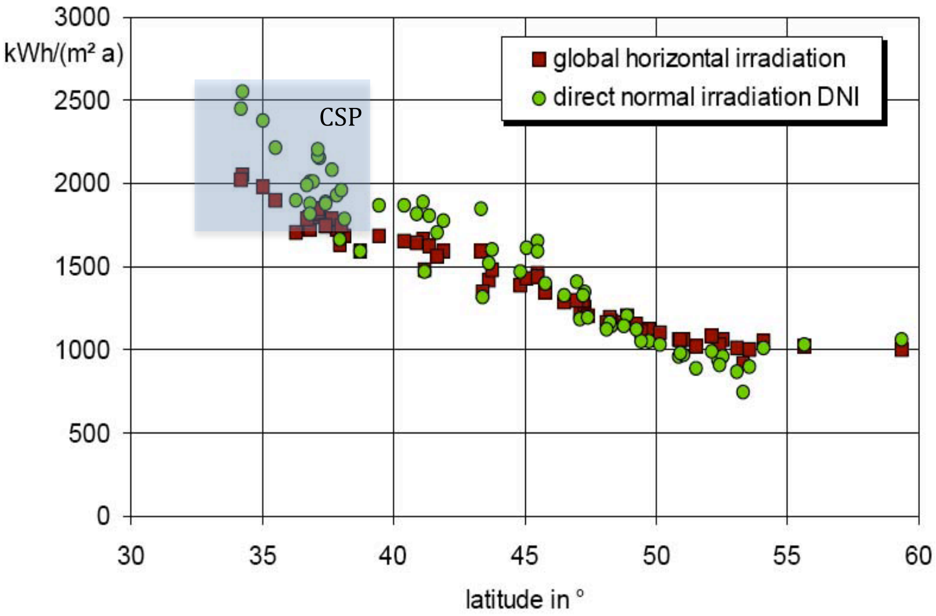
Direct Normal Insolation (DNI)

Global Insolation

Horizontal Plane

Diffuse Insolation

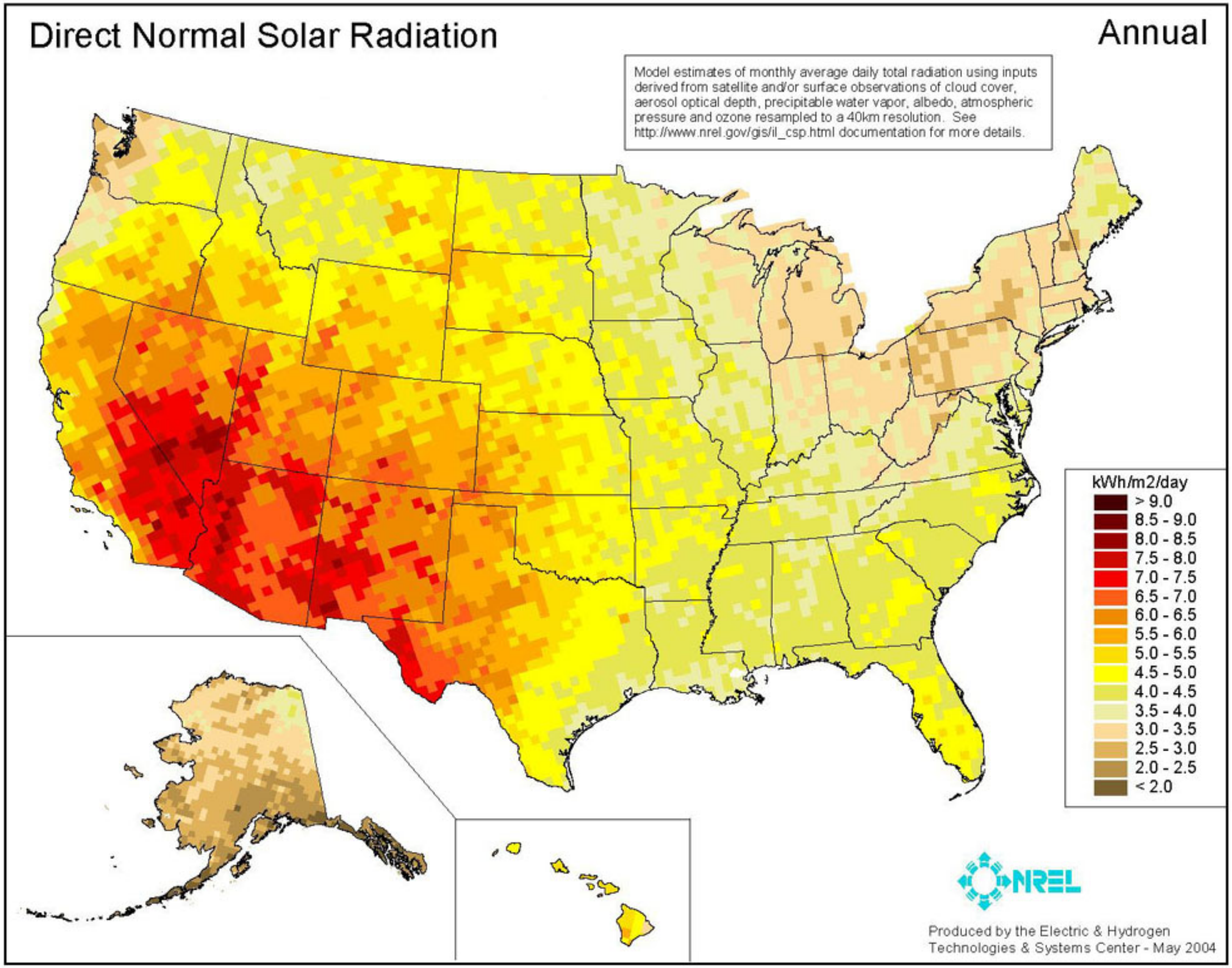
Annual DNI



Annual global irradiation in Europe and USA. (Source: Volker Quascning, DLR & Manuel Blanco Muriel, CIEMAT, Spain)

Location	**Site Latitude**	**Annual DNI (kWh/m2)**
United States		
Barstow, California	35°N	2,725
Las Vegas, Nevada	36°N	2,573
Tucson, Arizona	32°N	2,562
Alamosa, Colorado	37°N	2,491
Albuquerque, New Mexico	35°N	2,443
El Paso, Texas	32°N	2,443
International		
Northern Mexico	26-30°N	2,835
Wadi Rum, Jordan	30°N	2,500
Ouarzazate, Morocco	31°N	2,364
Crete, Greece	35°N	2,293
Jodhpur, India	26°N	2,200

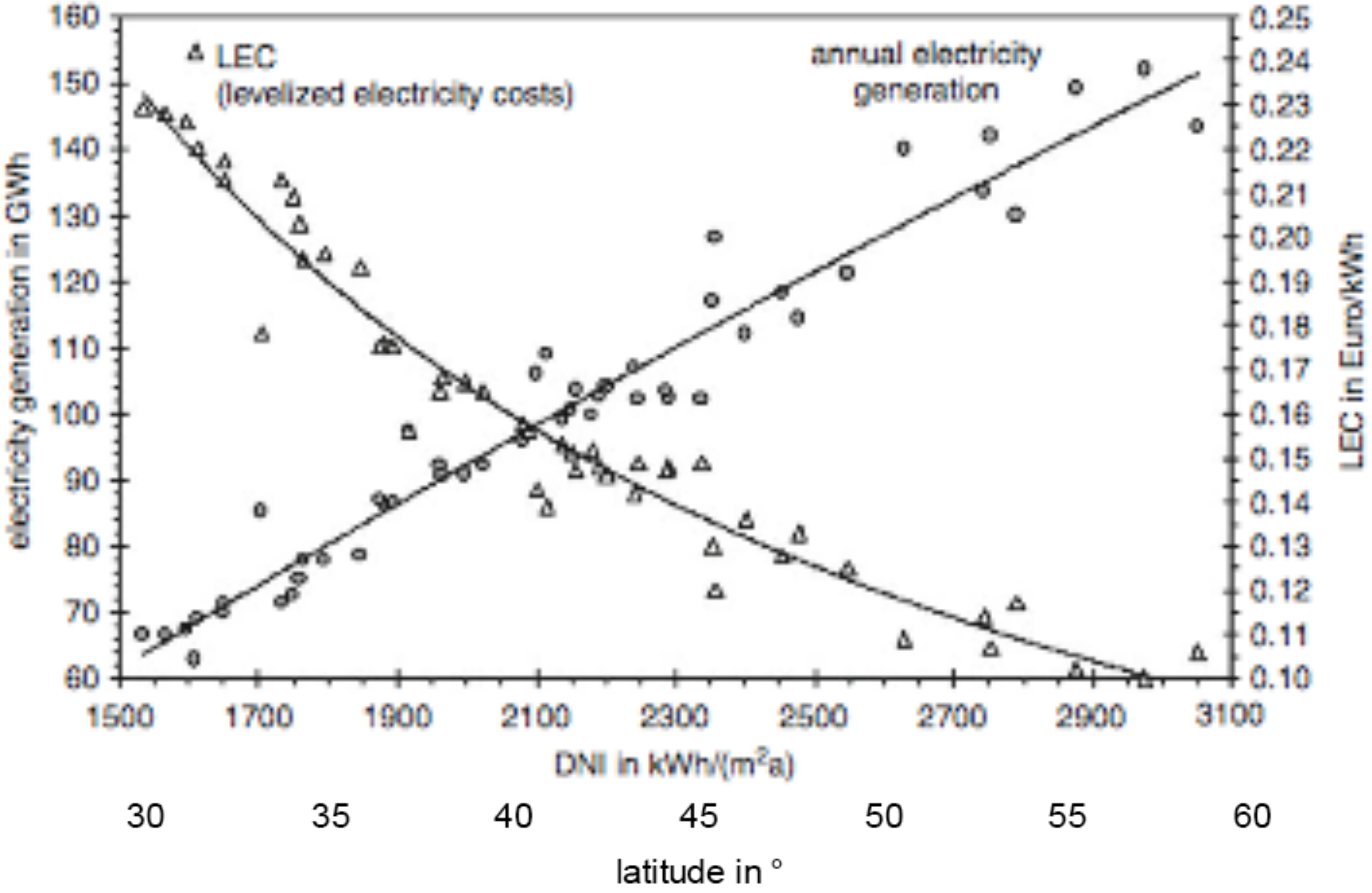
US Solar Radiation Map



Model estimates of monthly average daily total radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone resampled to a 40km resolution. See http://www.nrel.gov/gis/il_csp.html documentation for more details.

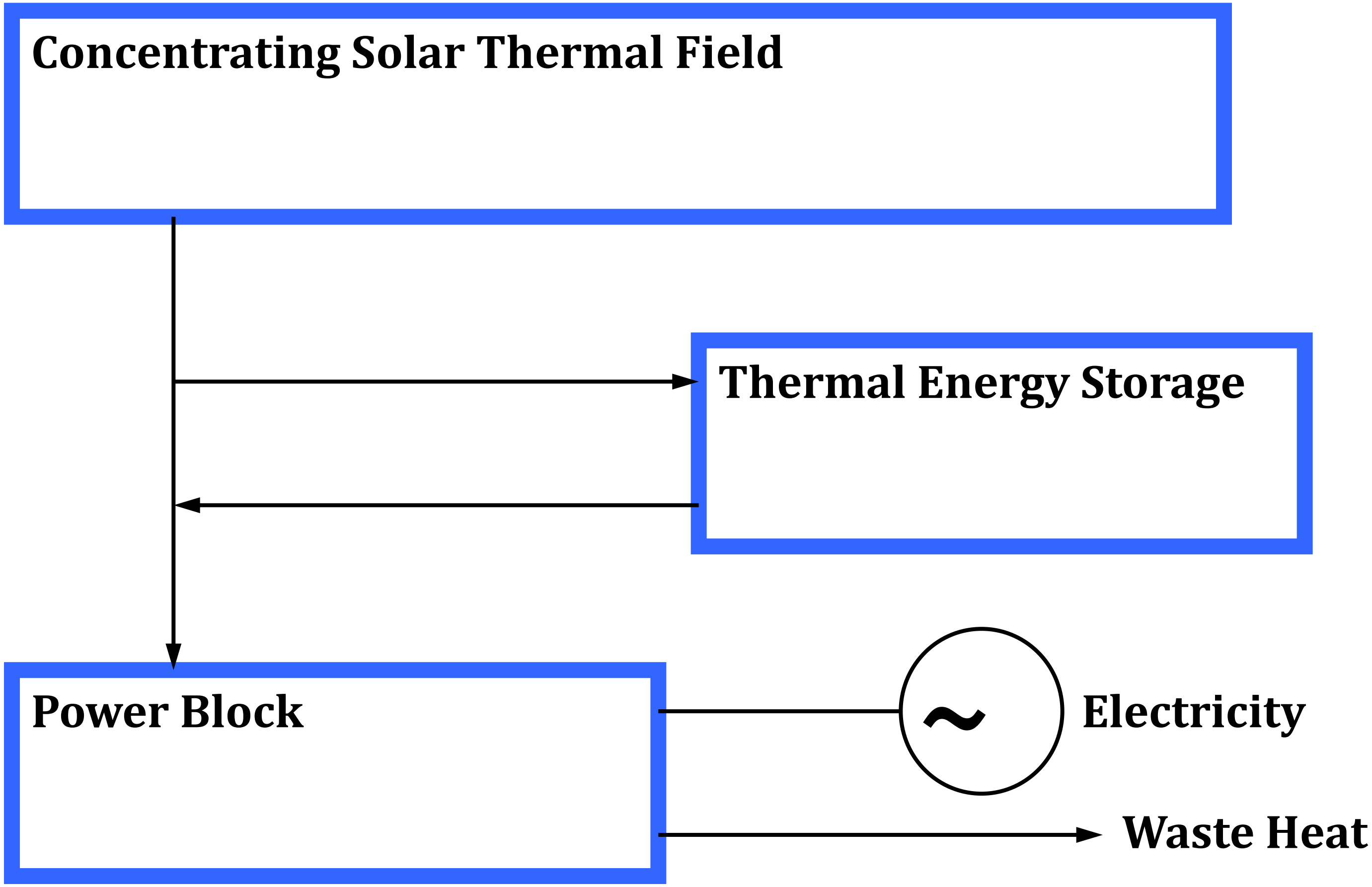
Produced by the Electric & Hydrogen Technologies & Systems Center - May 2004

