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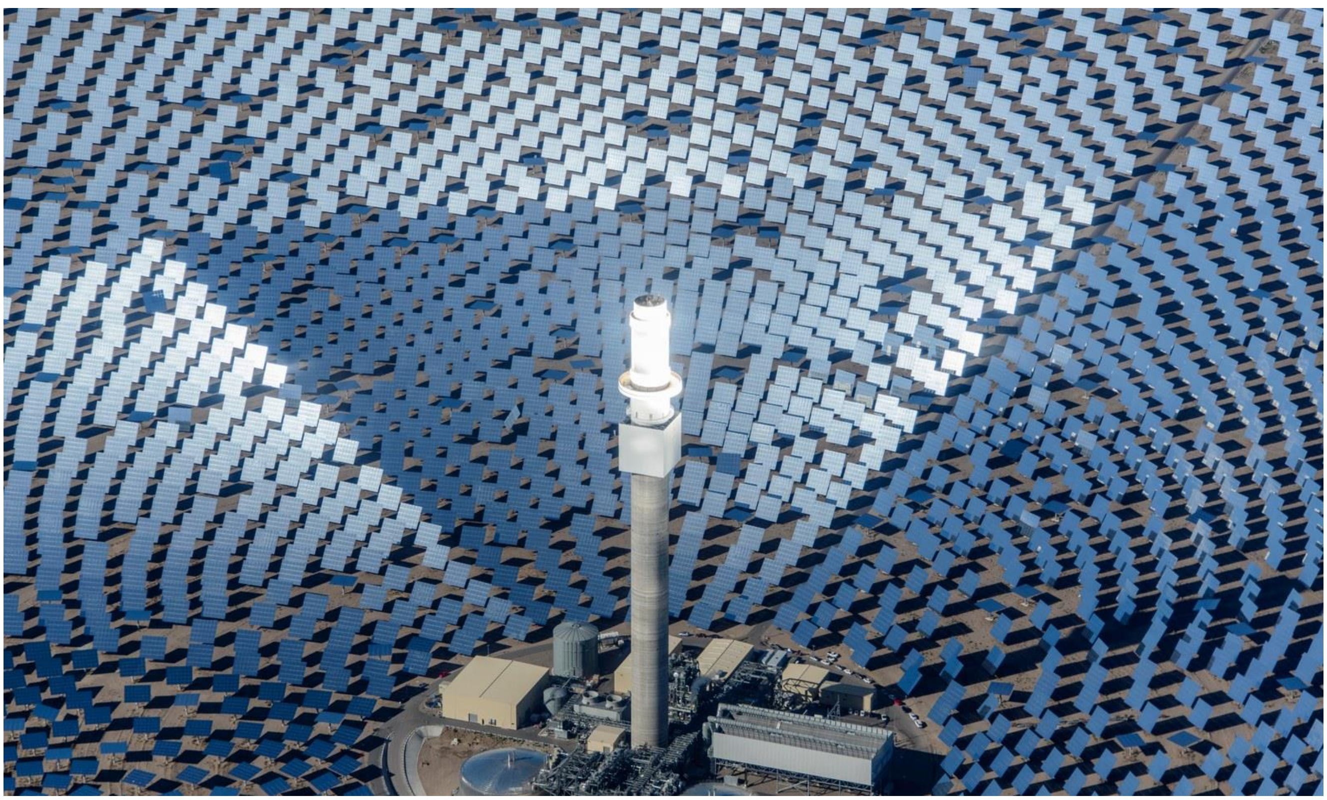
solar thermal power plant



prepared by electrical Engineer : -

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Introduction

The world's total energy demand could increase by 50% or higher by 2030. To address tomorrow's energy demands, secure, sustainable, and cost-e active carbon-free energy production is imperative. The rise in the energy demand due to the growing population and economy cannot be met by resorting to conventional energy sources such as fossil fuels or nuclear power. As per the Paris agreement, most of the world's countries are committed to reducing carbon emissions so as to limit the global average temperature rise to well below 2 C. Renewables in the global energy mix stand at 26% in the year 2018 and they have to reach 50% by 2030 according to the Sustainable Development Scenario (SDS) of the International Energy Agency (IEA).Solar thermal electricity generation offers a renewable and sustainable alternative to fossil fuels ,It contributes to reducing greenhouse gas emissions and mitigating climate change .

Solar thermal energy refers to the technology that harnesses solar radiation to generate thermal energy (heat).

Unlike photovoltaic (PV) systems that convert sunlight directly into electricity, solar thermal systems use sunlight to heat a fluid, which can then be used for various applications such as domestic hot water, space heating, or electricity generation.

Historical
* The concept of using solar energy for heating dates bake to ancient times, with the Greeks and Romans utilizing passive solar designs

* modern solar thermal technology development began in the 20^{th} century , with significant advancements during the energy crises of the 1970s .

