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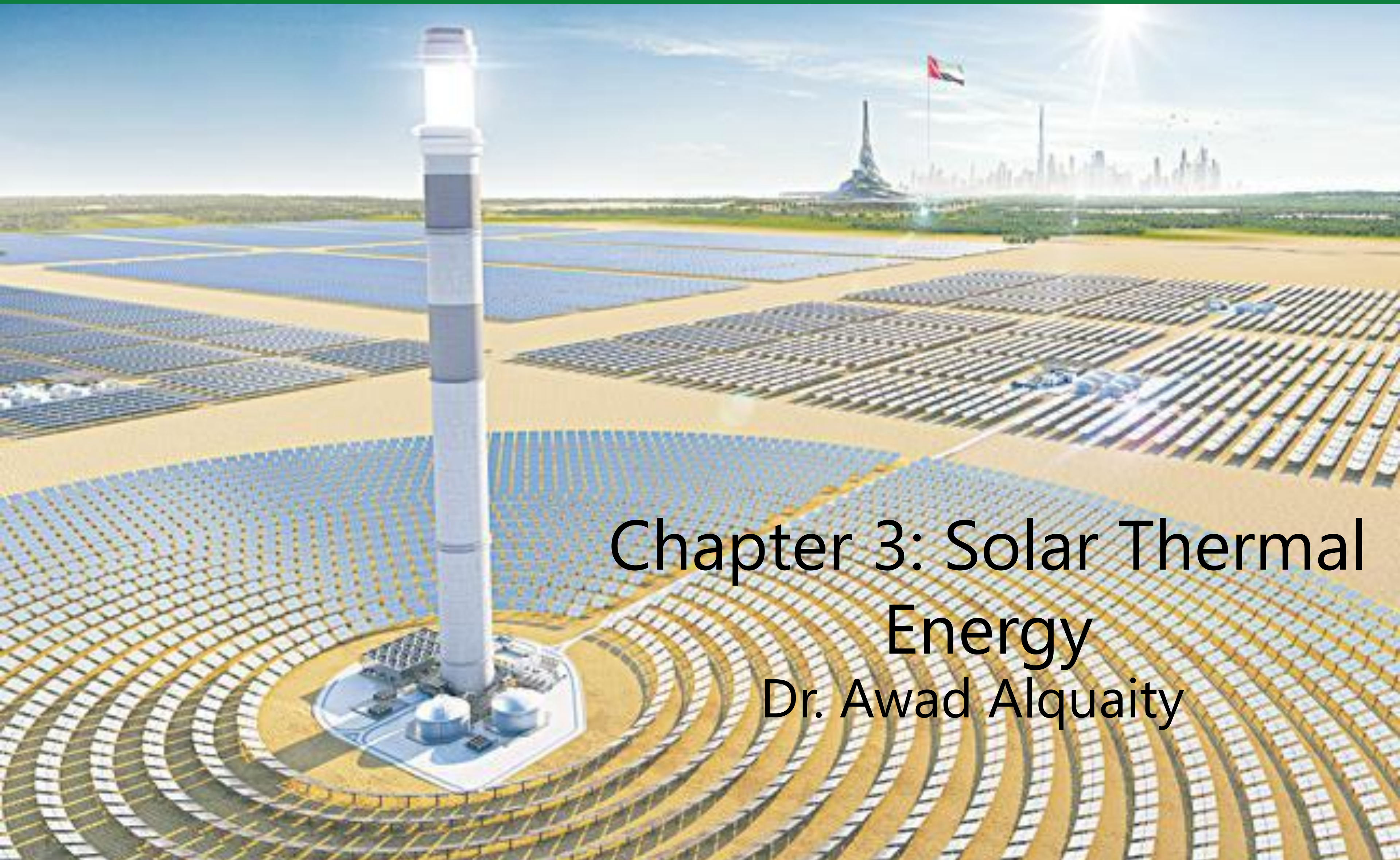


Chapter 3: Solar Thermal Energy

Dr. Awad Alquaity

Objectives

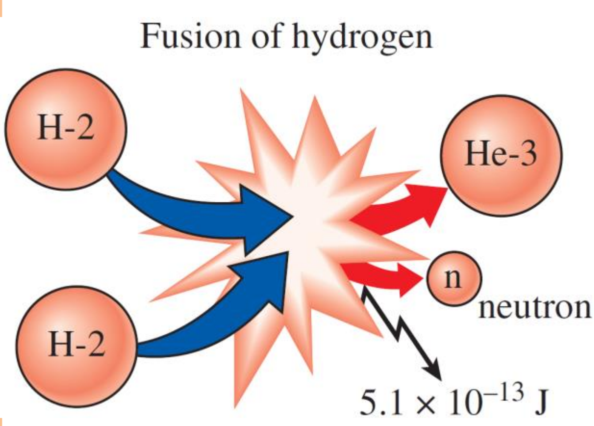
- Solar radiation
- Advantages and challenges of solar energy

- Solar energy conversion
- Flat-plate solar collector
- Concentrating solar collector

Solar Radiation

Sun emits radiation energy continuously at a rate of $E_{sun} \approx \mathbf{3.6 \times 10^{26}}$ W!

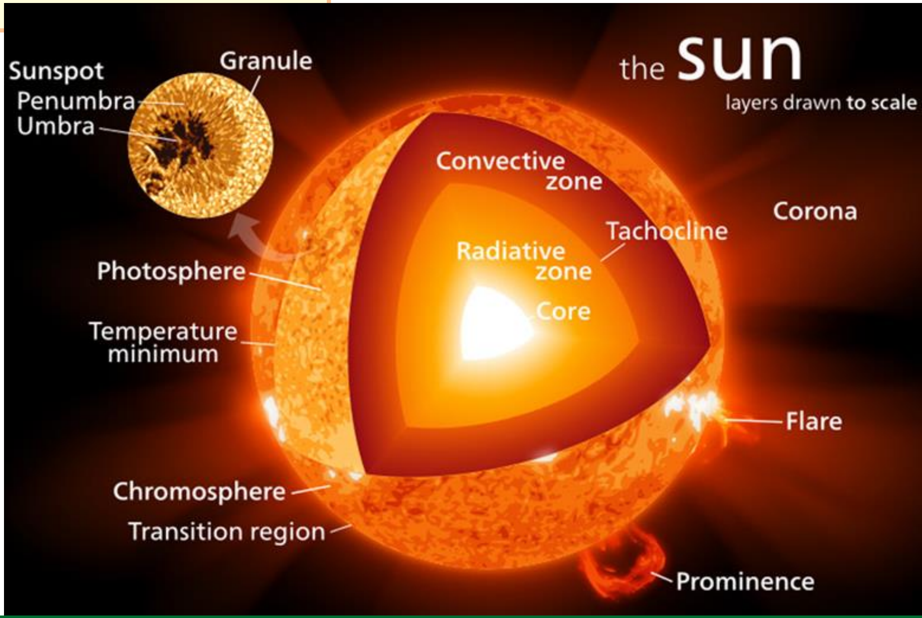
- The energy of the sun is due to the **continuous fusion reaction**.
- Every second the Sun converts about 657 million tons of **hydrogen isotopes** into (653 million tons) of **helium**.
- The residual 4 million tons is converted to energy ($E = mc^2$)
- **Sun is essentially a nuclear reactor**, with surface T as high as 5780K.
- Solar radiation (or solar heat or solar energy) reaches us in the form of electromagnetic waves (or radiation) after experiencing considerable interactions with atmosphere.



- Less than a billionth of solar radiation (about $1.7 \times 10^{17}\ W$) strikes earth.
- Only around 70% of this energy reaches the earth's surface, the rest being reflected by the atmosphere

The sun is a nearly spherical body

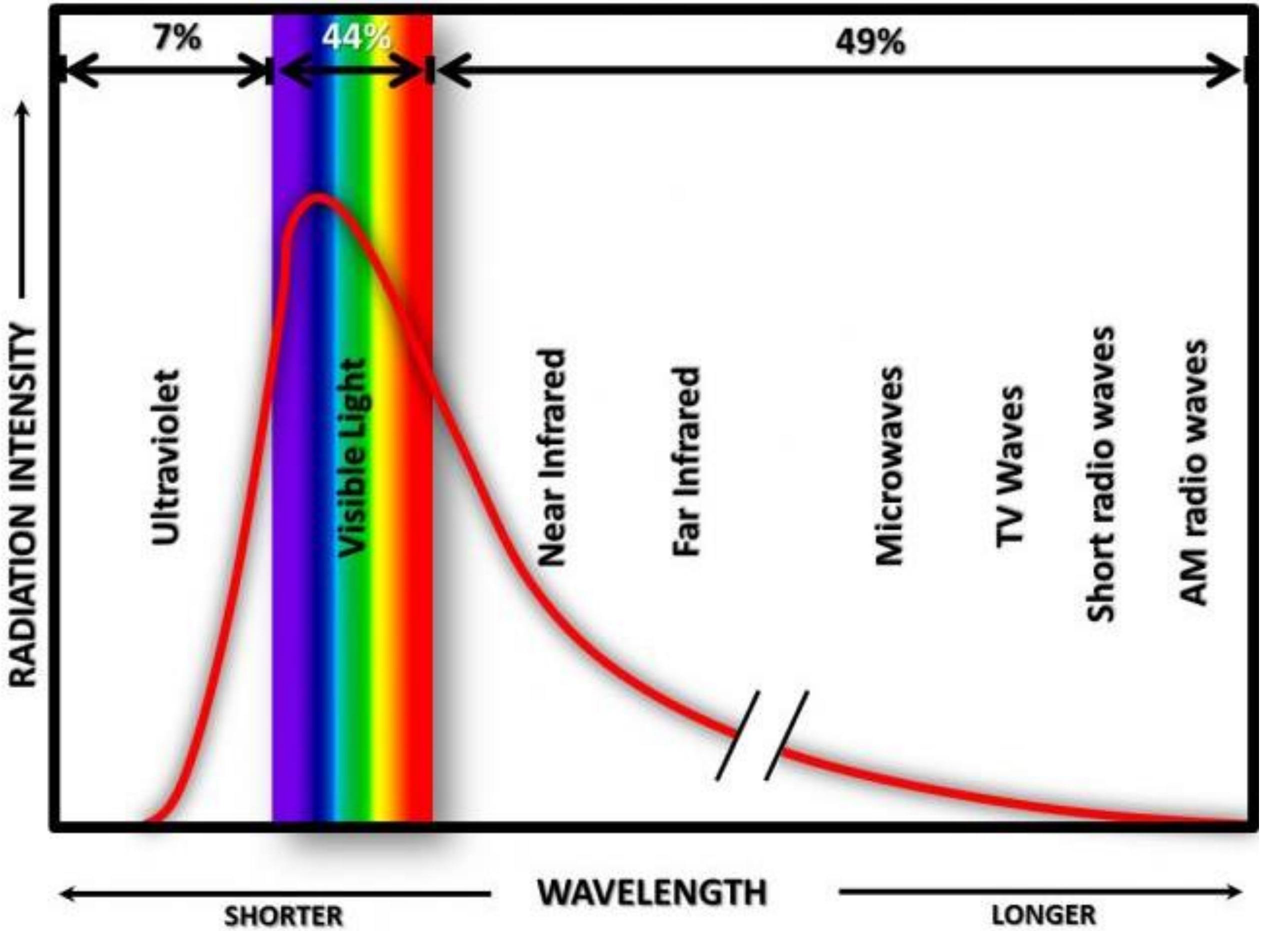
- diameter of $D \approx 1.39 \times 10^9$ m
- mass of $m \approx 2 \times 10^{30}$ kg
- mean distance from earth $\approx 1.496 \times 10^8$ km



Sun's Electromagnetic Spectrum

Sun's Electromagnetic Spectrum distribution beyond the earth's atmosphere

- This distribution resembles the energy emitted by a blackbody (i.e., a perfect emitter and absorber of radiation) at 5780 K.