DNI Effect CSP Costs



Quaschning V, Kistner R, Ortmanna W (2001) Simulation of parabolic trough power plants. Proceedings of the 5th Cologne Solar Symposium, Cologne, 46–50

CSP System



Concentrating Solar Thermal Field

Thermal Energy Storage

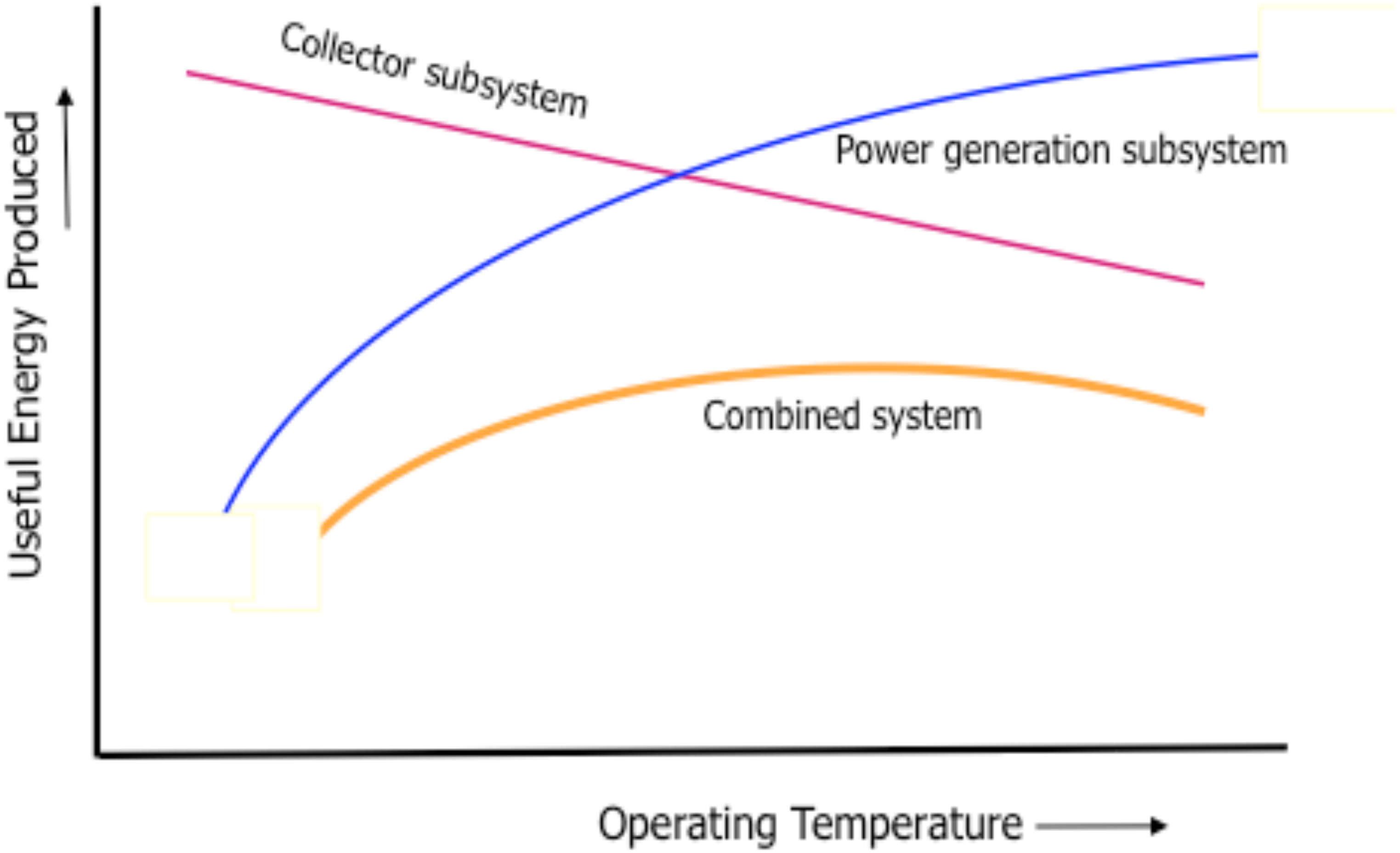
Power Block

~

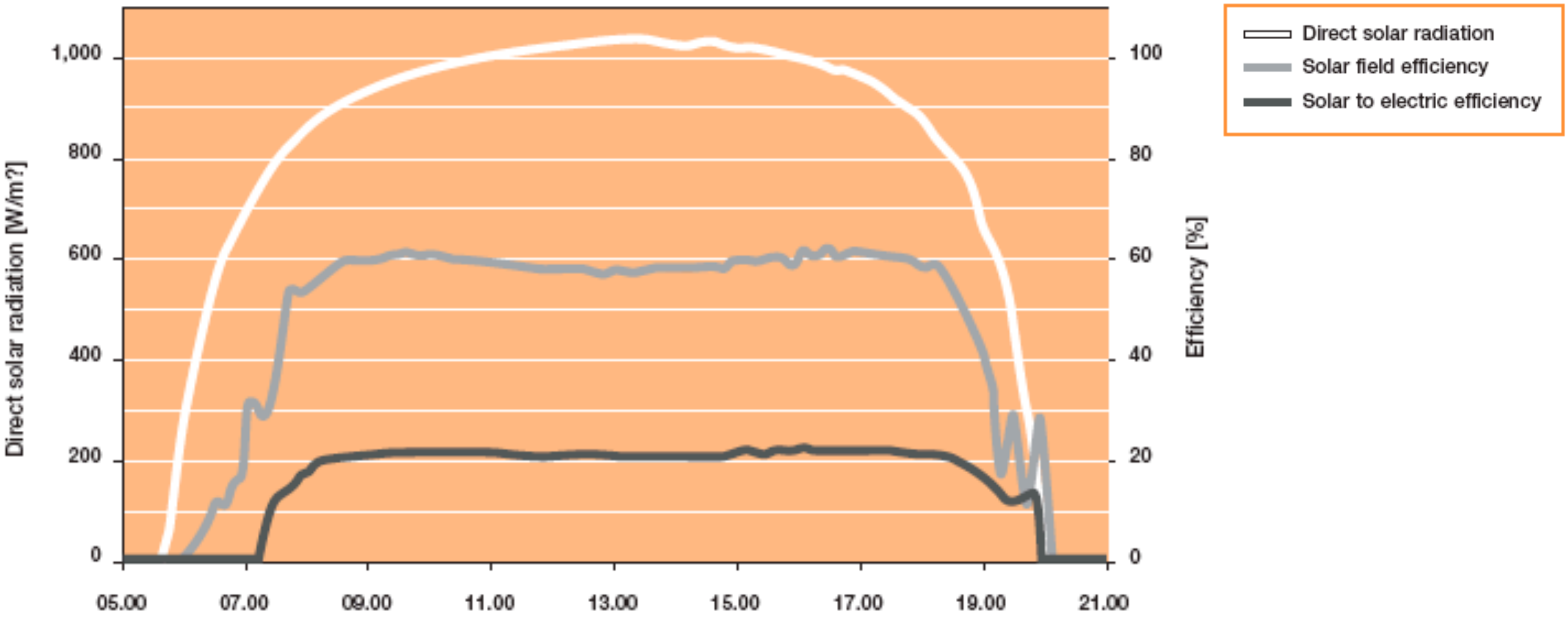
Electricity

Waste Heat

System Efficiency



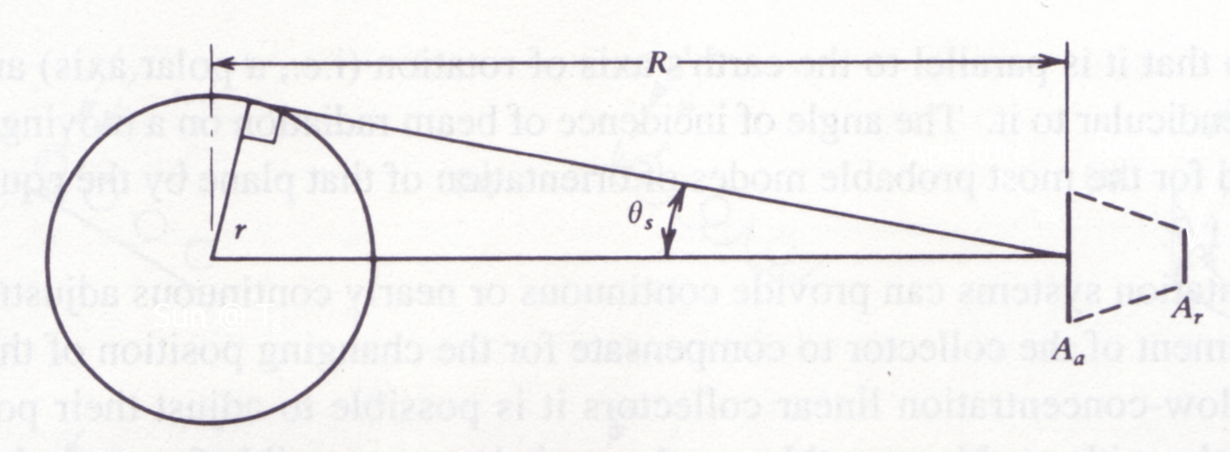
Daily Summer Output Pattern at the SEGS IV Plant in Kramer Junction, CA



Concentration Ratio

Area concentration ratio (geometric):

$$C = \frac{A_a}{A_r}$$



Optical concentration ratio:

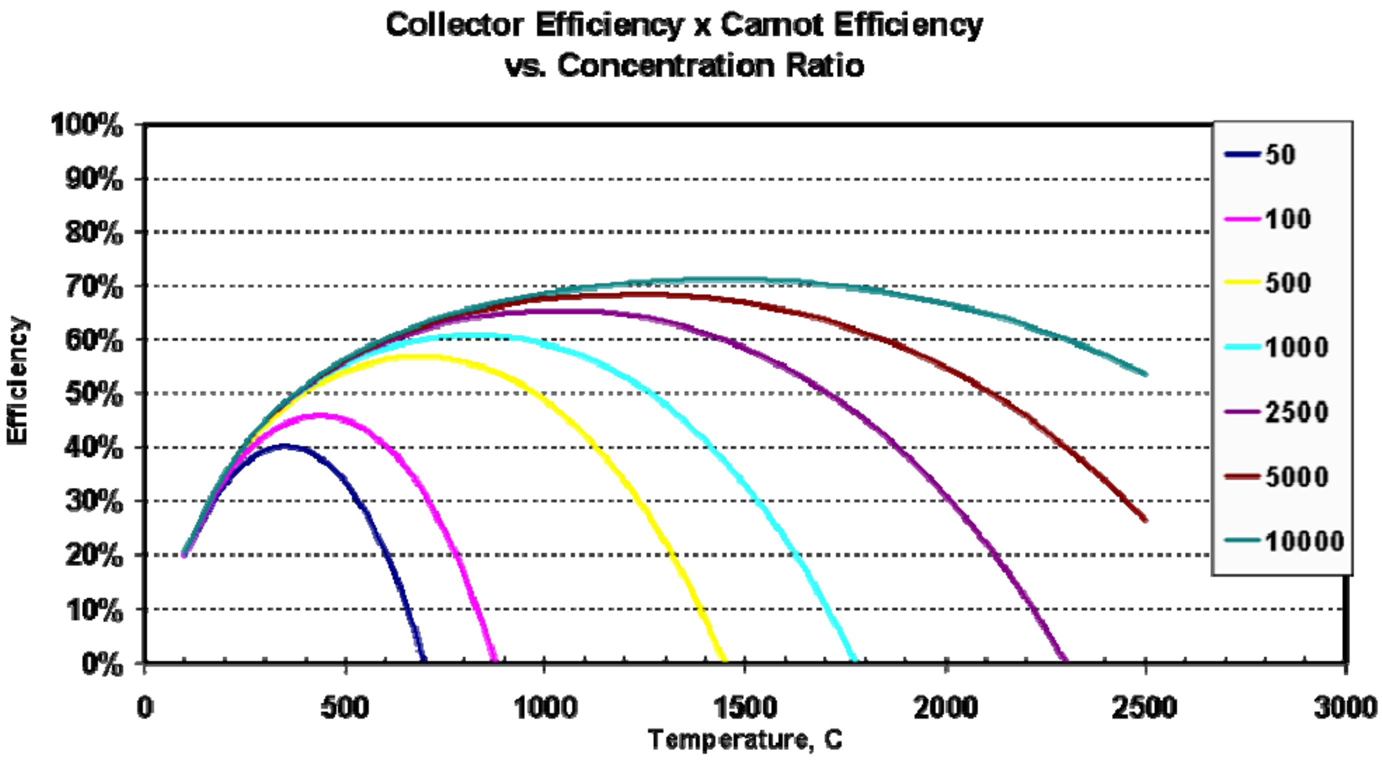
$$C_O = \frac{\frac{1}{A_r}\int I_r dA_r}{I_a}$$

I_r is the averaged irradiance
I_a is the insolation incident on the collector aperture

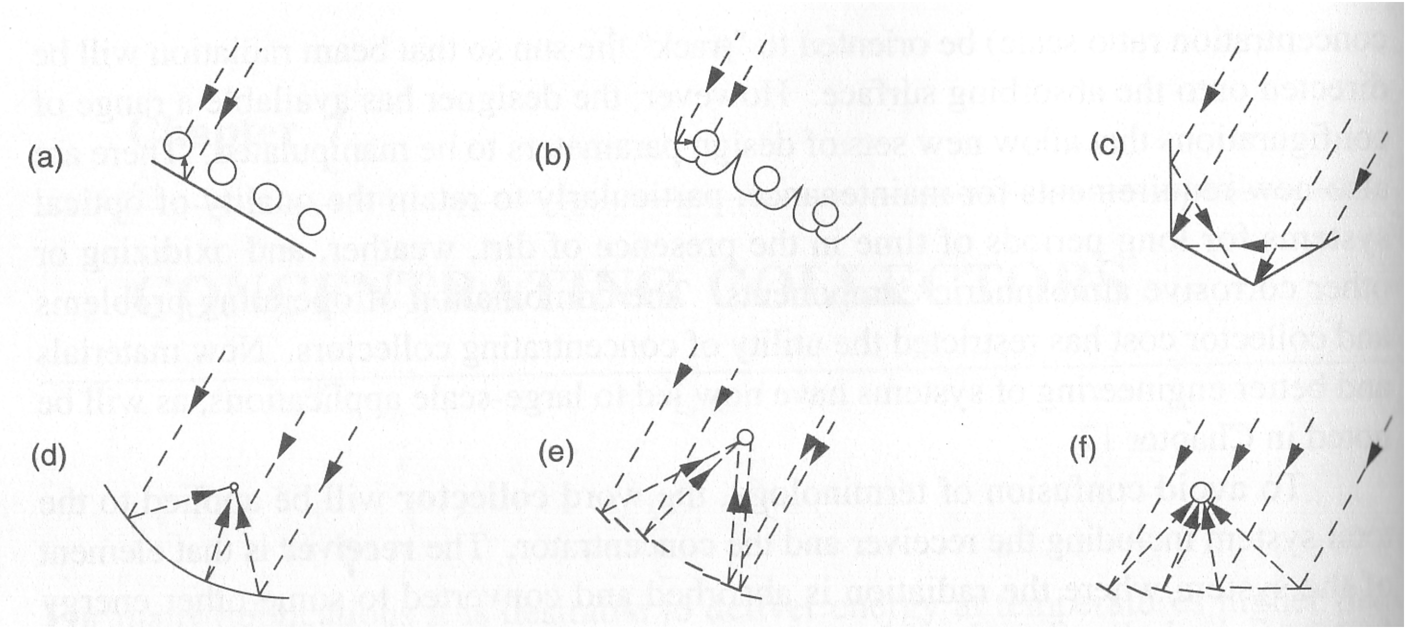
Duffie JA, Beckman WA (2006) Solar engineering of thermal processes, 3rd edn. Wiley, New York

System Efficiency

$$\eta_{system} = \eta_{collector} * \eta_{process}$$



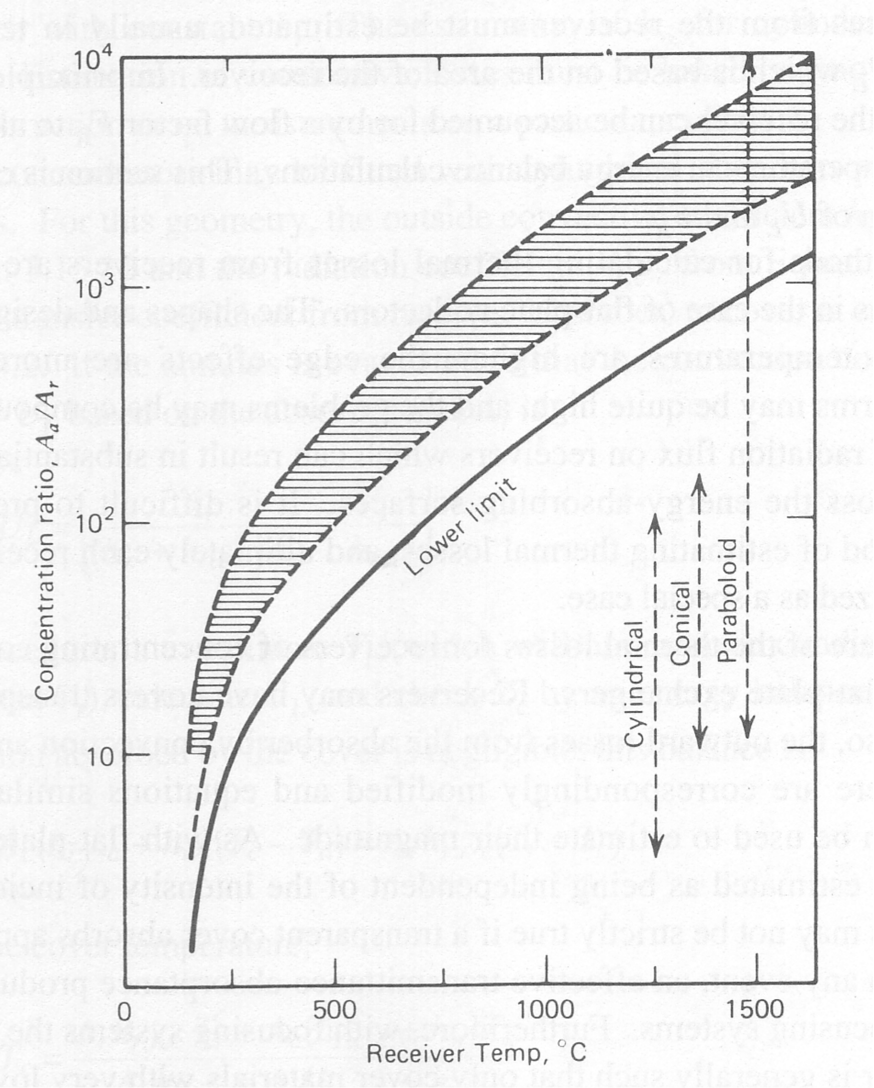
Collector Configurations



a) Tubular absorbers with diffusive back reflector; b) Tubular absorbers with specular cusp reflector; c) Plane receiver with plane reflector; d) parabolic concentrator; e) Fresnel reflector f) Array of heliostats with central receiver

Duffie JA, Beckman WA (2006) Solar engineering of thermal processes, 3rd edn. Wiley, New York

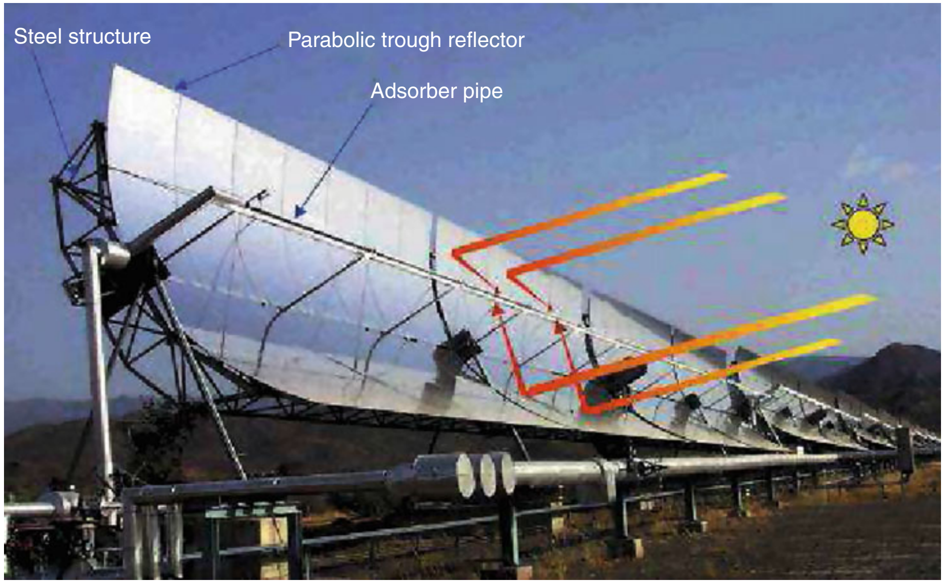
Concentration Ratio vs. Receiver Temperature

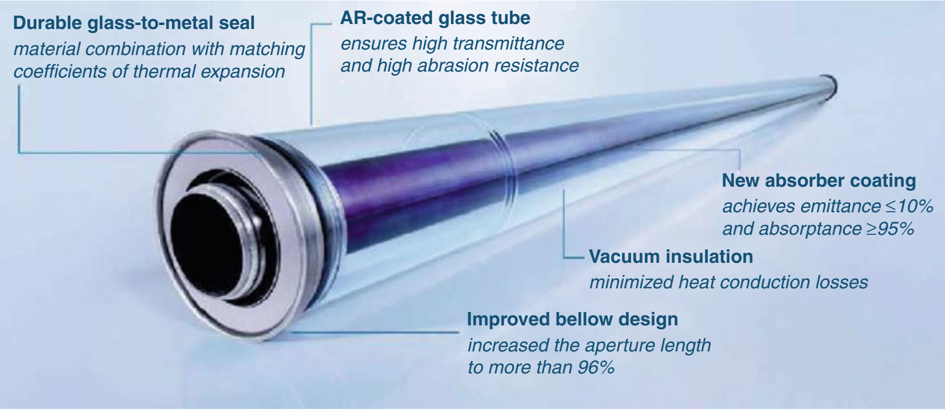


Lower limit:
thermal losses = absorbed energy

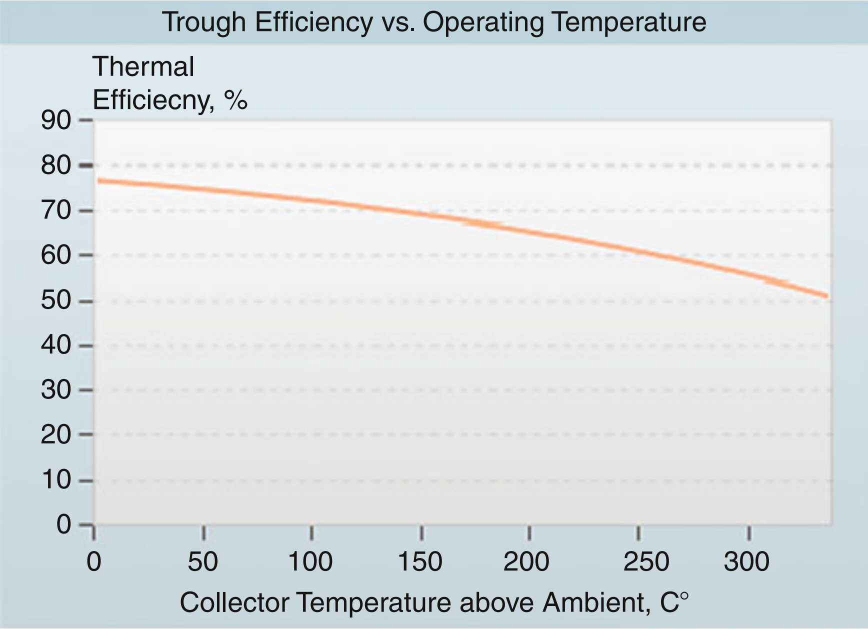
Duffie JA, Beckman WA (2006) Solar engineering of thermal processes, 3rd edn. Wiley, New York