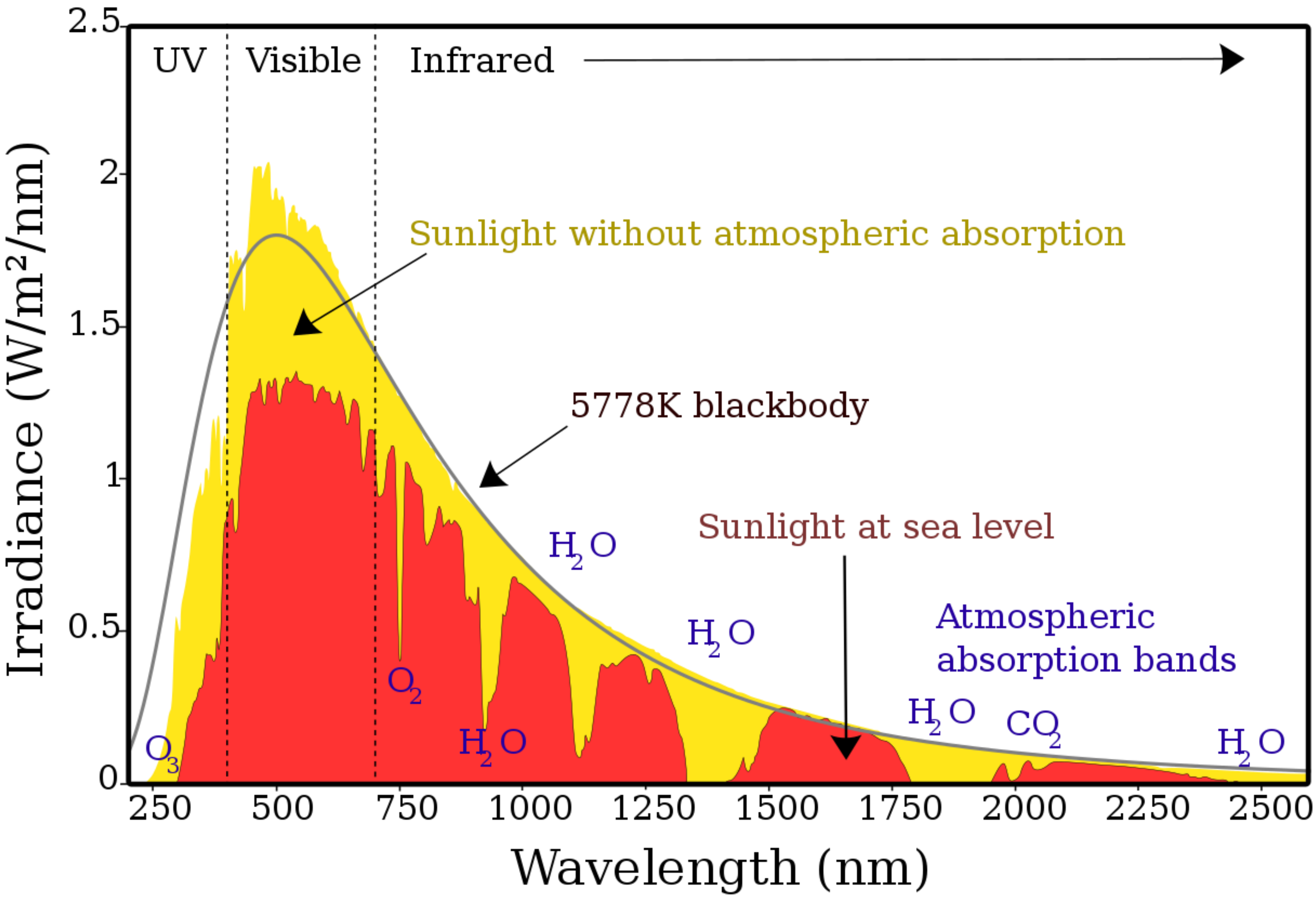


About half of the total energy is in the visible wavelengths below 700 nm!

Solar radiation undergoes considerable attenuation in the Earth's atmosphere. (because of absorption & scattering)

Due to absorption, the amount of solar energy reaching the earth's surface is weakened considerably, to about 950 W/m^2 on a clear day and much less on cloudy day.

Sun's Spectrum at various absorption levels



Advantages and Challenges of Solar Energy

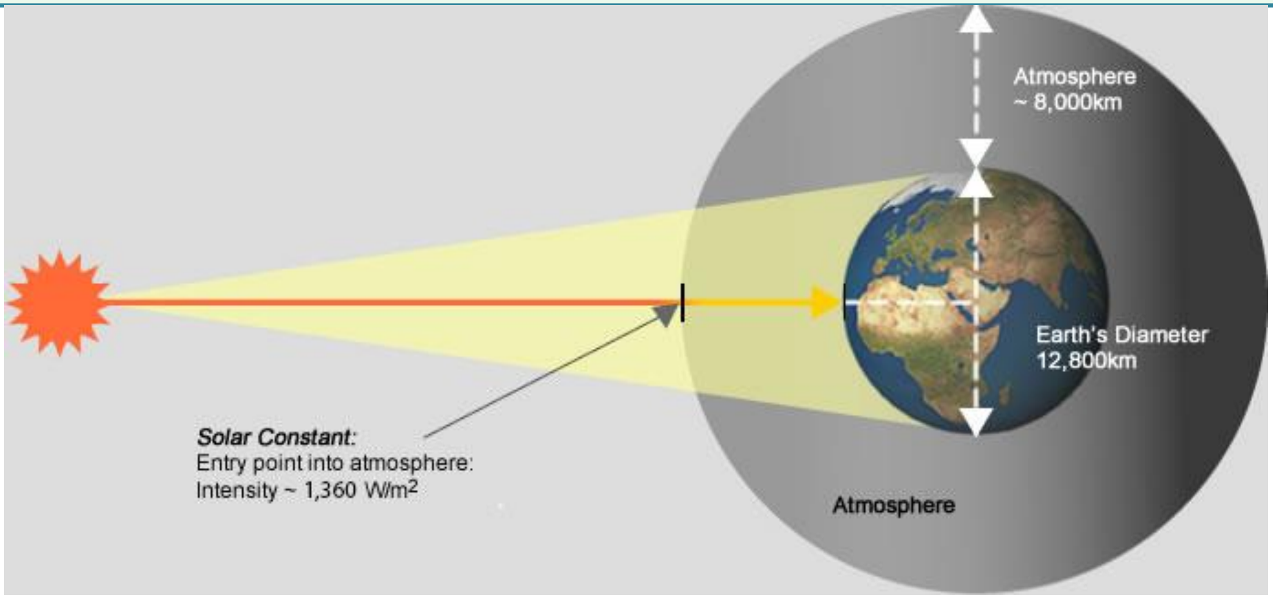
- Solar energy is **free** and **non-polluting**.
- The amount of solar energy reaching earth's surface in a month can **theoretically** meet **energy needs of the entire world**!

- Not economical and practical in some cases due to **low concentration of solar energy**.
  - Cost of solar energy systems may be high compared to conventional energy sources such as oil.
  - The rate of solar radiation on a unit surface is quite low and solar collectors with large surface areas must be installed. This is costly and requires a lot of space.
- Solar energy is available in large quantities in certain locations of the world, seasons of the year, and times of the day.
- One of the most attractive applications of solar energy is heating of buildings, but this is not needed in summer when solar energy is readily available.
- Storage of solar energy for night-time use is an option to tackle non-continuous feature of solar energy, but this adds to system cost and it may not be effective for most applications.
- Conversion of solar energy into a dispatchable form of energy such as hydrogen or ammonia is another option but it also adds to system costs.

Total Solar Irradiance (or Solar Constant)

The total solar irradiance (TSI) is the value of the **solar energy flux** over all wavelengths arriving at the **top of the terrestrial atmosphere**.

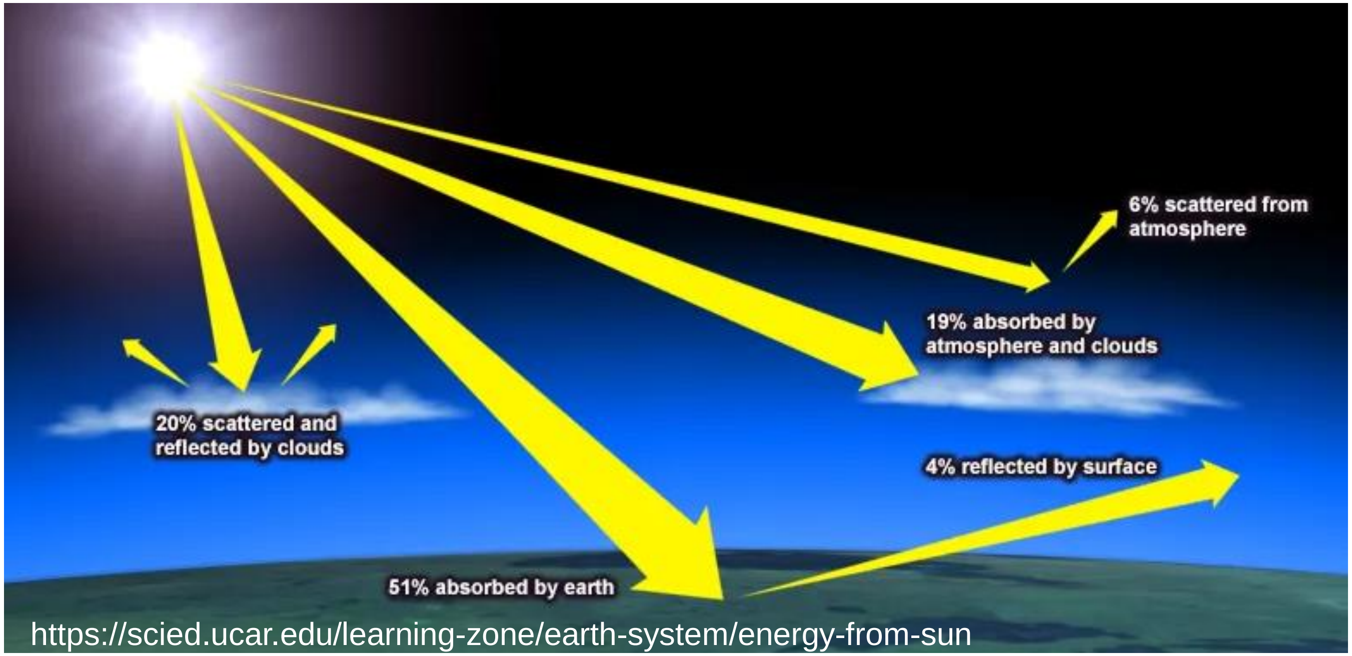
- OR, it is the solar energy reaching the earth's atmosphere expressed in power per unit area ($\mathrm{W/m^2}$).
- The accepted value of the **solar constant** is about 1360 $\mathrm{W/m^2}$,
- Solar "constant" changes by 3.5% from a maximum of 1418 $\mathrm{W/m^2}$ on January 3 when earth is closest to the sun, to a minimum of 1325 $\mathrm{W/m^2}$ on July 4 when the earth is farthest away from the sun.



Source: https://www.greenrhinoenergy.com/solar/radiation/extraterrestrial.php

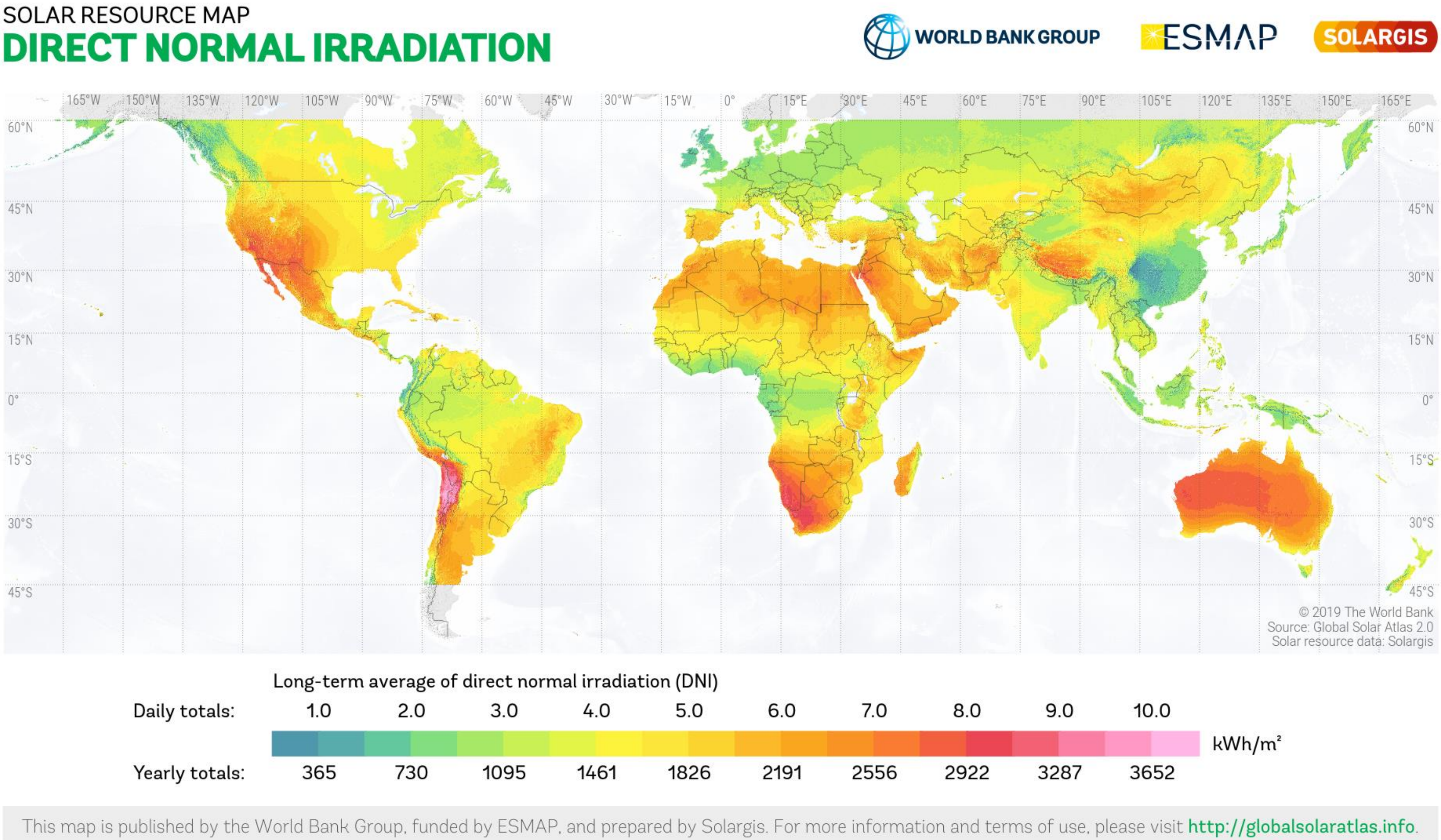
Total Solar Irradiance (or Solar Constant)

Although the solar radiation reaching the earth's atmosphere is about 1360 W/m^2, it reduces to about 850 to 900 W/m^2 on the earth's surface due to scattering and absorption in the atmosphere

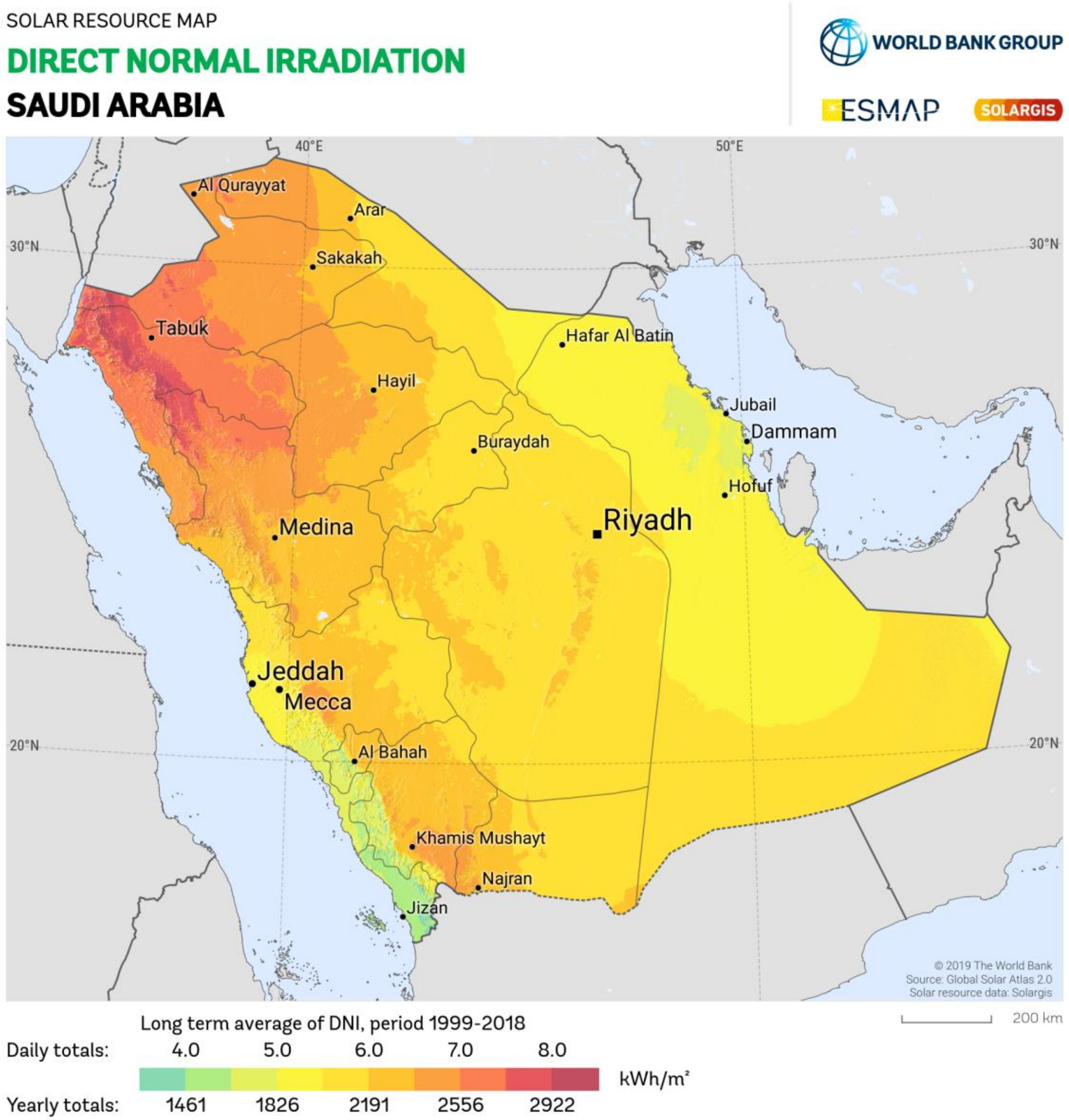


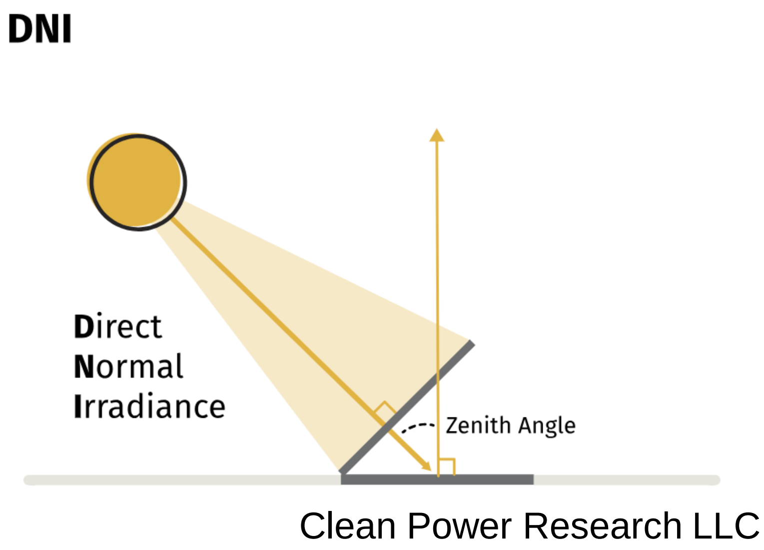
- Direct normal irradiance (DNI)– or beam radiation, measured on a surface perpendicular to sun's position in the sky – Important for concentrating solar technologies
- Diffuse horizontal irradiance (DHI) – diffuse sky radiation; radiation from light scattered by the atmosphere. There would be no DHI in absence of atmosphere
- Global horizontal irradiance (GHI) – total irradiance from sun on horizontal surface on earth – used for sizing flat plate collectors!