Linear Concentrators: Parabolic Cross Section





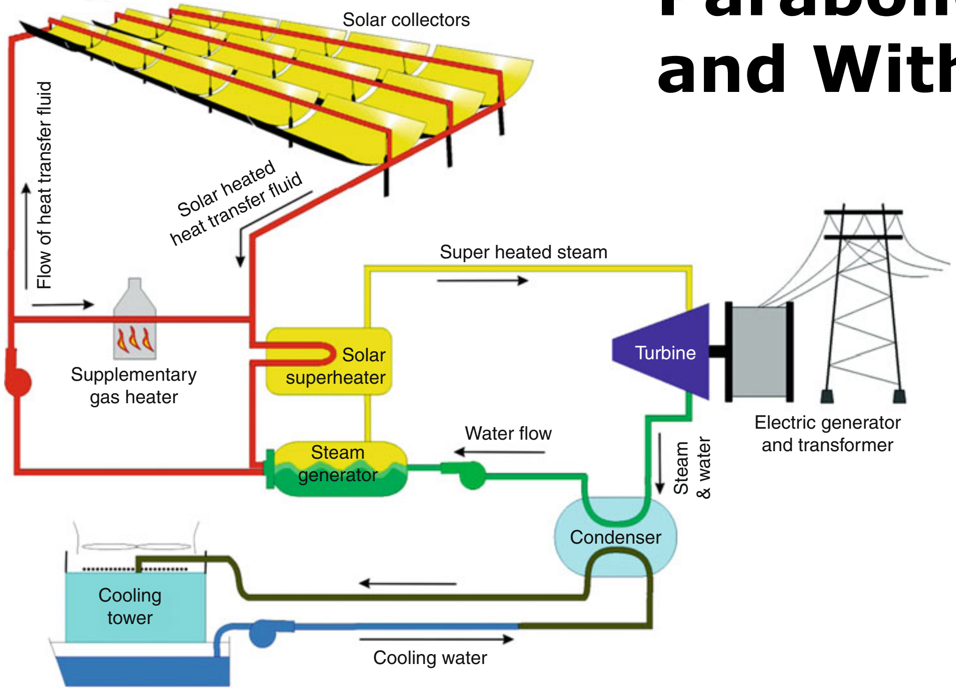
Parabolic Trough Technology

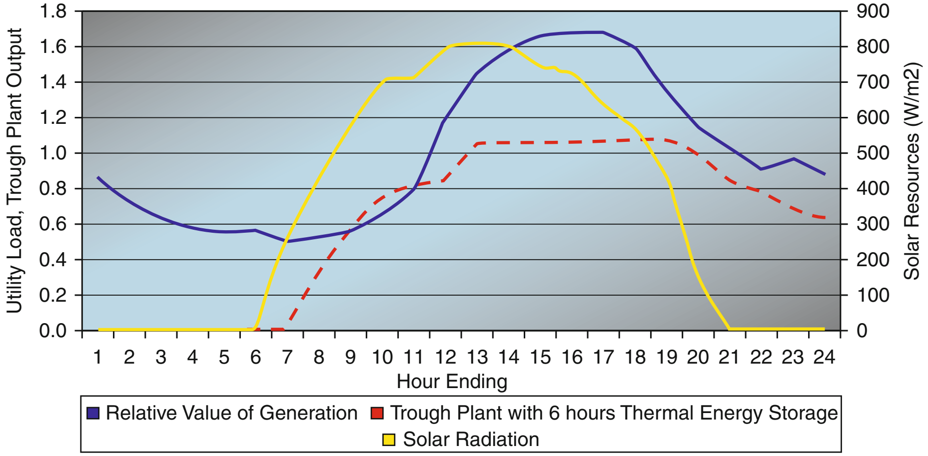


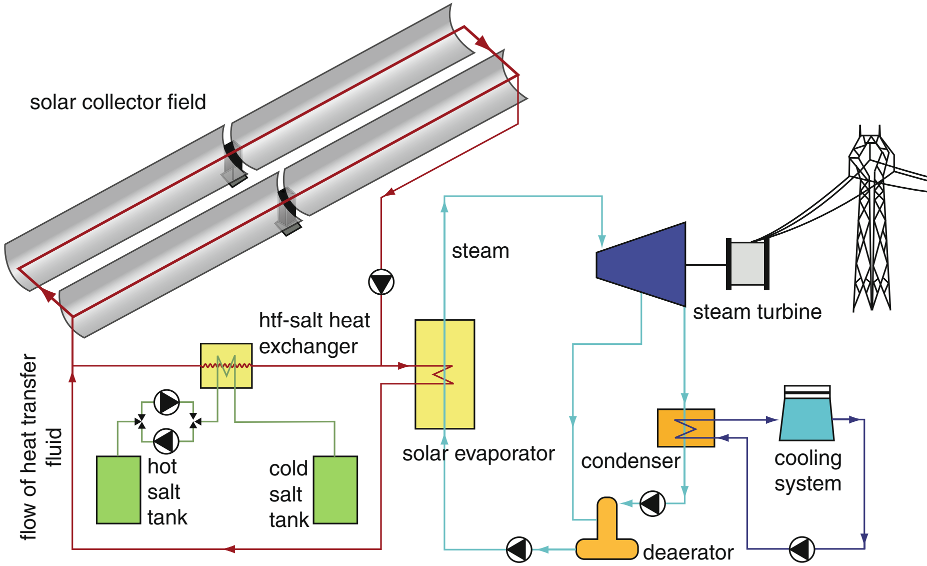
Thermal Conversion Efficiency = net heat collected/ incident solar radiation over the trough aperture area

Krothapalli, A. and Greska, B., “Concentrated Solar Thermal Power”, *Hand Book of Climate Change Mitigation and Adaption* Editors: Wei-Yin Chen, Toshio Suzuki and Maximilian Lackner, Springer-Verlag, 2017, 1503-1536.

Parabolic Trough Plant with and Without Storage







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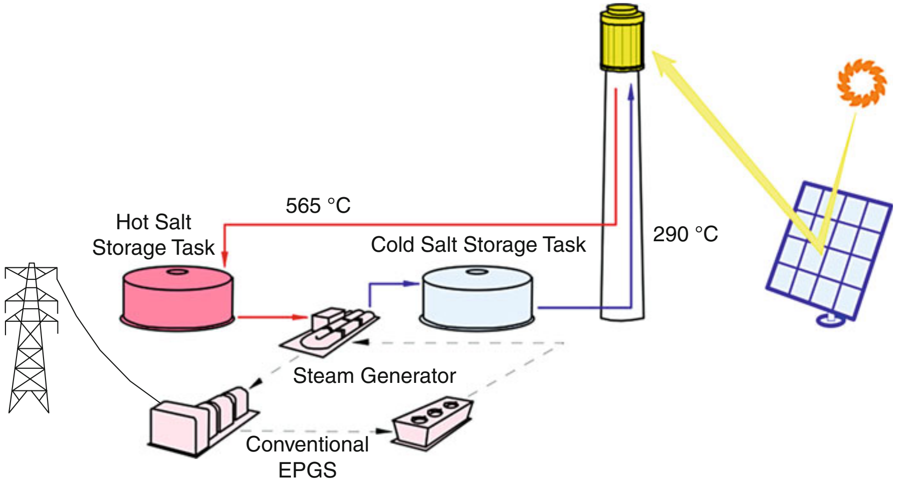
Power Tower Solar Power System



Ivanpah Solar Power Facility
The steam plant was designed for 28.72% gross efficiency.

The local irradiance near the area is about 7.4 kW·h/m^2/day (annual average)

Power Tower CSP


© SWNS.COM

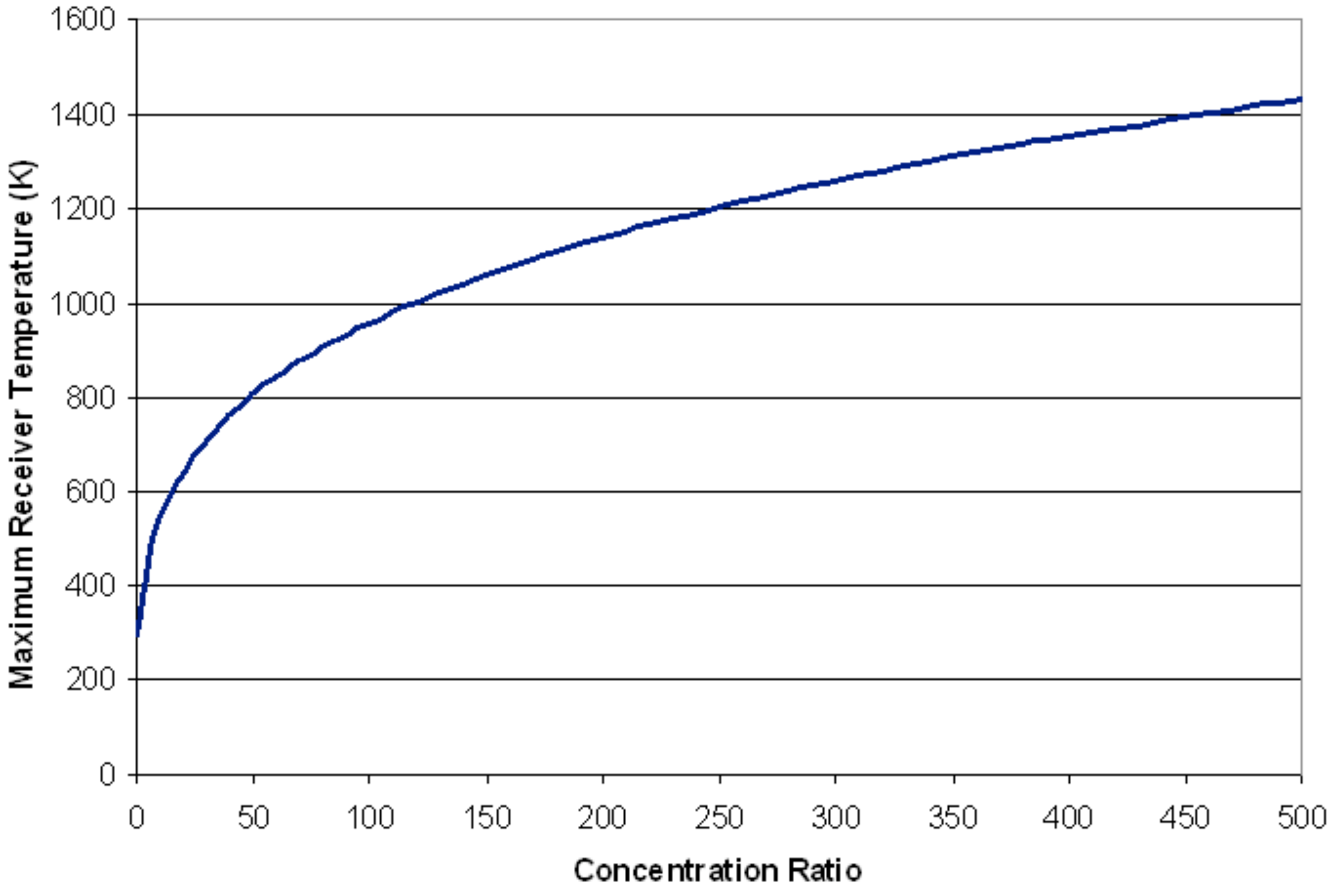
Operating Temperature: 565^{o}C; Capacity Factor: 63% (molten salt storage); Gemasolar 19.9 MW - Spain

Dish-Stirling CSP

Operating Temperature Range: 600-940^{o}C

Dish-Stirling system (η~ 20 - 30%), USA

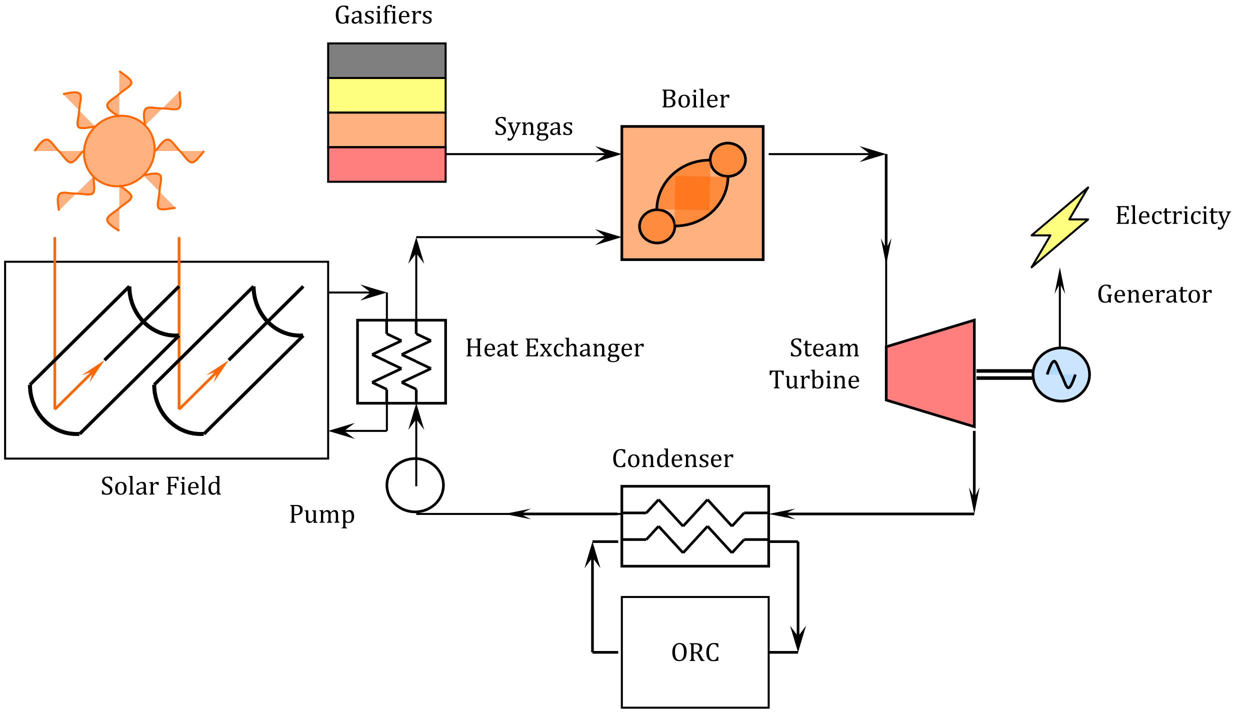
Maximum Receiver Temperature



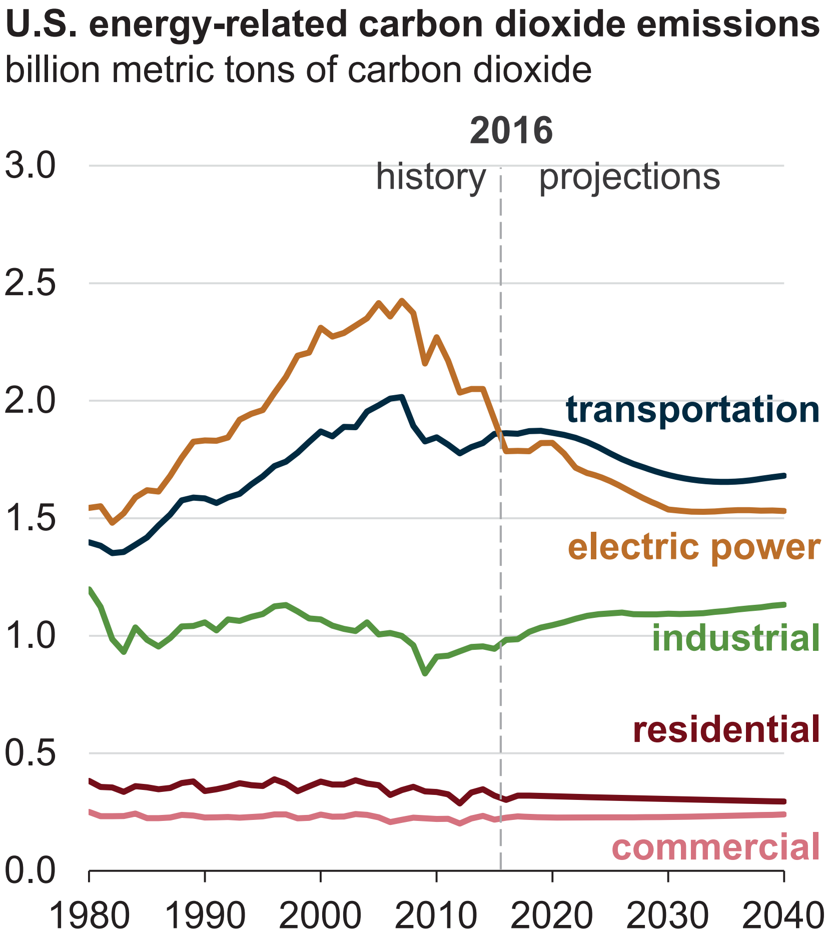
5MW CSP/Biomass Power Plant

A hybrid solar thermal/biomass scheme that improves the typical solar thermal capacity factor from 20% to 80%

An organic Rankine cycle (ORC) serves as a bottoming cycle to extract additional energy



CO_2 Emissions



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Can Solar Thermal Technologies play a role in Climate Change Mitigation!