Long Term Average of Direct Normal Irradiation

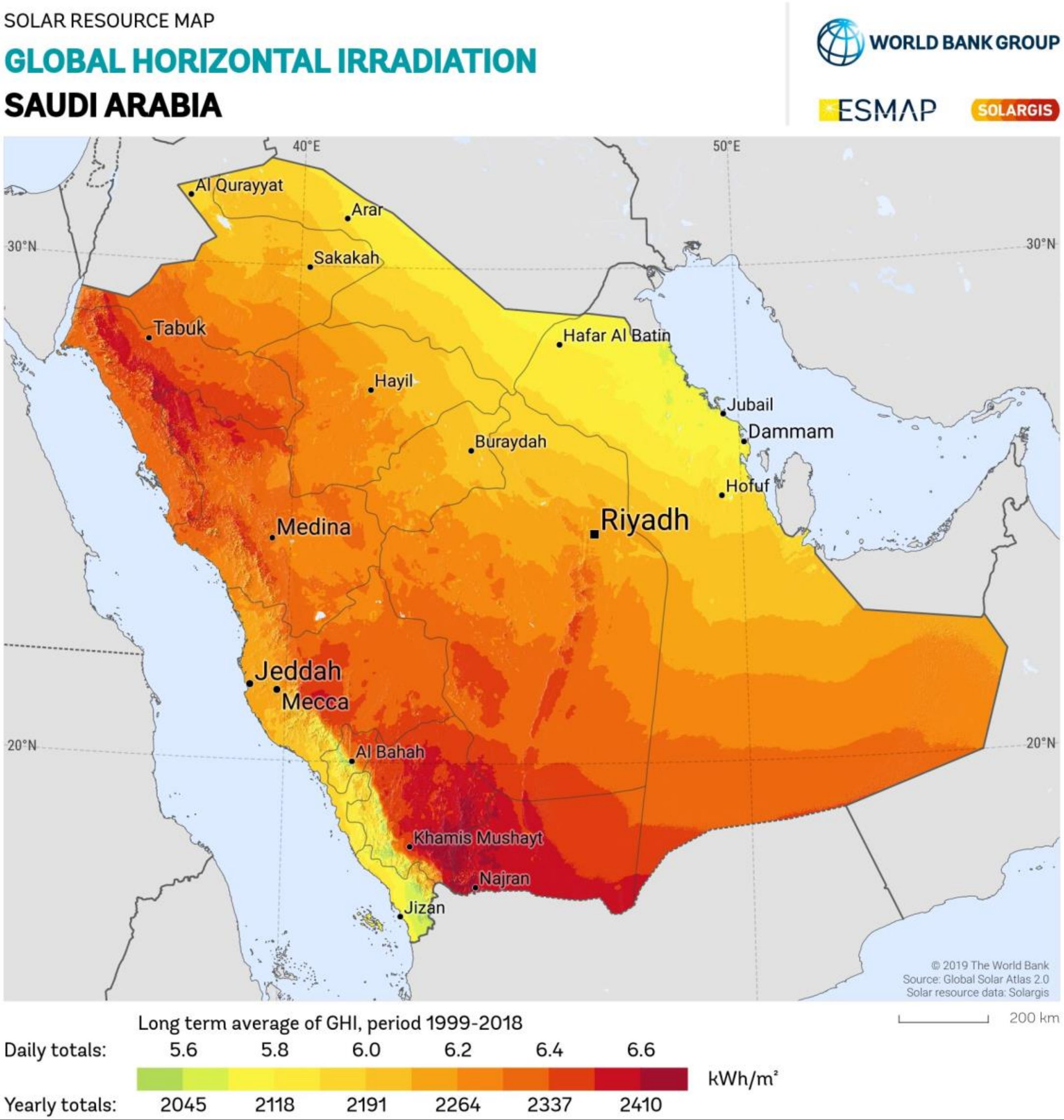


Long Term Average of DNI for KSA

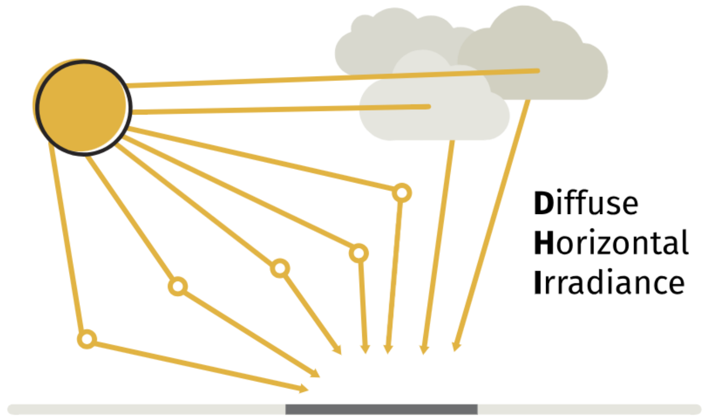




Long Term Average of GHI for KSA

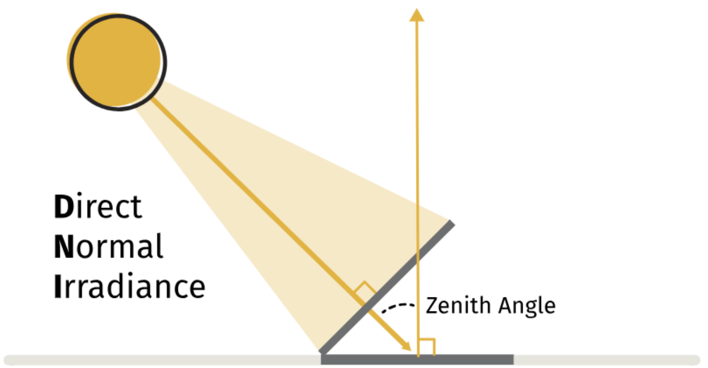


DHI



DNI

Clean Power Research LLC



GHI – total irradiance from sun on horizontal surface on earth

Solar Energy Conversion

Electromagnetic energy $\xrightarrow{\text{Heliochemical process}}$ **Chemical energy**

- Photosynthesis process (responsible for the production of fossil fuel & biomass)

Electromagnetic energy $\xrightarrow{\text{Heliothermal process}}$ **Thermal energy**

- Flat-plate collectors
- Concentrating collectors
- Heliostats

Electromagnetic energy $\xrightarrow{\text{Helioelectrical process}}$ **Electrical energy**

- Photovoltaic or solar cells

Awad.Alquaity@kfupm.edu.sa

Electromagnetic energy → Thermal energy

- Electricity can be produced from solar energy by using solar collectors to collect solar heat into a fluid and routing this fluid into a turbine.

- This may be viewed as indirect conversion of solar energy into electricity.

    - Flat-plate collectors
    - Concentrating collectors
    - Heliostats or Solar Tower

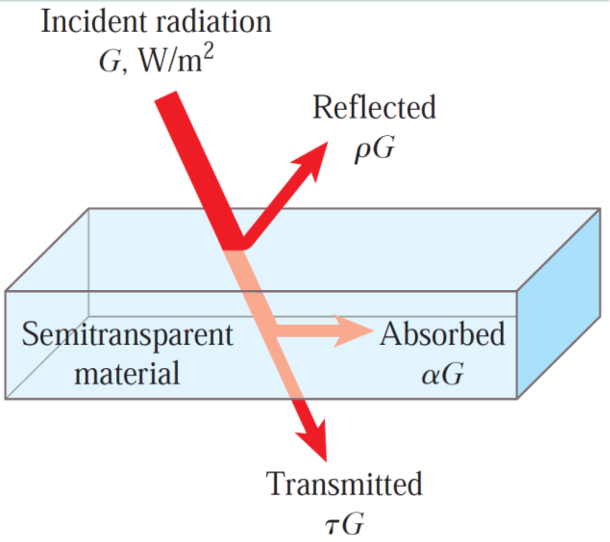
Absorption, Reflection, and Transmission

Applying **conservation of energy** to a surface for solar energy;

$$\begin{pmatrix}\text{Incident solar}\\ \text{radiation}\end{pmatrix} = \begin{pmatrix}\text{Reflected}\\ \text{radiation}\end{pmatrix} + \begin{pmatrix}\text{Absorbed}\\ \text{radiation}\end{pmatrix} + \begin{pmatrix}\text{Transmitted}\\ \text{radiation}\end{pmatrix}$$

reflectivity + absorptivity +transmissivity = 1

$$\rho + \alpha + \tau = 1$$



- **Emissivity ε** of a surface is a measure of how closely a real surface approximate a black body, for which $\varepsilon = 1$.
  - For a surface, $0 < \varepsilon < 1$
- **Spectral distributions** of incident solar radiation and emitted radiation by the surfaces are very different from each other.
- Solar radiation are concentrated in the short wavelength region and emitted radiation in the infrared region.
- Surfaces are assumed to have **two sets of properties**: one for solar radiation and another for infrared radiation at **room T**.
  - solar absorptivity α_s & emissivity ε of materials

at room temperature

Surface	α_s	ε
Aluminum		
Polished	0.09	0.03
Foil	0.15	0.05
Stainless steel		
Polished	0.37	0.60
Dull	0.50	0.21

For heat collection, materials with large values of α_s/ε are required.

For heat rejection, materials with small values of α_s/ε are desirable.

Flat-Plate Solar Collector – I

The objective of a solar collector is to produce useful heat from solar energy.

Applications: → Produce hot water for domestic use

→ Product hot water for 'process heating' in industrial facilities

→ Space heating in winter.

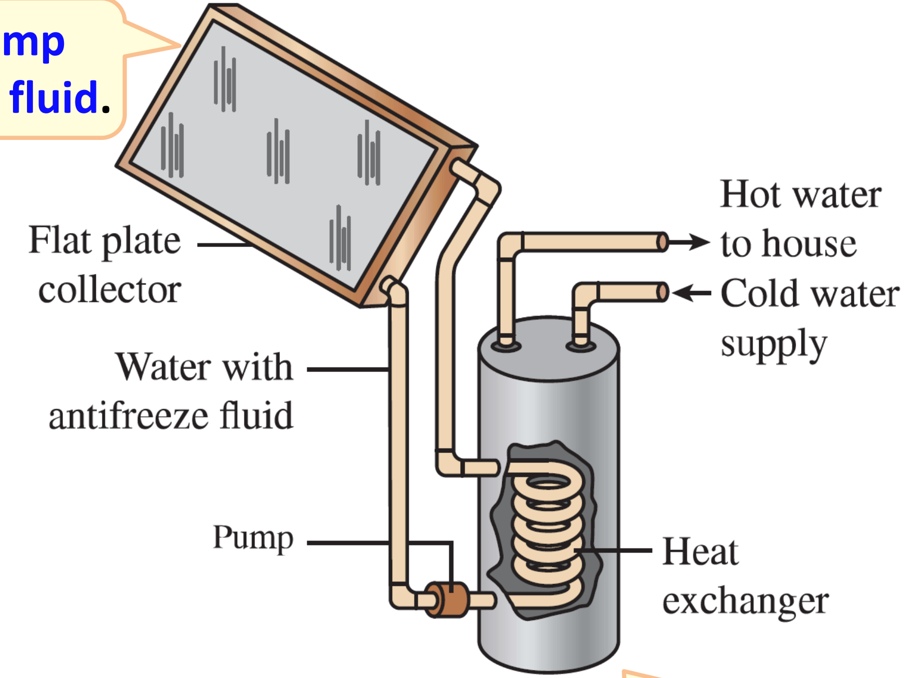
Solar collectors are very common in southern Europe and Asia where solar energy is available for more than 200 days a year.

The solar collector shown here is a **thermosyphon solar water heat system**, which operates on a natural circulation.

Water flows through the system when warm water rises into the tank as cooler water sinks.

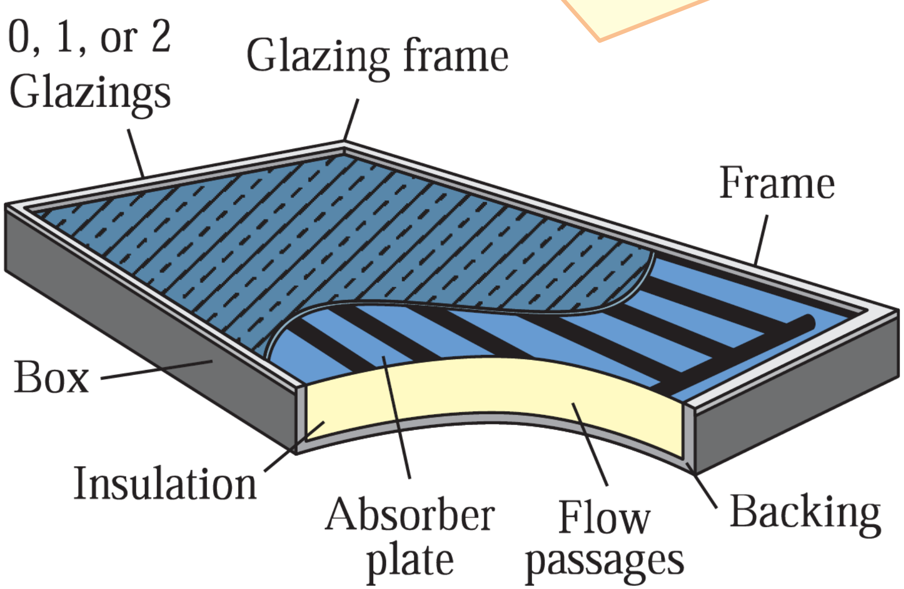
Flat-Plate Solar Collector – II

An active, closed loop solar water heater uses a pump for the recirculation of water containing antifreeze fluid.



Absorber plate absorbs solar energy transmitted through the glazing, which is a type of glass.

Flow tubes are attached to the absorber plate and water is heated as it flows in the tubes by absorbing heat from the absorber plate.



This system may be equipped with an electric resistance heater to provide hot water when solar energy is not available.

Flat-Plate Solar Collector – III

Rate of solar heat absorbed by the absorber plate is $\dot{Q}_{\text{abs}} = \tau\alpha AG$

Overall heat transfer coefficient for combined effects of conv. & rad.