Source: EIA

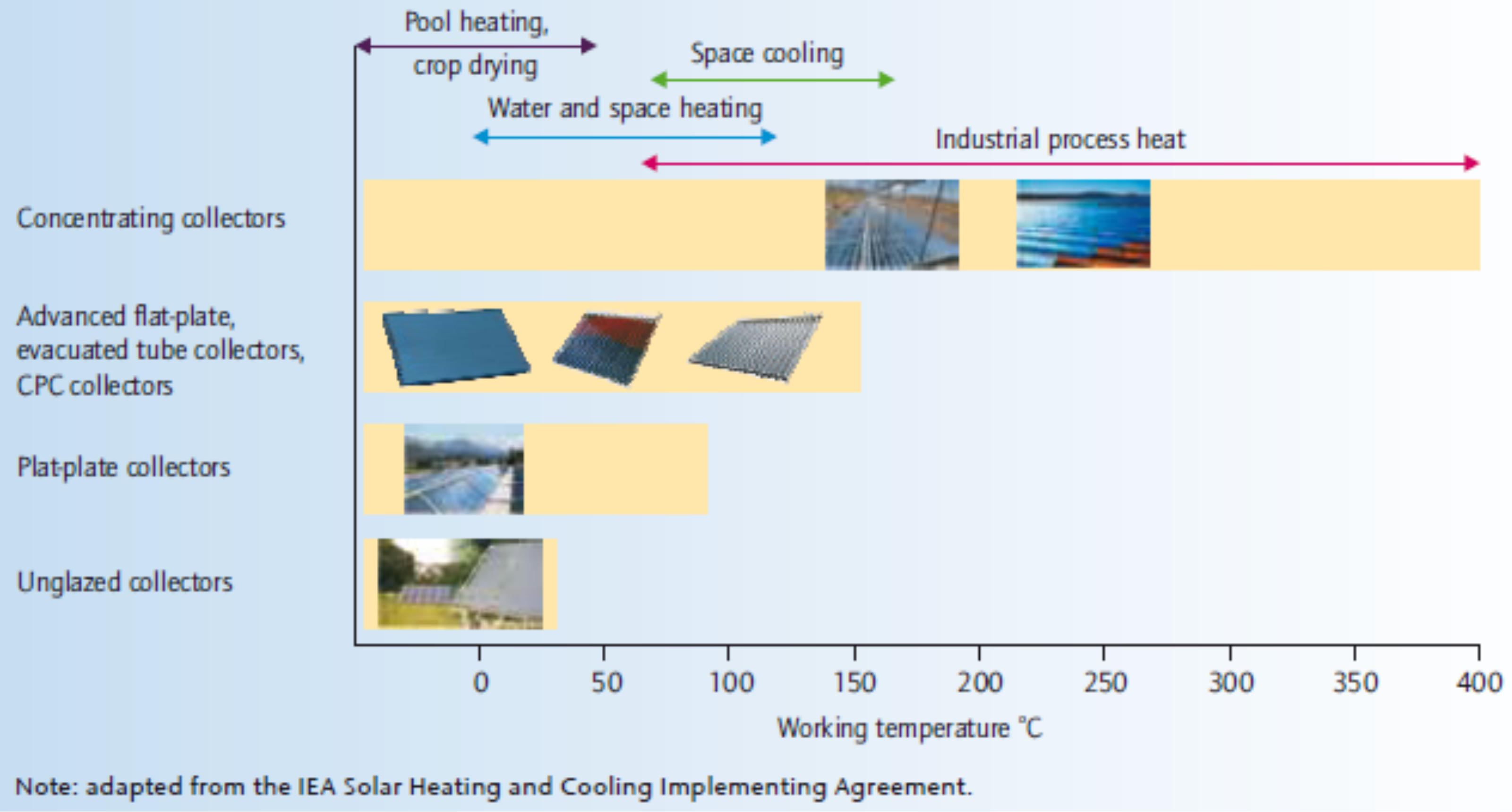
Industrial Process Heat

Greatest Potential for Solar Thermal Use

Industrial Sector	Process	Temperature (^{o}C)
Food and Beverages	Drying Washing Pasteurizing Boiling Sterilizing Heat Treatment	30 – 90 40 – 80 80 – 100 95 – 105 140 – 150 40 – 60
Textile Industry	Washing Bleaching Dyeing	40 – 80 60 – 100 100 – 160
Chemical Industry	Boiling Distilling Various Chemical Processes	95 – 105 110 – 300 120 – 180
All Sectors	Pre-heating of boiler feed water Heating of production halls	30 – 100 30 – 80

Medium Temperature Heat: 80^{o}C – 200^{o}C

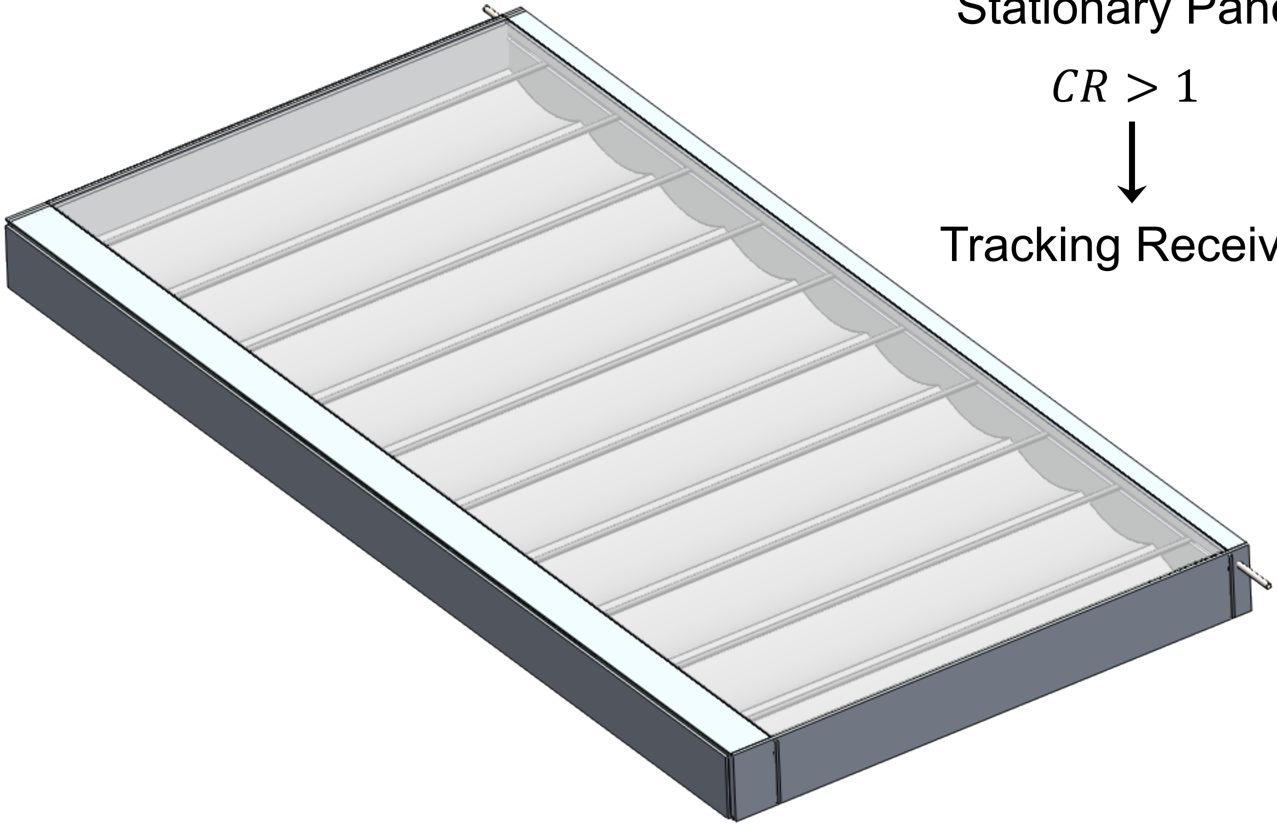
Modern Solar Thermal Collectors



Note: adapted from the IEA Solar Heating and Cooling Implementing Agreement.