Heat lost from the collector by convection to surrounding air and by radiation to surrounding surfaces and sky → $\dot{Q}_{\text{loss}} = UA\left(T_{\text{avg, }c} - T_{\text{air}}\right)$

Useful heat transferred to the water is $\dot{Q}_{\text{useful}} = \dot{Q}_{\text{abs}} - \dot{Q}_{\text{loss}} = A\left[\tau\alpha G - U\left(T_{\text{avg, }c} - T_{\text{air}}\right)\right]$

Thus the useful heat is maximized by minimizing $\dot{Q}_{\text{loss}}$ and maximizing $\dot{Q}_{\text{abs}}$!

If $\dot{m}$ of water flowing through collector is known; $\dot{Q}_{\text{useful}} = \dot{m}_w c_P\left(T_{w,\text{ out}} - T_{w,\text{ in}}\right)$

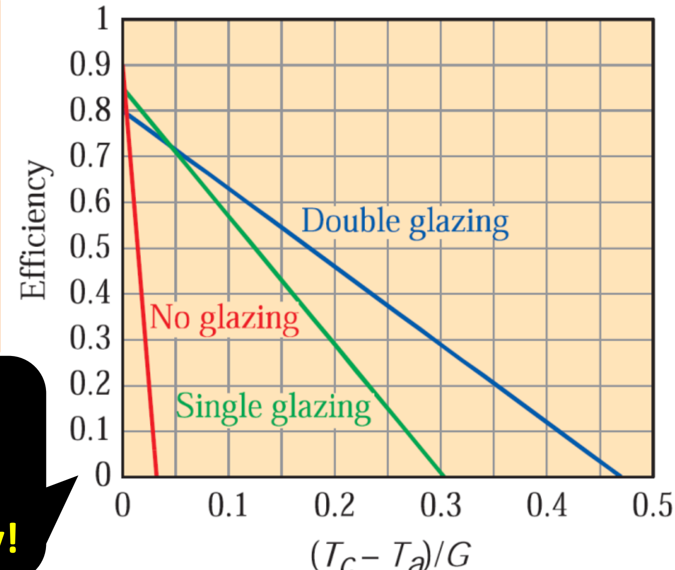
NOTE: For the same useful heat, a higher $\dot{m}_w$ would yield a lower $T_{w,\text{ out}}$.

Efficiency of a solar collector

$$\eta_c = \frac{\dot{Q}_{\text{useful}}}{\dot{Q}_{\text{incident}}} = \frac{A\left[\tau\alpha G - U\left(T_{\text{avg, }c} - T_{\text{air}}\right)\right]}{AG}$$

$$\eta_c = \tau\alpha - U\frac{T_{\text{avg, }c} - T_{\text{air}}}{G}$$

η_c is maximized for max. values of τ and α and for min. values values of U and $\left(T_{\text{avg, }c} - T_{\text{air}}\right)$



Unglazed collector allows more solar radiation input to the collector due to high $\tau\alpha$ values but also involves higher values of U.

Glazing reduces $\tau\alpha$ values, but U values decrease more significantly!

Flat-Plate Solar Collector – IV

$$\eta_c = \tau\alpha - U\frac{T_{\text{avg},\,c} - T_{\text{air}}}{G}$$

The collector's average temperature is usually not available. Instead, water temperature at the collector inlet is available

Therefore, η_c may be defined as a function of the water inlet temperature as:

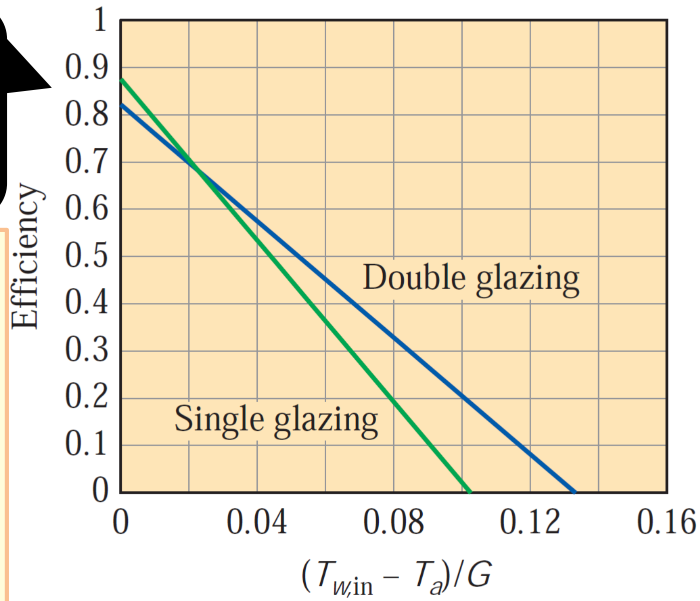
$\eta_c = F_R\tau\alpha - F_R U\frac{T_{w,\,\text{in}} - T_{\text{air}}}{G}$ *where* F_R is the collector heat removal factor as proposed by ASHRAE

- **The slope of the resulting straight line is $-F_R U$.**
- **The maximum η_c in this case is equal to the intercept of the line which is equal to $F_R\tau\alpha$.**

- The solar collector is normally fixed in a position.
- As the angle of solar incident radiation changes throughout the day, the product $\tau\alpha$ also changes.
- **Incident angle modifier** $K_{\tau\alpha}$ is used to account for this change.

$$\eta_c = F_R K_{\tau\alpha}\tau\alpha - F_R U\frac{T_{w,\,\text{in}} - T_{\text{air}}}{G}$$

$K_{\tau\alpha}$ is a function of the incident angle, and its value changes between 0 and 1.



Typical flat-plate solar collector properties

	$\tau\alpha$	U, W/m²·°C	U, Btu/h·ft²·°F
No glazing	0.90	28	5
Single glazing	0.85	2.8	0.5
Double glazing	0.80	1.7	0.3

Example: Efficiency of a Flat-Plat Solar Collector – I

The specifications of **two flat-plate collectors** are as follows:

Single glazing: τ=0.96, α=0.96, U=9 $\mathrm{W/m^2{\cdot}°C}$ **Double glazing**: τ=0.93, α=0.93, U=6.5 $\mathrm{W/m^2{\cdot}°C}$

Heat removal factor for both collectors is 0.95, solar insolation is 550 $\mathrm{W/m^2}$, and ambient T_{air} is 23°C.

Take the incident angle modifier to be 1.

(a) For each collector, determine the collector efficiency if the water enters the collector at 45°C.

Single glazing: $\eta_c = F_R K_{\tau\alpha}\tau\alpha - F_R U \dfrac{T_{w,\mathrm{in}} - T_a}{G} = \mathbf{0.534}$

Double glazing: $\eta_c = F_R K_{\tau\alpha}\tau\alpha - F_R U \dfrac{T_{w,\mathrm{in}} - T_a}{G} = \mathbf{0.575}$

(b) For each collector, find the temperature of water for which the collector efficiency is zero.

$$\eta_c = F_R K_{\tau\alpha}\tau\alpha - F_R U \frac{T_{w,\,\mathrm{in}} - T_{\mathrm{air}}}{G} \xrightarrow{\text{setting } \eta_c=0} F_R K_{\tau\alpha}\tau\alpha = F_R U \frac{T_{w,\,\mathrm{in}} - T_{\mathrm{air}}}{G}$$

Single glazing: $T_{w,\,\mathrm{in}} = 79.3°\mathrm{C}$

Double glazing: $T_{w,\,\mathrm{in}} = 96.2°\mathrm{C}$

Example: Efficiency of a Flat-Plat Solar Collector – II

The specifications of **two flat-plate collectors** are as follows:

Single glazing: τ=0.96, α=0.96, U=9 $\mathrm{W/m^2{\cdot}°C}$ **Double glazing**: τ=0.93, α=0.93, U=6.5 $\mathrm{W/m^2{\cdot}°C}$

Heat removal factor for both collectors is 0.95, solar insolation is 550 $\mathrm{W/m^2}$, and ambient T_{air} is 23°C. Take the incident angle modifier to be 1.

(c) For each collector, find the maximum collector efficiency.

$$\eta_c = F_R K_{\tau\alpha}\tau\alpha - F_R U \frac{T_{w,\text{ in}} - T_{\text{air}}}{G}$$

The collector efficiency is maximum when the water is equal to the air temperature $T_{w,\text{ in}} = T_{\text{air}}$

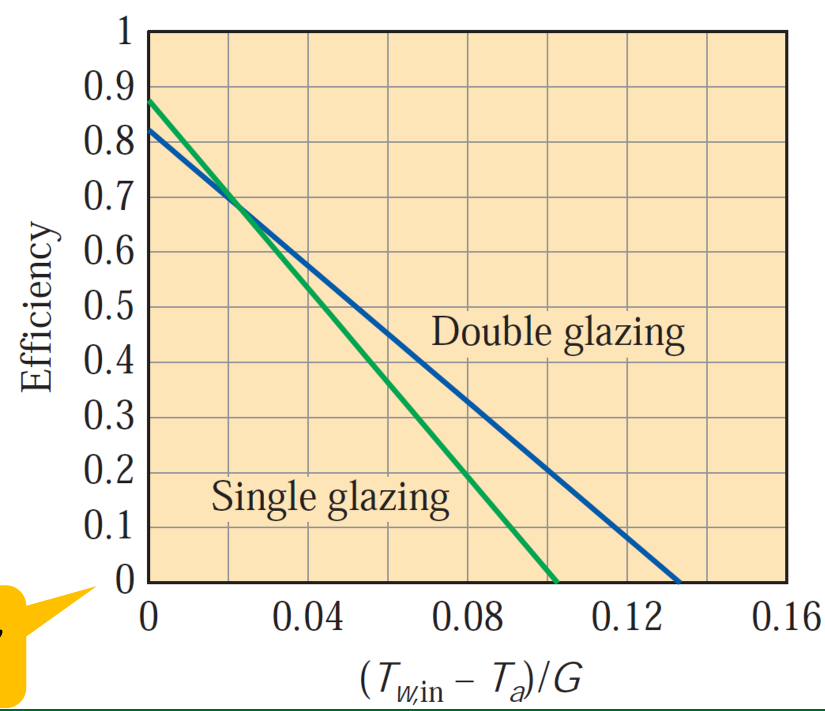
Therefore, $\eta_{c,\max} = F_R K_{\tau\alpha}\tau\alpha$

Single glazing: $\eta_{c,\max} = F_R K_{\tau\alpha}\tau\alpha = \mathbf{0.876}$

Double glazing: $\eta_{c,\max} = F_R K_{\tau\alpha}\tau\alpha = \mathbf{0.822}$

It turns out that collector with single glazing has a higher $\eta_{c,\max}$ than the collector with double glazing.

d) Plot the collector efficiency as a function of $(T_{w,\text{in}} - T_a)/G$ for each collector.



Note that the intercept on the figure represents the $\eta_{c,\max}$, as obtained in part (c)

Solar Water Heater Vs Electrical Heater

Pay back period is about 3 years in most cities in Saudi Arabia (about 400 SAR in annual savings)

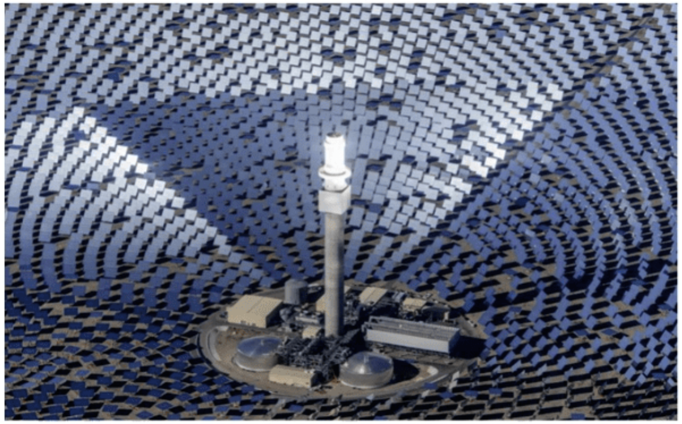
Recent revisions (2018) in electricity prices have made solar water heaters more attractive!

Solar-heated pools in hotels and residential buildings are driving demand for hot water in the country!

Solar Thermal Electricity Generation

CSP Technology Comparison

SUPCONSOLAR



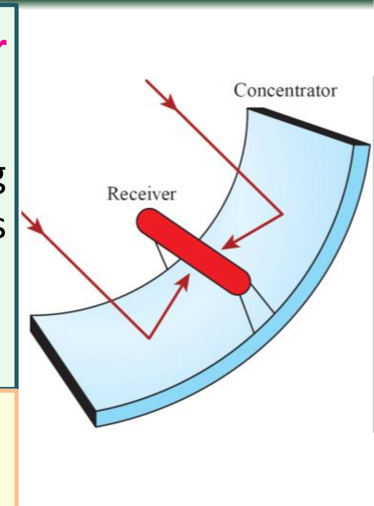
Comparison between Tower and Parabolic Trough		
Technology	**Tower**	**Parabolic Trough**
Technology Requirements	High requirements on logic control and tracking accuracy	Relatively simple and easy, low threshold of technology
Focusing Method	Point Focusing	Linear Focusing
Sunshine Tracking	Dual Axis	Single Axis
Thermal Loss	Low	High
Insulation	Simple and Cheap	Complex and Expensive
Storage		3 Times larger than Tower
Heat Exchanger	1 Set	2 Sets
Medium Temperature	565℃	390℃
Turbine Efficiency	45%	38.5%

https://www.solarpaces.org/how-chinas-cosin-solar-solved-some-tower-csp-challenges/

Concentrating Solar Collector – I

Solar energy concentration is low, and as a result, the temperature of hot water obtainable in a flat-plate collector is low (usually under 80°C).

- Hot fluid (water, steam, air, or another fluid) at higher T's can be produced using **concentrating collectors** by concentrating solar radiation on a small area. Examples include Parabolic trough, Fresnel reflector, Dish Stirling, and Power Tower.
- Most common type of concentrating solar collector is parabolic trough collector.



- **Solar radiation is incident** on the collector surface called aperture area, A_a.
- Incident radiation is then **reflected/redirected** into a smaller receiver area, A_r.

Concentration factor, $\mathrm{CR} = \dfrac{A_a}{A_r} > 1$

- The greater the value of CR, the greater the hot fluid temperature.
- The **effectiveness of the aperture-to-receiver process** is a function of **orientation of surface** and their **radiative properties** such as absorptivity and reflectivity.
- This effectiveness is expressed by an **optical efficiency** term η_{ar}.

Concentrating Solar Collector – II

Net rate of solar radiation supplied to the receiver → $\dot{Q}_r = \eta_{ar} A_a G$

Heat lost from the collector by convection to surrounding air and by radiation to surrounding surfaces and sky → $\dot{Q}_{\text{loss}} = UA_r\left(T_{\text{avg, }c} - T_{\text{air}}\right)$

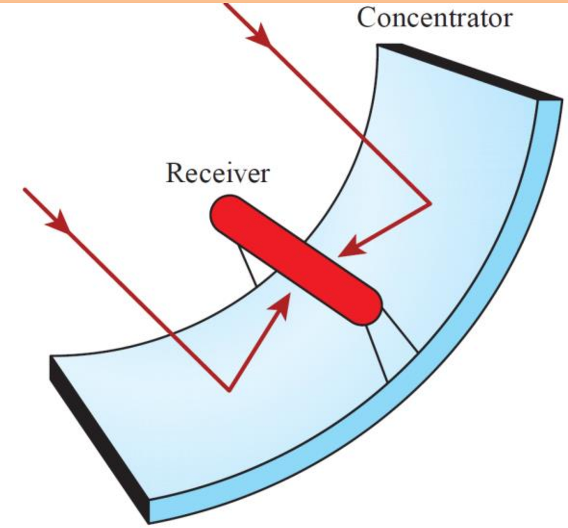
Useful heat transferred to the water → $\dot{Q}_{\text{useful}} = \dot{Q}_r - \dot{Q}_{\text{loss}} = \eta_{ar} A_a G - UA_r\left(T_{\text{avg, }c} - T_{\text{air}}\right)$

Concentrating solar collector's efficiency $$\eta_c = \frac{\dot{Q}_{\text{useful}}}{\dot{Q}_{\text{incident}}} = \frac{\eta_{ar} A_a G - UA_r\left(T_{\text{avg, }c} - T_{\text{air}}\right)}{A_a G} = \eta_{ar} - \frac{UA_r\left(T_{\text{avg, }c} - T_{\text{air}}\right)}{A_a G}$$

$$\eta_c = \eta_{ar} - \frac{U\left(T_{\text{avg, }c} - T_{\text{air}}\right)}{\text{CR} \times G} \qquad \because \text{CR} = \frac{A_a}{A_r}$$

Note: η_c is maximized for max. values ofof η_{ar} and CR and min. values of U and $\left(T_{\text{avg, }c} - T_{\text{air}}\right)$

- η_c of concentrating collectors $>$ η_c of flat-plate collectors
- Plot of η_c vs $\left(T_{\text{avg, }c} - T_{\text{air}}\right)/(\text{CR} \times G)$ gives a straight line with slope equal to $-U$.
- T's in the receiver of a concentrating collector can reach 400°C .
- The heat transfer fluid is usually thermal oil and water is converted to steam in a heat exchanger to drive a steam turbine.



Linear Concentrating Solar Power (CSP) Collector – I

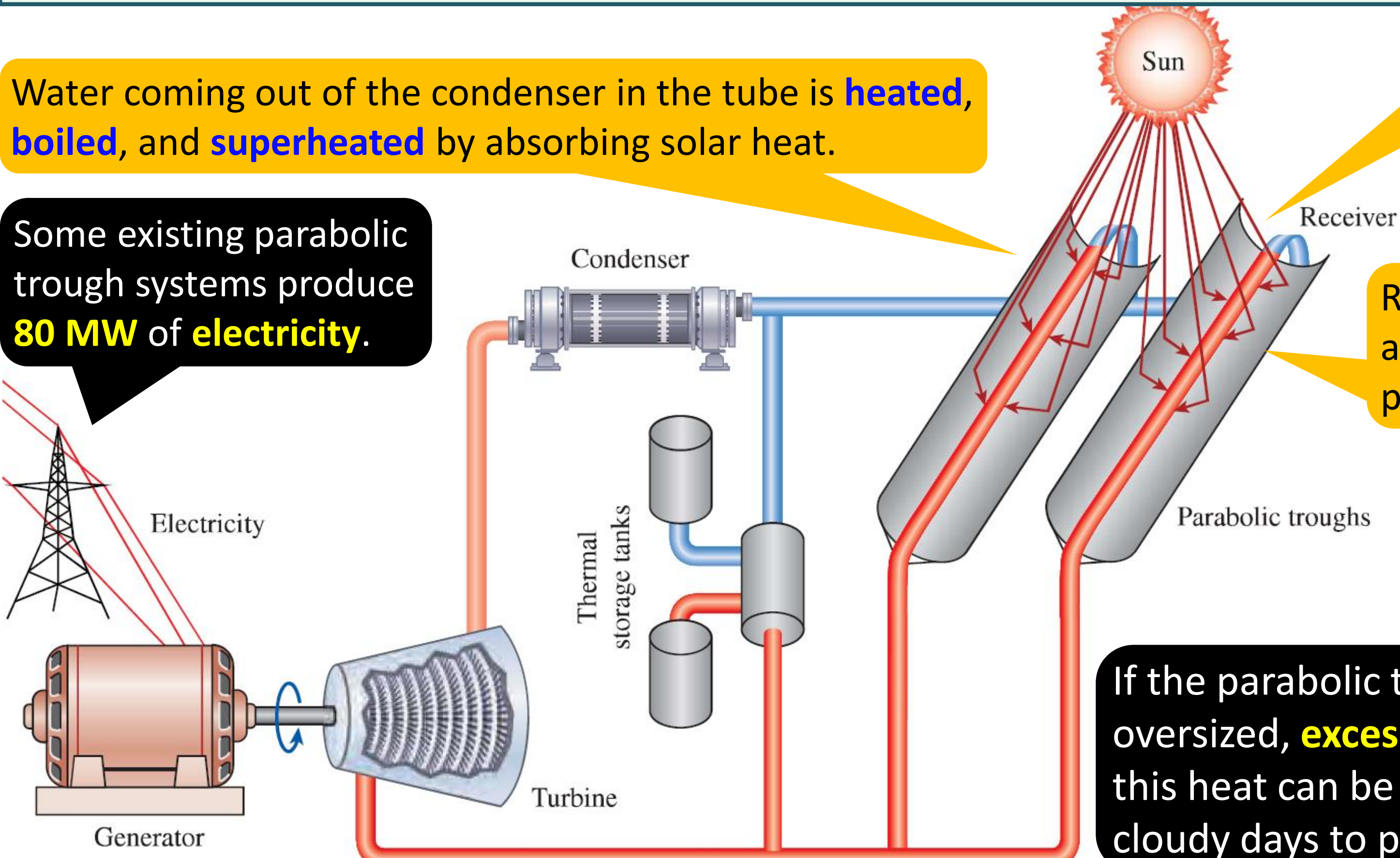
Linear CSP collectors are used to capture and reflect solar radiation onto a linear receiver tube.

- **Common Application:** Produce steam to drive a steam turbine to generate electricity.
- In order to produce **reasonable amounts** of electrical power, **a large number of collectors in parallel rows** are used to collect solar heat.

Water coming out of the condenser in the tube is **heated**, **boiled**, and **superheated** by absorbing solar heat.

The most common linear concentrator is **parabolic trough collector**.

Some existing parabolic trough systems produce **80 MW** of **electricity**.



Receiver tube is positioned along the **focal line** of each parabolic reflector.

Note: All steam power plants have a pump, schematic lacks details

If the parabolic trough collectors are oversized, **excess heat can be stored** and this heat can be used during nighttime or cloudy days to produce electricity.

Linear Concentrating Solar Power (CSP) Collector – II

- These solar plants can be **integrated with conventional power plants** utilizing natural gas or coal.
- The system may be designed such that **electricity is supplied by solar as much as possible** and **conventional system is used as backup** when solar heat is not available.

The **efficiency of a solar system** used to produced electricity may be defined as the power produced divided by the total solar irradiation.