Technology Roadmap: Solar Heating and Cooling. IEA, 2012

Concept



Stationary Panel

$CR > 1$

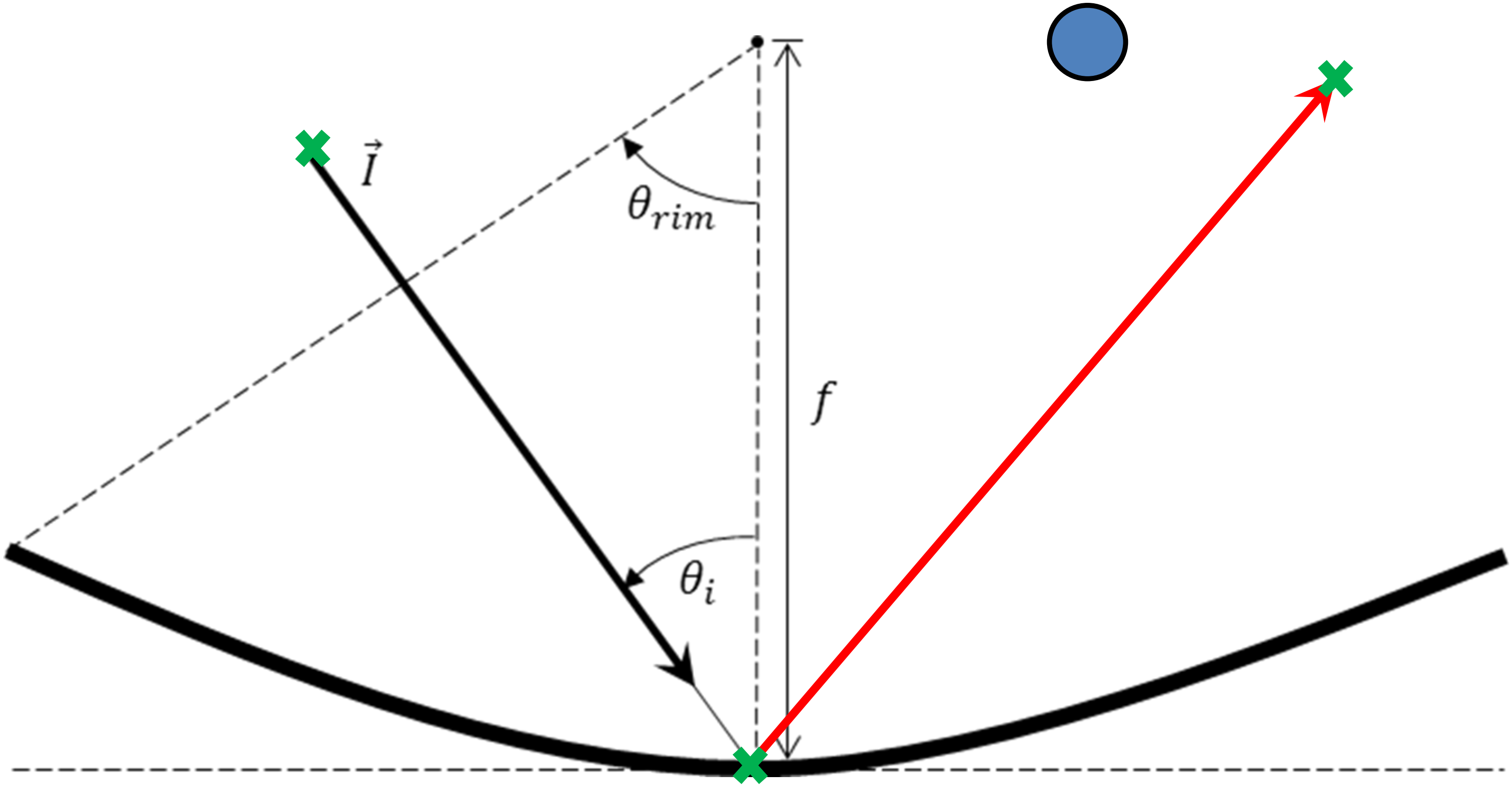
↓

Tracking Receiver

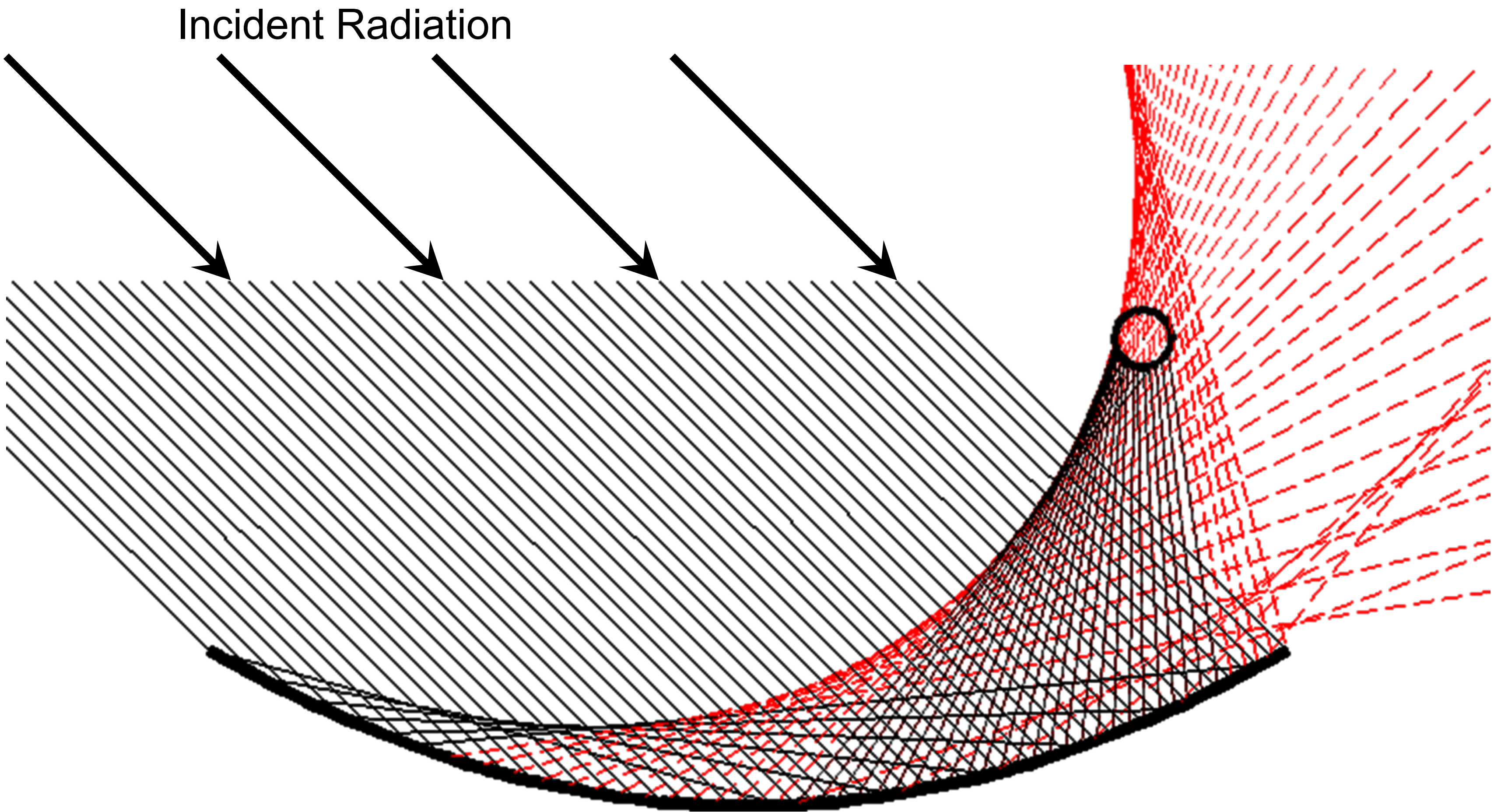
Designed Working Fluid Temperature: 150^{o}C

This work was carried out by Dr. John Pandolfini as part of his Ph.D. Dissertation at FSU