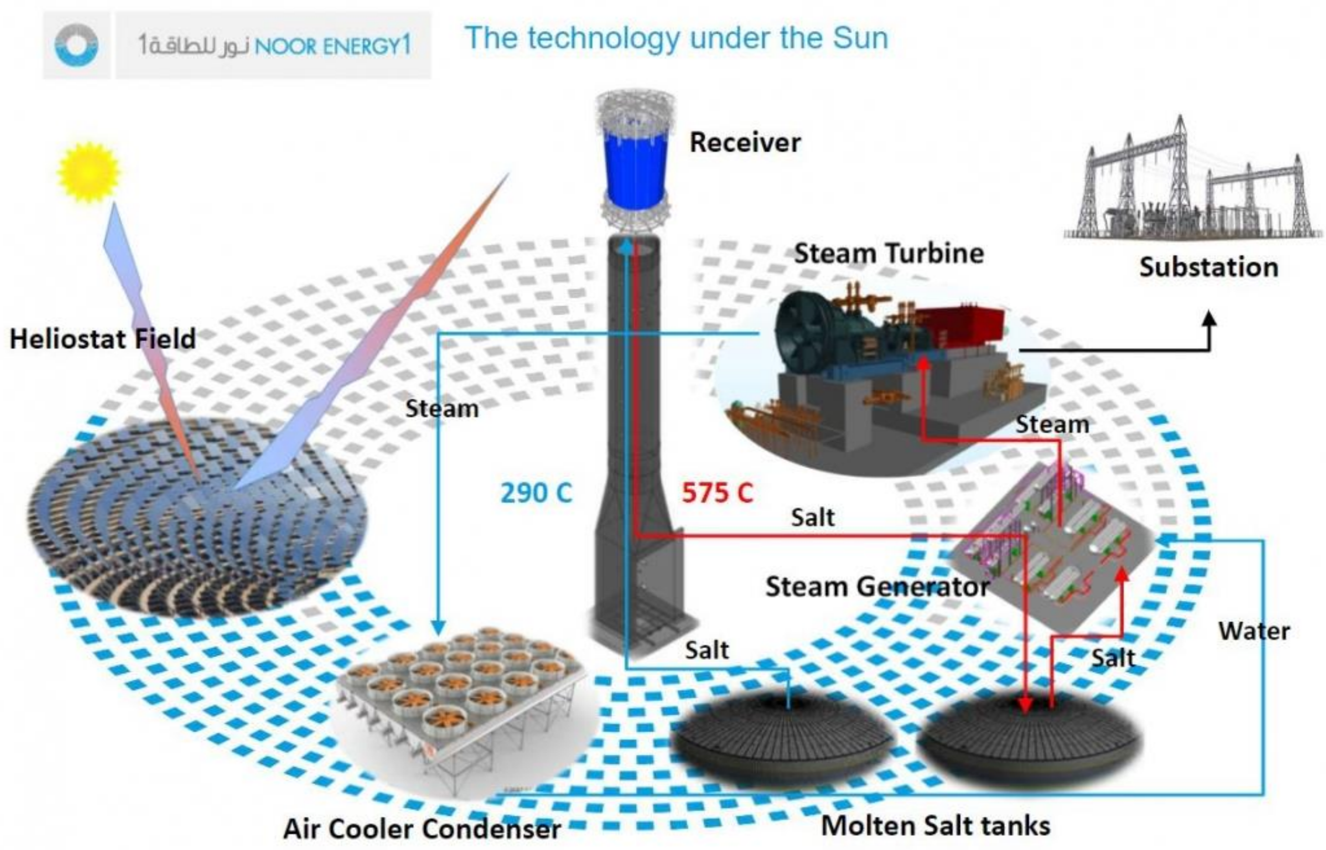
$$\eta_{\text{th,solar}} = \frac{\dot{W}_{\text{out}}}{\dot{Q}_{\text{incident}}} = \frac{\dot{W}_{\text{out}}}{A_c G}$$

where, A_c is the collector surface area receiving solar irradiation
G is the solar irradiation

Point Focus type Collector: Solar-Power-Tower Plant – I

A solar-power-tower plant uses a large array of mirrors called heliostats that track the sun and reflects solar radiation into a receiver mounted on top of a tower.

- Point focus type collectors have CR of about 500 compared to 50 for linear focus type collectors.
- Water is heated, boiled, and superheated by absorbing heat from the receiver system.
- The resulting steam is directed to a turbine to produce power.
- A generator is connected to turbine to convert turbine shaft power into electricity.



Note: All steam power plants have a pump, schematic lacks details

Solar-Power-Tower Plant – II

- The **Gemasolar power plant** in Spain occupying a field of 185 hectares, consists of **2650 heliostats** that focus **95% of solar radiation** onto a giant receiver.
- The temperatures as high as **900**°C are obtained at the receiver.

- Molten salt tanks are heated by concentrated solar heat reaching a temperature of above 500°C.
- Water runs through the molten salt tanks in which it is **boiled** and **superheated**.
- The resulting steam is directed to **turbines** to produce power.
- Steam leaving the turbine is **condensed** and **pumped back** to the molten salt tanks to repeat the **heat engine cycle**.
- The plant can **store heat** and use it for a period of 15 hours in absence of daylight.

The plant has an installed capacity of 19.9 MW and can produce 110 GWh of electricity per year.

- Enough electricity is produced for 25,000 homes for 270 days a year.
- Cost has reduced from **10 times** higher than electricity produced by fossil fuel power plants to only **2 times higher** in certain regions!

China’s 100 MW Solar Tower Plant

https://www.youtube.com/watch?v=sPRMOUVM4BM

Example: Thermodynamic analysis of a solar-power-tower plant – I

A **solar-power-tower plant** is considered for Dhahran. Heliostats with a total area of 80,000 m^2 are to be used to reflect solar radiation into a receiver. When the solar irradiation is 950 W/m^2, steam is produced at 2 MPa and 400°C at a rate of 20 kg/s. This steam is expanded in a turbine to 20 kPa pressure. The isentropic efficiency of the turbine is 85%. Neglect the work input to the pump.

(a) Determine the $\dot{W}_{\text{output}}$ and the η_{th} of the plant under these operating conditions.

Assumptions: Steady operating conditions exist; $\Delta KE = \Delta PE = 0$

$$\dot{W}_{\text{out}} = \dot{m}(h_1 - h_2)$$

$$\left.\begin{array}{l} P_1 = 2\text{ MPa} \\ T_1 = 400°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 3248.4\text{ kJ/kg} \\ s_1 = 7.1292\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 20\text{ kPa} \\ s_2 = s_1 \end{array}\right\} h_{2s} = 2349.7\text{ kJ/kg}$$

$$\eta_T = \frac{h_1 - h_2}{h_1 - h_{2s}} \longrightarrow h_2 = h_1 - \eta_T(h_1 - h_{2s}) = 2484.5\text{ kJ/kg}$$

$$\dot{W}_{\text{out}} = \dot{m}(h_1 - h_2) = \mathbf{15{,}280\ kW}$$

The thermal efficiency of this power plant is equal to power output divided by the total solar incident on the heliostats:

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{out}}}{AG} = \frac{15{,}280\text{ kW}}{(80{,}000\text{ m}^2)(0.950\text{ kW/m}^2)} = 0.201 \text{ or } \mathbf{20.1\%}$$

Example: Thermodynamic analysis of a solar-power-tower plant – II

A **solar-power-tower plant** is considered for Dhahran. Heliostats with a total area of 80,000 m^2 are to be used to reflect solar radiation into a receiver. When the solar irradiation is 950 $\mathrm{W/m^2}$, steam is produced at 2 MPa and 400°C at a rate of 20 kg/s. This steam is expanded in a turbine to 20 kPa pressure. The isentropic efficiency of the turbine is 85%.

(b) How much electricity can be produced per year if the average η_{th} is 15% and the generator efficiency is 96%.

Average annual DNI or beam irradiation in Dhahran → 1843.6 kWh/m^2 (Source: Solar Atlas)

Estimate of solar irradiation on all the heliostat surfaces = 1843.6 kWh/m^2 × 80000 m^2

$$\eta_{\mathrm{th}} = \frac{W_{\mathrm{out}}}{AG} \quad \rightarrow \quad W_{\mathrm{out}} = \eta_{\mathrm{th}} AG = 0.15 \times 80000 \times 1843.6$$

$$W_{\mathrm{out}} = 22.12 \times 10^6 \; kWh$$

This is total work output from the turbine.

The electrical energy output from the generator is:

$$W_{\mathrm{elect}} = \eta_{\mathrm{gen}} W_{\mathrm{out}} = 0.96 \times 22.12 \times 10^6 = 21.23 \times 10^6 \; kWh$$

If the electricity produced by this plant is sold at a price of SAR 0.18/kWh, the potential revenue from selling of electricity becomes SAR 3.8 million per year.

Solar Thermal Plan in KSA & Global Outlook

- By 2030, close to 60 GW of electricity will come from renewables in Saudi Arabia with 40 GW coming from solar PV, 16 GW from wind and 2.7 GW from concentrated solar power technologies.
- Recent reductions in the price for the new CSP technology reaching 7.3 cents per kWh for the Power Tower Project (Noor I) in UAE has provided an immense fillip to the technology – project being developed by ACWA Power – a Saudi based company
- According to International Energy Agency (IEA), concentrated solar power could account for up to 25% of the world's energy needs by 2050.

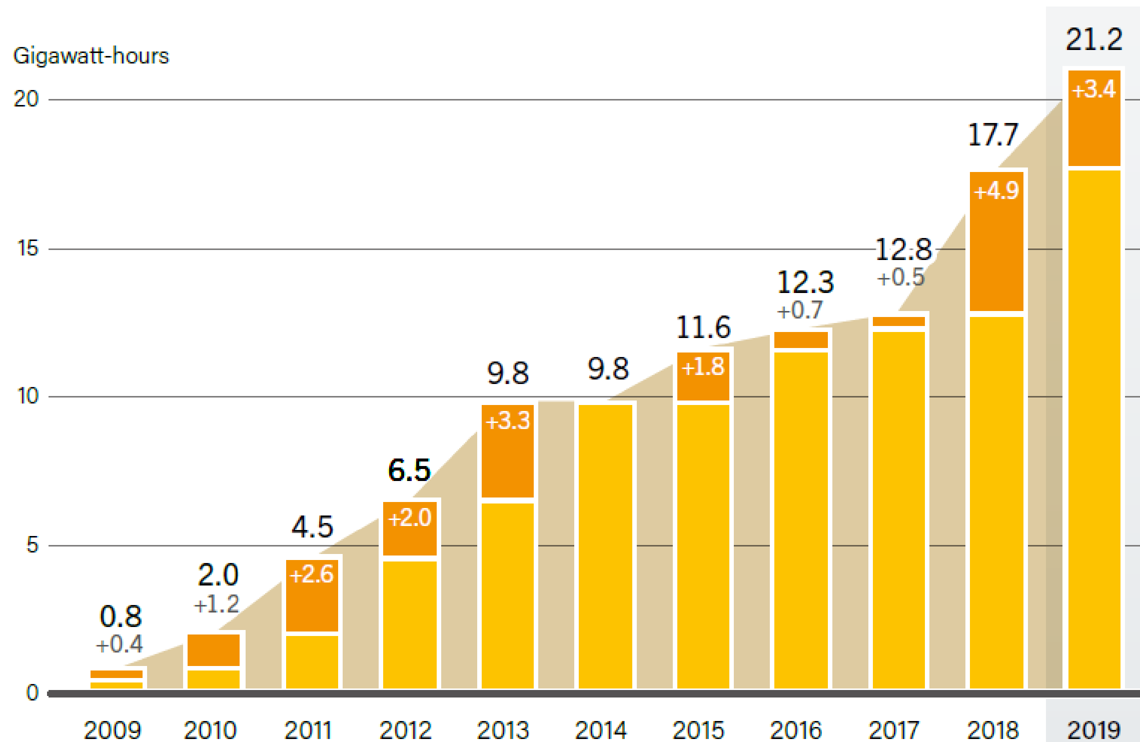


Figure. CSP Thermal Energy Storage Global Capacity and Annual Additions (Renewables 2020: Global Status Report)

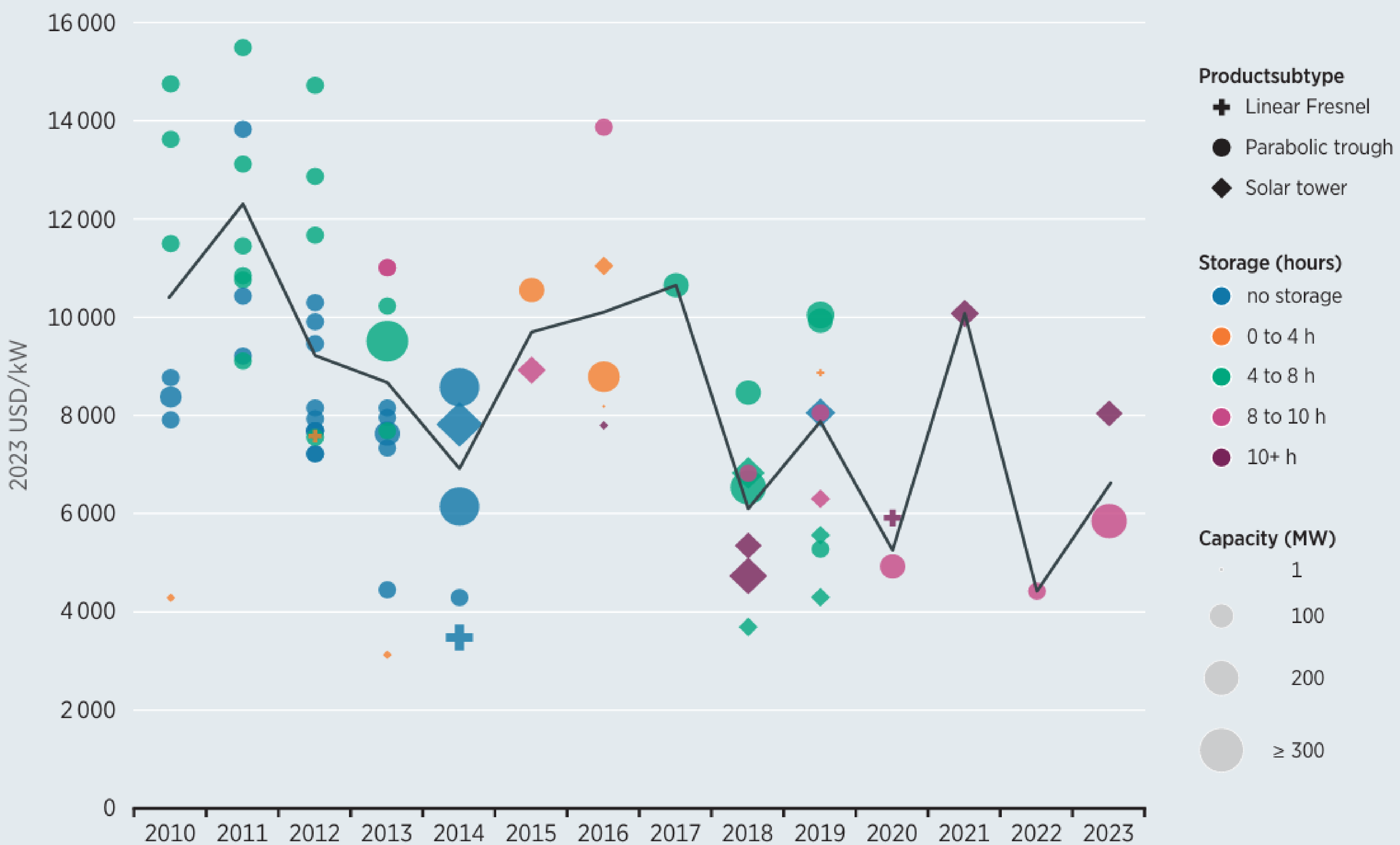
Integrated Solar Combined Cycle - Duba

- The Green Duba integrated solar combined-cycle (ISCC) power plant is a 600MW project under construction in Tabuk along the Red Sea coast
- Being implemented by state-owned Saudi Electricity Company (SEC), Green Duba will be Saudi Arabia's first fossil fuel-fired power plant to utilize solar energy for more efficient power generation
- The integrated project consists of a 550MW gas/condensate-fired combined-cycle facility and a parabolic trough type concentrated solar power (CSP) facility capable of generating up to 50MW of additional electricity.
- The Green Duba combined-cycle power plant will feature two GE F-Class gas turbines, as well as a steam turbine, two heat recovery steam generators (HRSG), a condenser, and boiler feed pumps also from GE.

- Details of combined cycle power plant and CSP facility – in HW

Source: https://www.nsenergybusiness.com/projects/green-duba-integrated-solar-combined-cycle-power-plant/

Total Installation Cost by Technology



IRENA (2024), Renewable power generation costs in 2023, International Renewable Energy Agency, Abu Dhabi.

LCOE Example – I

A **solar power plant** is planned for construction in **Tabuk**, **Saudi Arabia**, utilizing **Concentrated Solar Power (CSP) technologies**: **parabolic trough** and **solar tower**. The total installed capacity of each technology is **100 MW**, with an expected operational lifetime of **25 years**. The plant operates with the following parameters:

Solar Parabolic Trough:
Capacity Factor: 45% (10 hours of storage)
Operation Hours per Year: 3,950 hours
Total Capital Costs: SAR 15 million/MW
O&M Costs: SAR 49/MWh

Solar Tower:
Capacity Factor: 55% (15 hours of storage)
Operation Hours per Year: 4,380 hours
Total Capital Costs: SAR 20 million/MW
O&M Costs: SAR 45/MWh

Given these parameters, determine the **Levelized Cost of Electricity (LCOE)** in **SAR per MWh** to assess the cost-effectiveness of the plant. How does it compare with the LCOE of SAR 172/MWh for the 1800 MW Rumah 1 Combined Cycle power plant?

LCOE Example – Solution

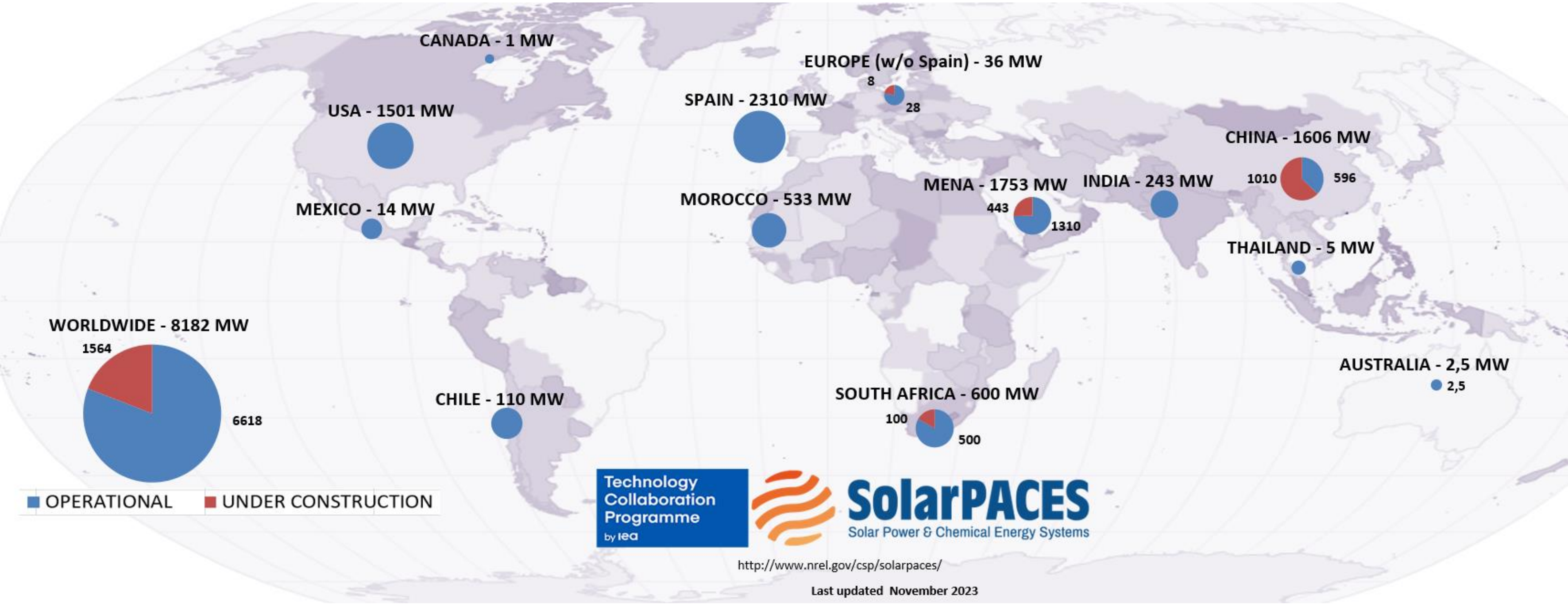
1. **Solar Parabolic Trough LCOE calculation:**
    1. Capital cost = 15 x 100 million SAR = 1500 million SAR
    2. Annual energy output = Capacity Factor x Capacity x Operation Hours/Year
       = 0.45 x 100 MW x 3950 = 177750 MWh
    3. Annual O&M costs = 49 x 177750 = 8.709 million SAR
    4. Total lifetime cost = Capital cost + O&M cost = 1500 + 25 x 8.709
       = 1717.74 million SAR
    5. Total lifetime energy = 25 x 177750 = 4443750 MWh

    LCOE = Total lifetime cost/Total lifetime energy = **386.5 SAR/MWh**
2. **Solar Tower LCOE calculation:**
    1. Capital cost = 20 x 100 million SAR = 2000 million SAR
    2. Annual energy output = Capacity Factor x Capacity x Operation Hours/Year
       = 0.55 x 100 MW x 4380 = 240900 MWh
    3. Annual O&M costs = 45 x 240900 = 10.84 million SAR
    4. Total lifetime cost = Capital cost + O&M cost = 2000 + 25 x 10.84
       = 2271 million SAR
    5. Total lifetime energy = 25 x 240900 = 6022500 MWh

    LCOE = Total lifetime cost/Total lifetime energy = **377.1 SAR/MWh**

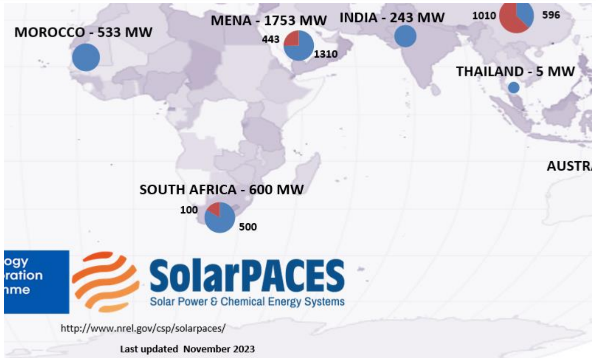
LCOE for Solar Tower and Solar Trough is similar and is about 2.2 times the LCOE for combined cycle power plant!

Solar Thermal Plants Globally



https://www.solarpaces.org/worldwide-csp/csp-projects-around-the-world

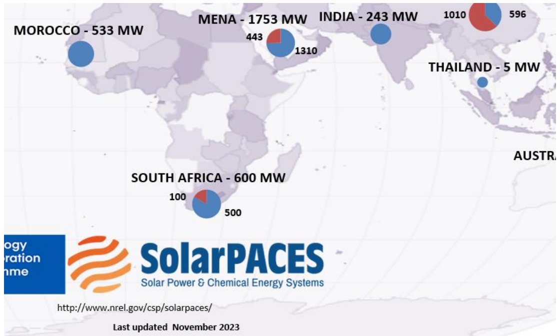
Solar Thermal Plants Globally – Group Activity – I



https://solarpaces.nrel.gov/concentrating-solar-power-projects-country

Location	Power Output	Type	Details: Working Fluid, Storage Receiver inlet and outlet T's, Cooling
ISCC Hassi Algeria	20 MW	Parabolic	Thermal oil, 293 C inlet temperature and 393 C outlet temperature, Dry cooling
ISCC Kuraymat, Egypt	20 MW	Parabolic	Thermal oil, 293 C inlet temperature and 393 C outlet temperature, Wet cooling
Noor Energy 1, UAE	600 MW	Parabolic Trough	Thermal oil, molten salt as storage
Noor III, Morocco	150 MW	Tower	Molten salt, 290 C inlet and 590 C outlet
Shams 1, UAE	100 MW	Parabolic	Thermal oil, 300 C inlet temperature and 400 C outlet temperature

Solar Thermal Plants Globally – Group Activity – II



https://solarpaces.nrel.gov/concentrating-solar-power-projects-country

Location	Power Output	Type	Details: Working Fluid, Storage Receiver inlet and outlet T's, Cooling