Ray Tracing

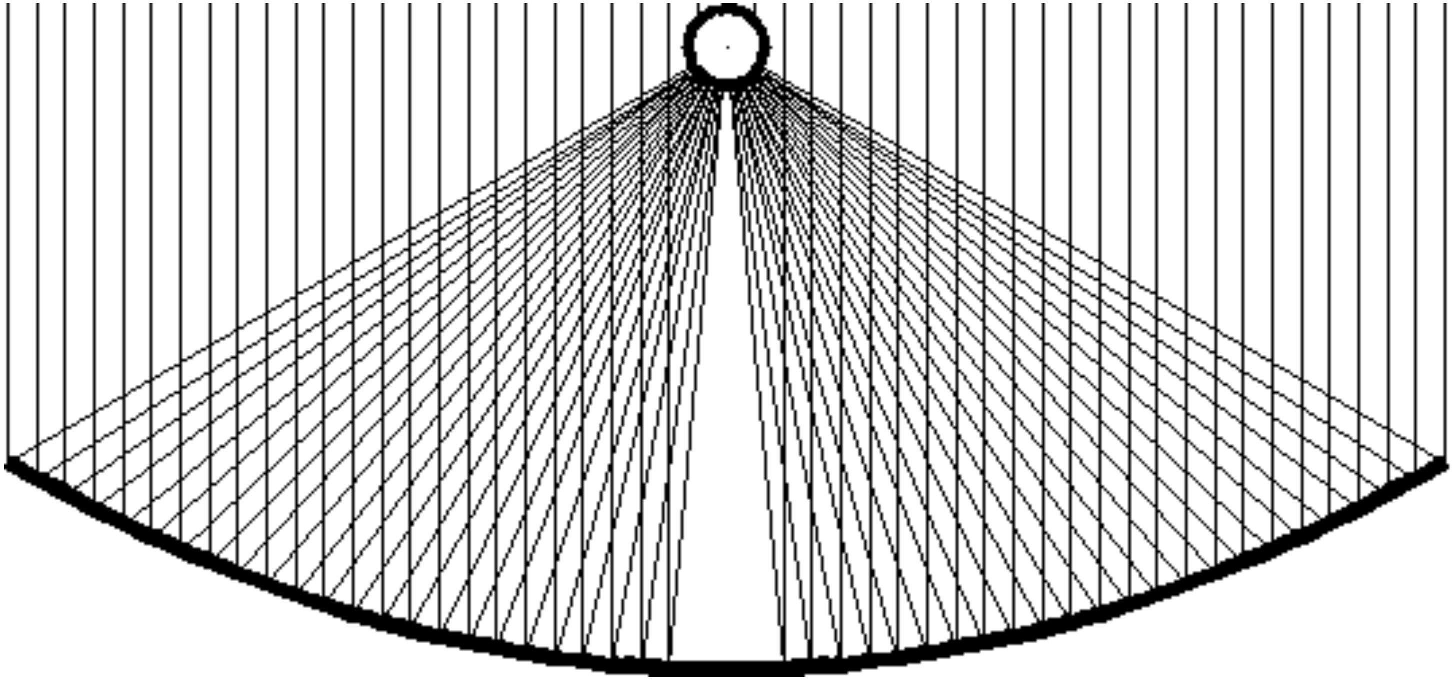


Ray Tracing



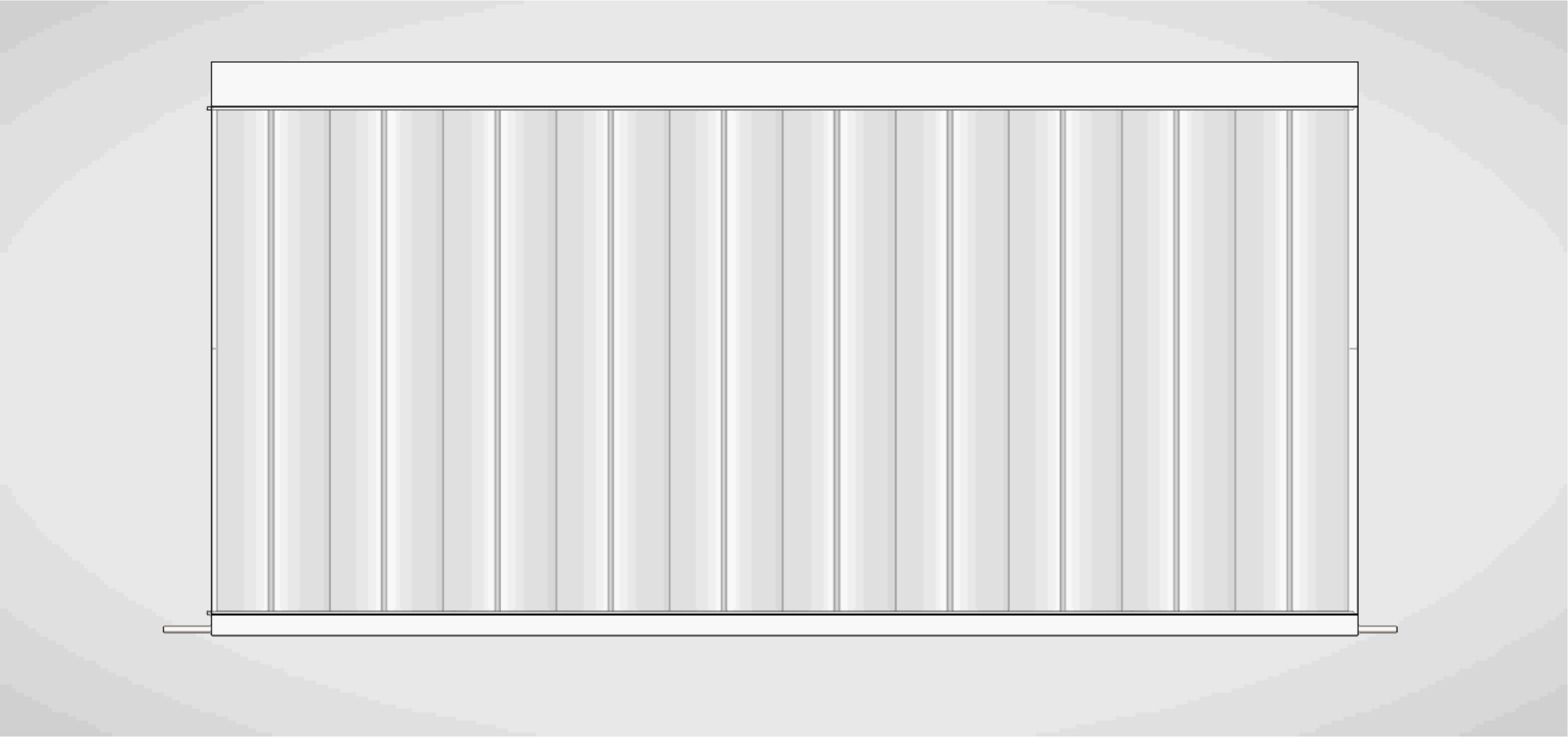
$$\gamma \approx \#Hit/N$$

Parabolic Reflector with Moving Receiver

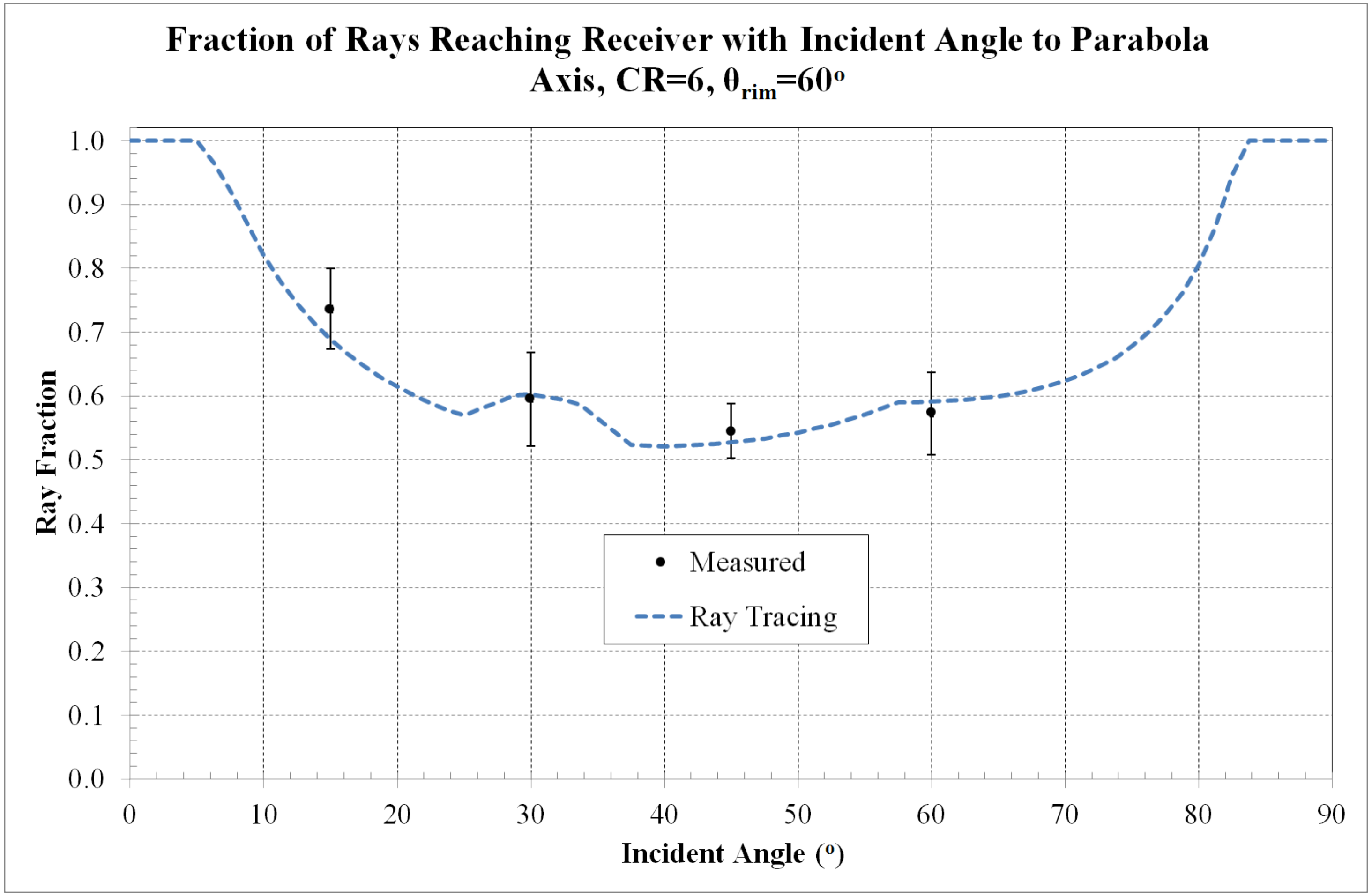


$$\gamma = F(\theta_i)$$

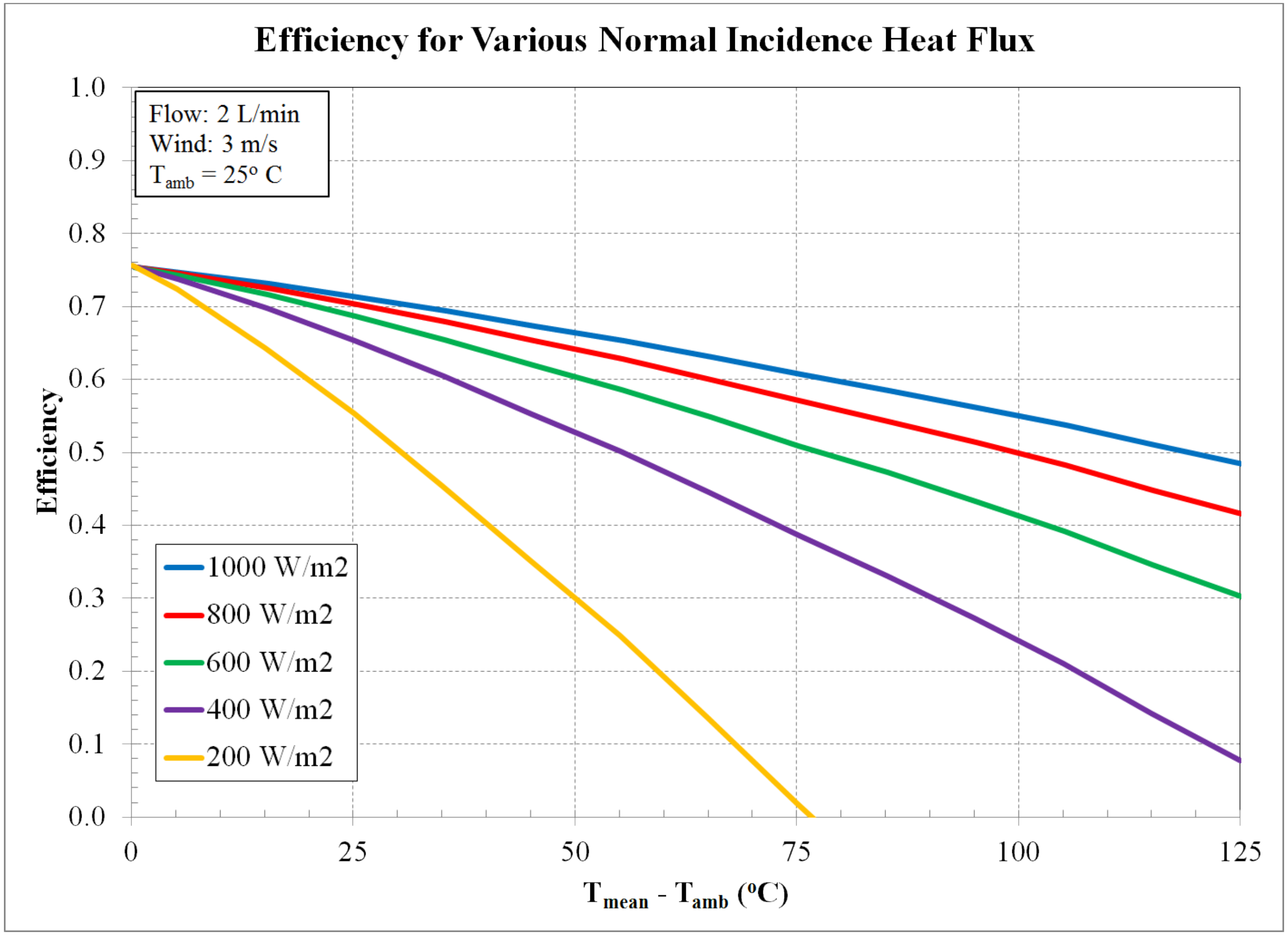
Concept



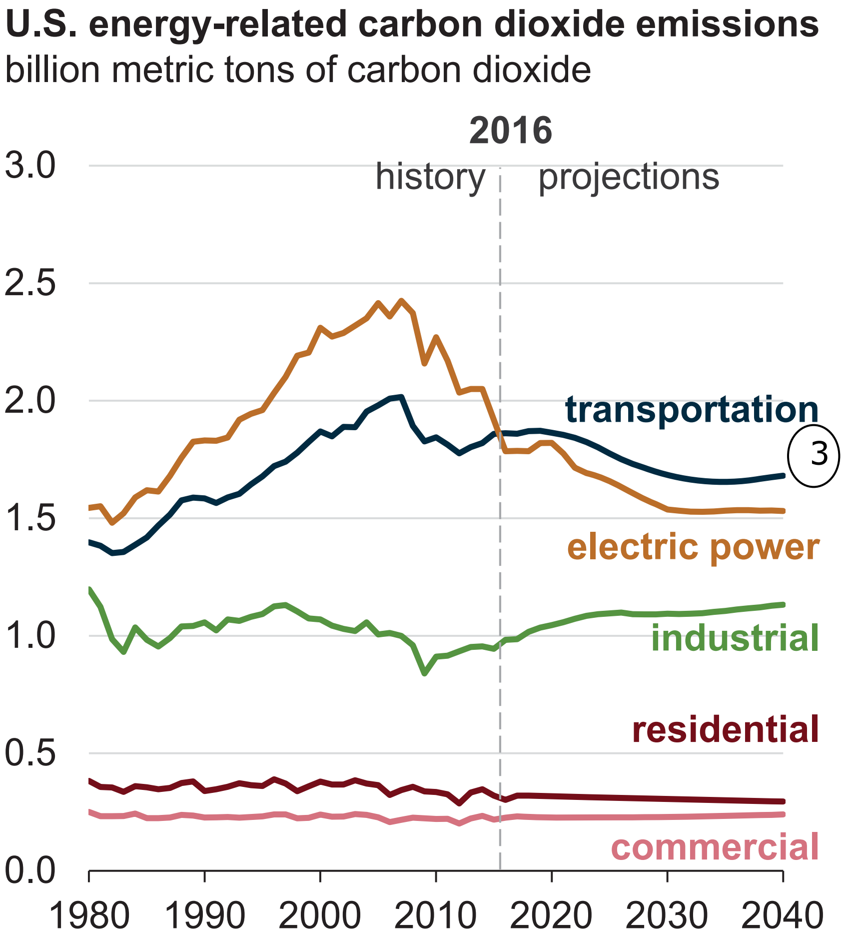
Intercept Factor



Collector Model



CO_2 Emissions



U.S. energy-related carbon dioxide emissions
billion metric tons of carbon dioxide

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Source: EIA

Energy Density

Method	**kWh/kg**
Gasoline	14
Li-Ion Batteries	0.3
Hydrostorage	$0.3/m^3$
Flywheel, Steel	0.05
Flywheel, Carbon Fiber	0.2
Flywheel, Fused Silica	0.9
Hydrogen	38
Compressed Air	$2/m^3$

Hydrogen Powered Fuel Cell Cars

Typical Range : 585 Km

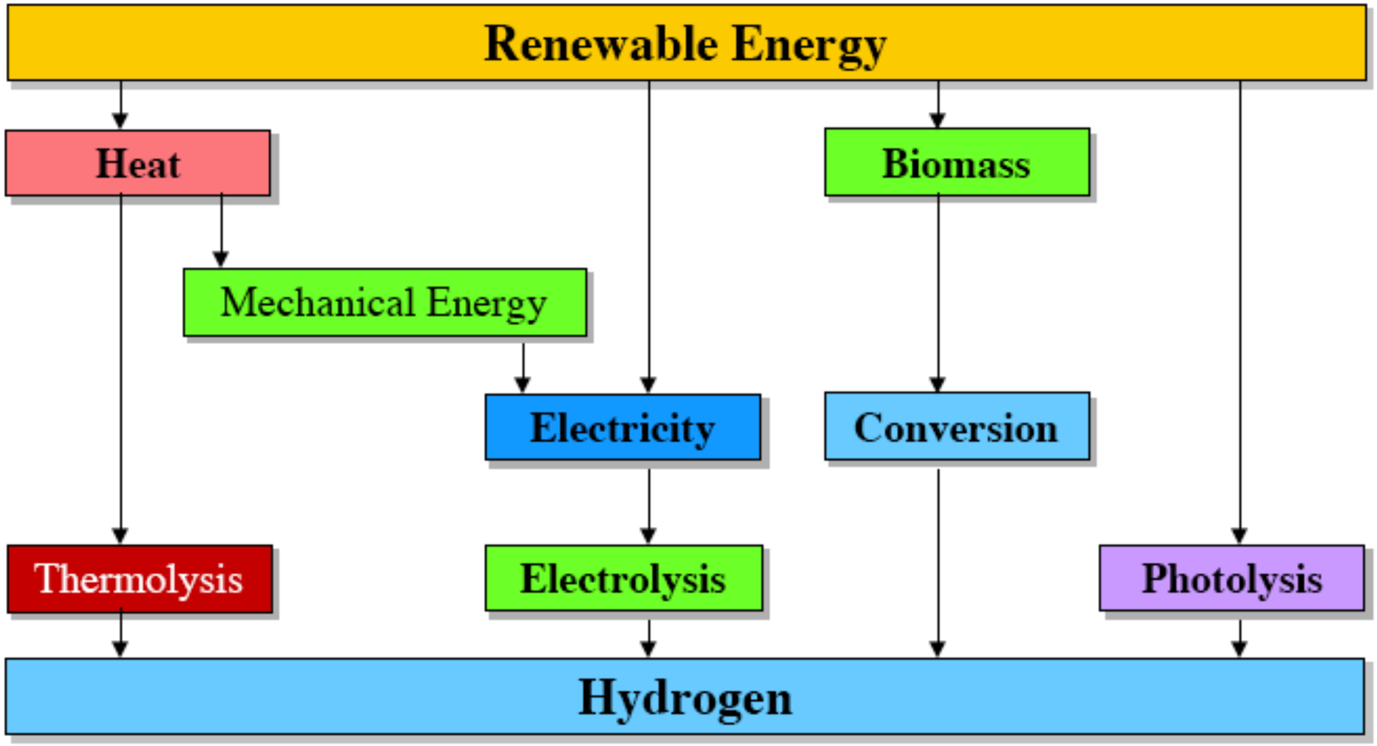
Top Speeds: 170 km/h

H_2 Storage: 5.5 kg @ 689 bar

Expected cost of fuel cell stack: $50/kW

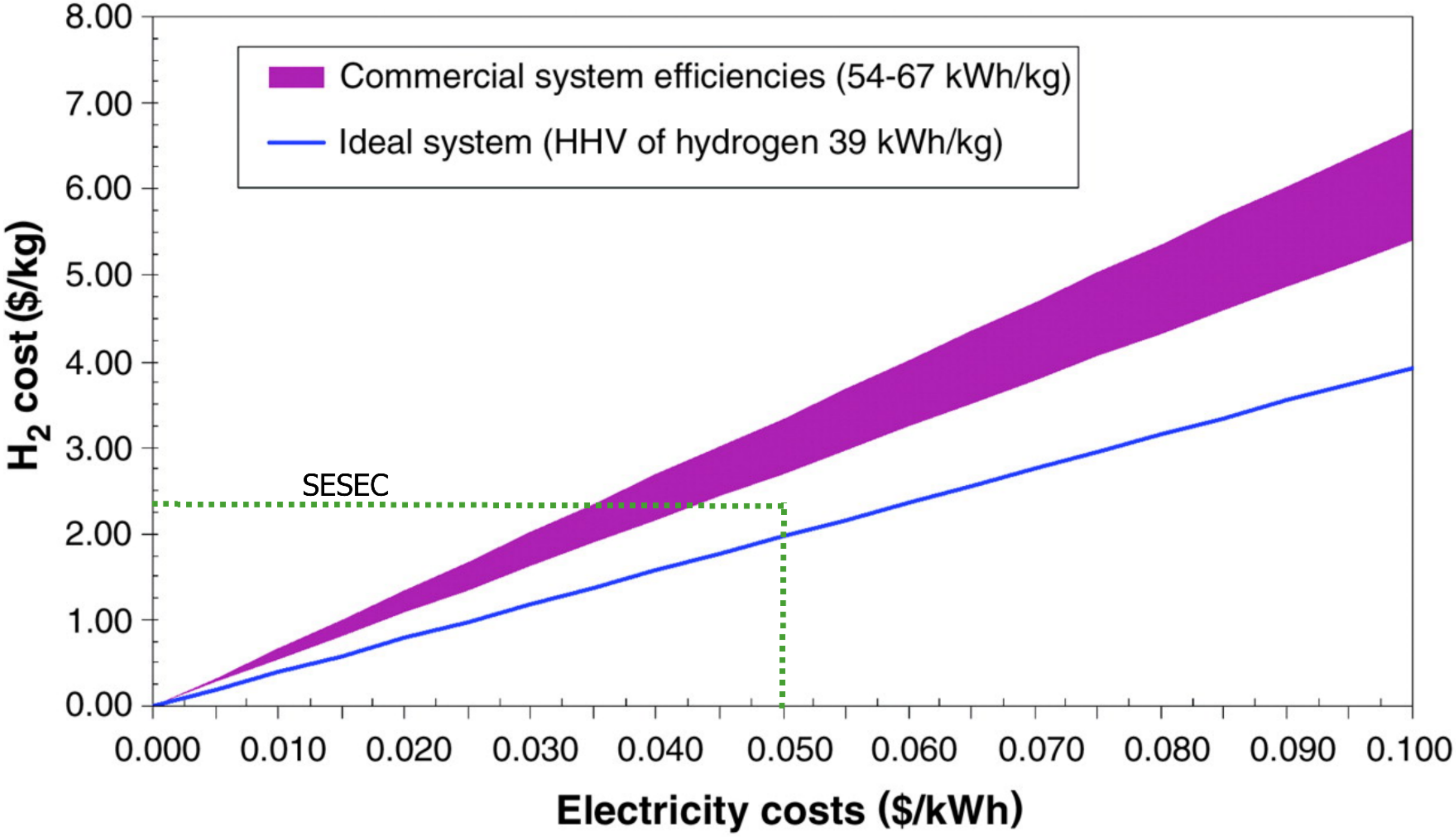
Expected Hydrogen cost:$6/kg
(produced at the point of delivery)

Sustainable Paths to Hydrogen



Source: D. Brent MacQueen
Brent.macqueen@sri.com
SRI International, Menlo Park CA

Hydrogen-Electricity



Technical grade Hydrogen currently costs about $6/kg

Compressing the gas, delivering it to a filling station, storing it and dispensing it to fuel cell vehicles cost about $13/kg

Energy Efficiency of Electrolysis

$$\frac{\text{Chemical Potential}}{\text{Electrolysis Potential}} = \frac{1.23}{1.45} = 85\ \%$$

Coupling to a 20% Photo Voltaic array gives a

solar to hydrogen efficiency of about 17.5%.

Requirement for Electrolysis: High Purity Water & Electricity

Water Splitting – Hydrogen Production

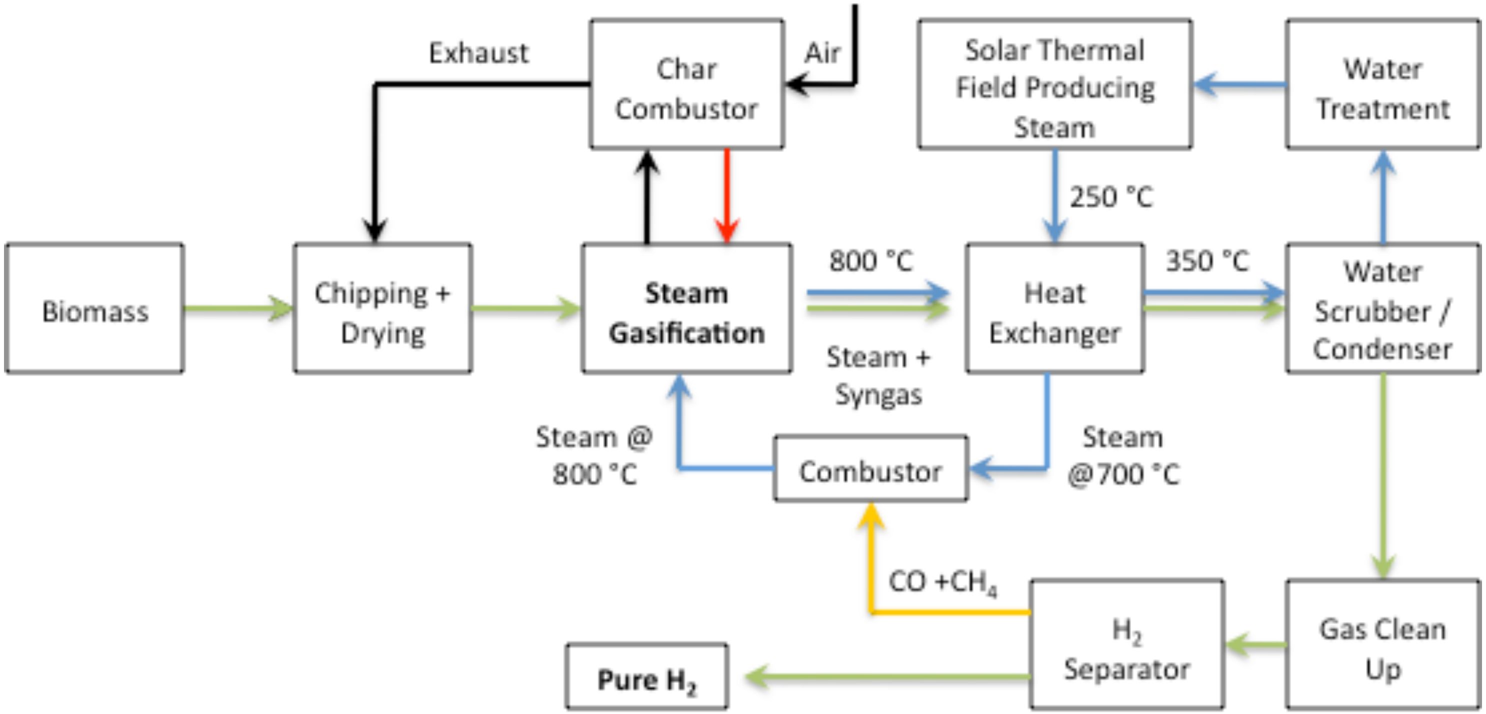
750 kW Facility

Sun heats redox materials, such as nickel ferrite or cerium oxide, in the interior of the reactor to 1400 degrees Celsius At these temperatures, the metal oxide is chemically reduced, that is oxygen is released and transported out of the reactor.

The actual water splitting occurs in the second step, which takes place at 800 to 1000 degrees Celsius. Here, the water vapor flow through the reactor. The previously reduced material is reoxidised. As the oxygen is now bound into a metal oxide, it remains in the reactor, whilst the hydrogen is free to be transported out of the reactor.
Once the material is completely reoxidised, it is regenerated through the first step of the procedure and the cycle starts again.

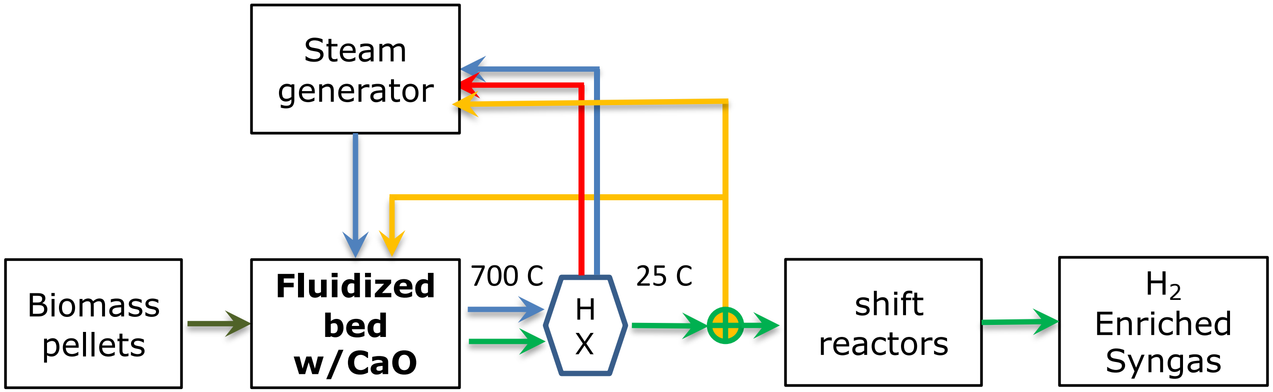
CERTH-CPERI-APTL

Hydrogen Production From Biomass



Source: John Dascomb, Ph.D dissertation, FSU, 2013

Hydrogen Production Efficiency



Steam generator

Biomass pellets

Fluidized bed w/CaO

700 C

H X

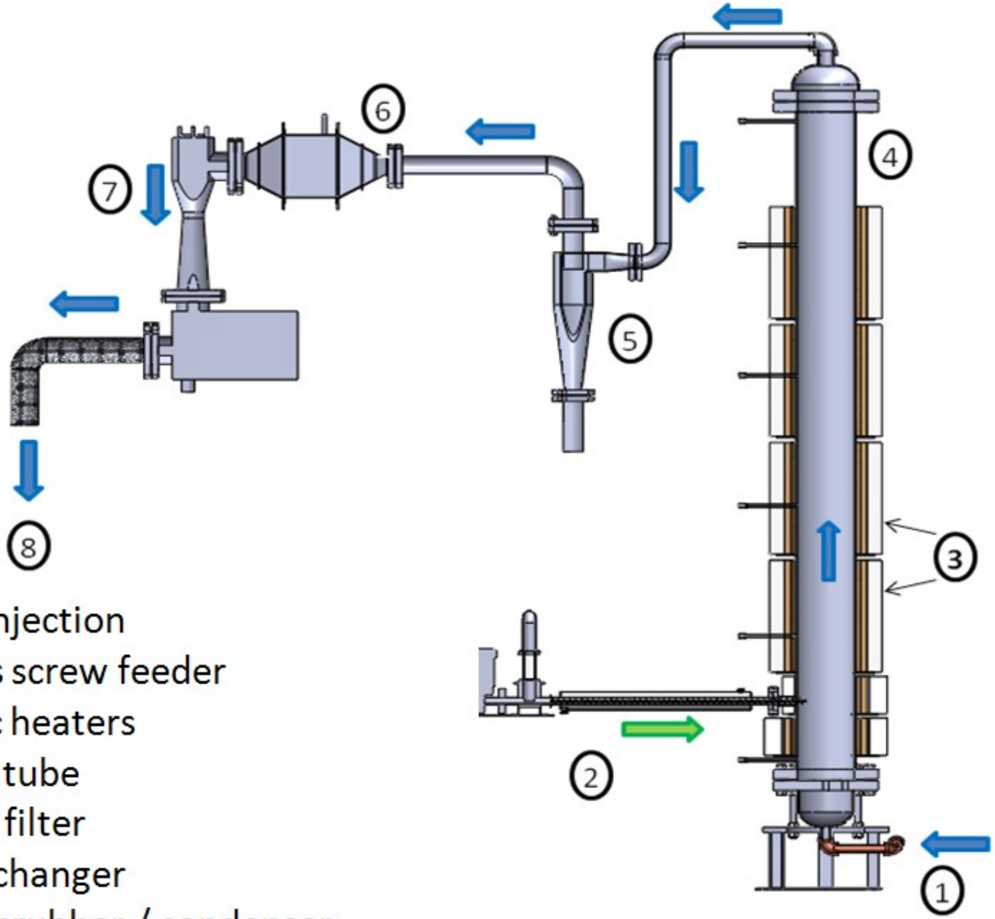
25 C

shift reactors

H_2 Enriched Syngas

	As tested	with single heat exchanger
Hydrogen (mol %)	68.3	68.3
Total energy efficiency (%)	50	68
Elemental H_2 prod. effic. (%)	29	40

Hydrogen Enriched Synthesis Gas Production Plant



1 Steam injection
2 Biomass screw feeder
3 Ceramic heaters
4 Reactor tube
5 Cyclone filter
6 Heat exchanger
7 Water scrubber / condenser
8 Cooled product gas exhaust

Dascomb, J., and Krothapalli, A., "Hydrogen Enriched Syngas from Biomass Steam Gasification for Use in Land Based Gas Turbines", *Novel Combustion Concepts for Sustainable Energy Development*, Eds: A.K. Agarwal et al., Springer, 2014, 89-110

Steam Gasification with CaO

Test #	1	2	3
Reactor temperature (^{o}C)	657	690	701
S/B ratio	2.9	2.9	2.1
Gas residence time (sec)	2.7	2.6	2.7
Syngas component	Average gas conc. (dry mol %)		
Hydrogen	65.5	69.4	68.3
Methane	11.1	8.8	8.7
Carbon monoxide	10.8	7.5	9.3
Carbon dioxide	9.4	12.0	11.3
Ethylene	1.6	1.3	1.4
Ethane	0.5	0.8	0.6
Acetylene	0.1	0.1	0.1
Propylene	0.4	0.8	0.4
HHV (dry MJ/m^3)	15.6	14.2	14.3

Dascomb, J., and Krothapalli, A., "Hydrogen Enriched Syngas from Biomass Steam Gasification for Use in Land Based Gas Turbines", *Novel Combustion Concepts for Sustainable Energy Development*, Eds: A.K. Agarwal et al., Springer, 2014, 89-110

Conclusions

Concentrated Solar Thermal Technologies best suited for energy storage

Multiple Parabolic Reflector Flat Panel Collector design for Industrial process heat

Most Efficient Solar energy to Split Water to Hydrogen is Concentrated Solar Power