1. Basic Principles

- **Conversion Process**
  - ⇛ Solar radiation is concentrated to produce high-temperature heat.
  - ⇛ This heat is used to generate steam.
  - ⇛ The steam drives a turbine connected to a generator, producing electricity.
- **Components Involved**
  - ⇛ **Solar Collectors**: Concentrate sunlight.
  - ⇛ **Heat Transfer Fluid (HTF)**: Absorbs and transports heat.
  - ⇛ **Steam Generator**: Converts heat to steam.
  - ⇛ **Turbine and Generator**: Convert mechanical energy into electricity.

2. Types of Solar Thermal Power Plants

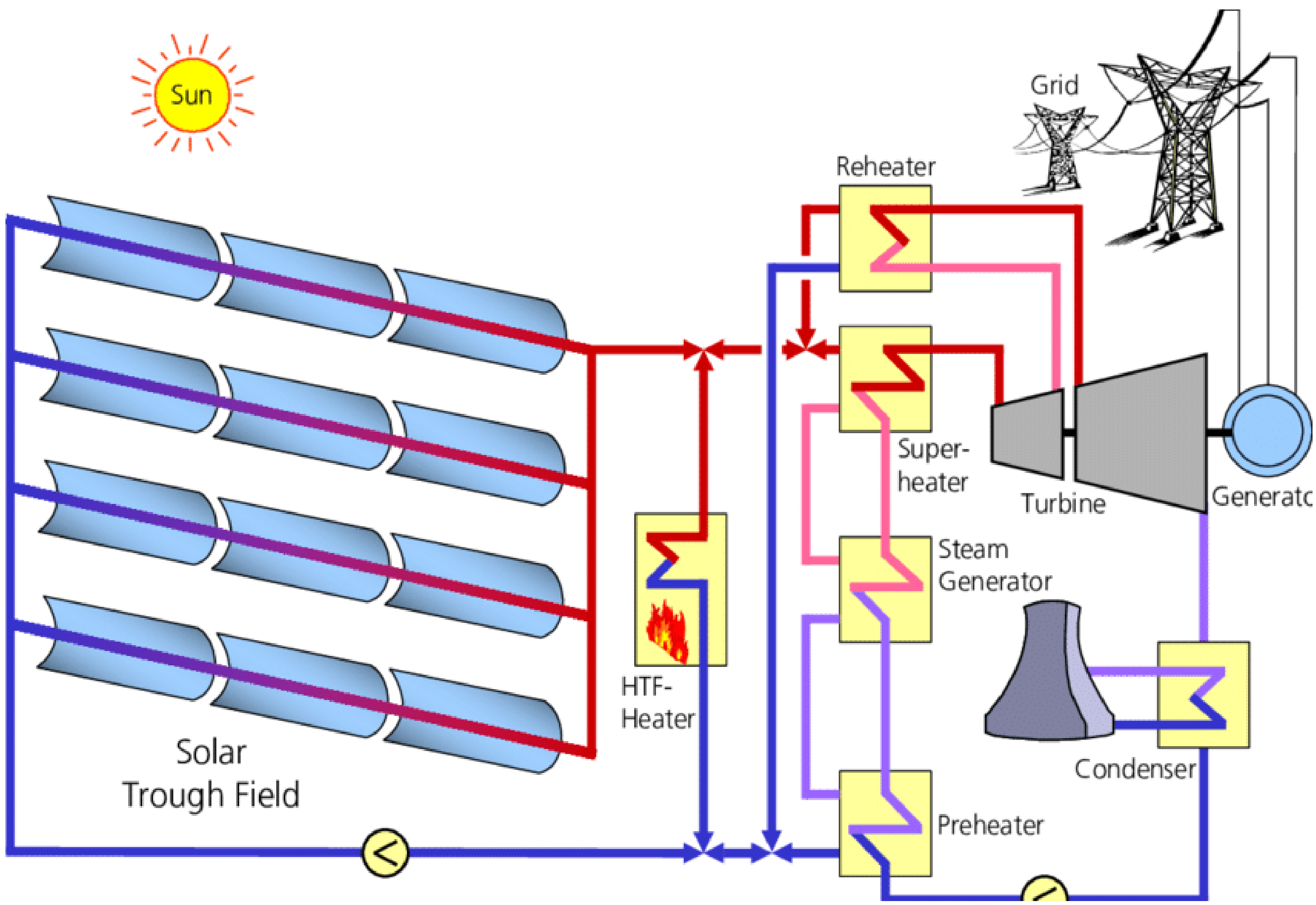
A-Parabolic Trough Systems

- **Description**
  - Uses parabolic-shaped mirrors to focus sunlight onto a receiver tube running along the focal line of the trough.
  - The HTF in the receiver tube is heated and used to produce steam.

⇒ **Applications**
  - Suitable for large-scale power generation in regions with high direct sunlight.

⇒ **Advantages**
  - Established technology with numerous operational plants.
  - High efficiency and scalability.

⇒ **Disadvantages**
  - Requires large land areas.
  - High initial investment costs.



B-Power Tower (Central Receiver) Systems

⇒ **Description**

- A field of mirrors (heliostats) focuses sunlight onto a central receiver atop a tower.
- The HTF, often molten salt, is heated in the receiver and used to generate steam.

⇒ **Applications**

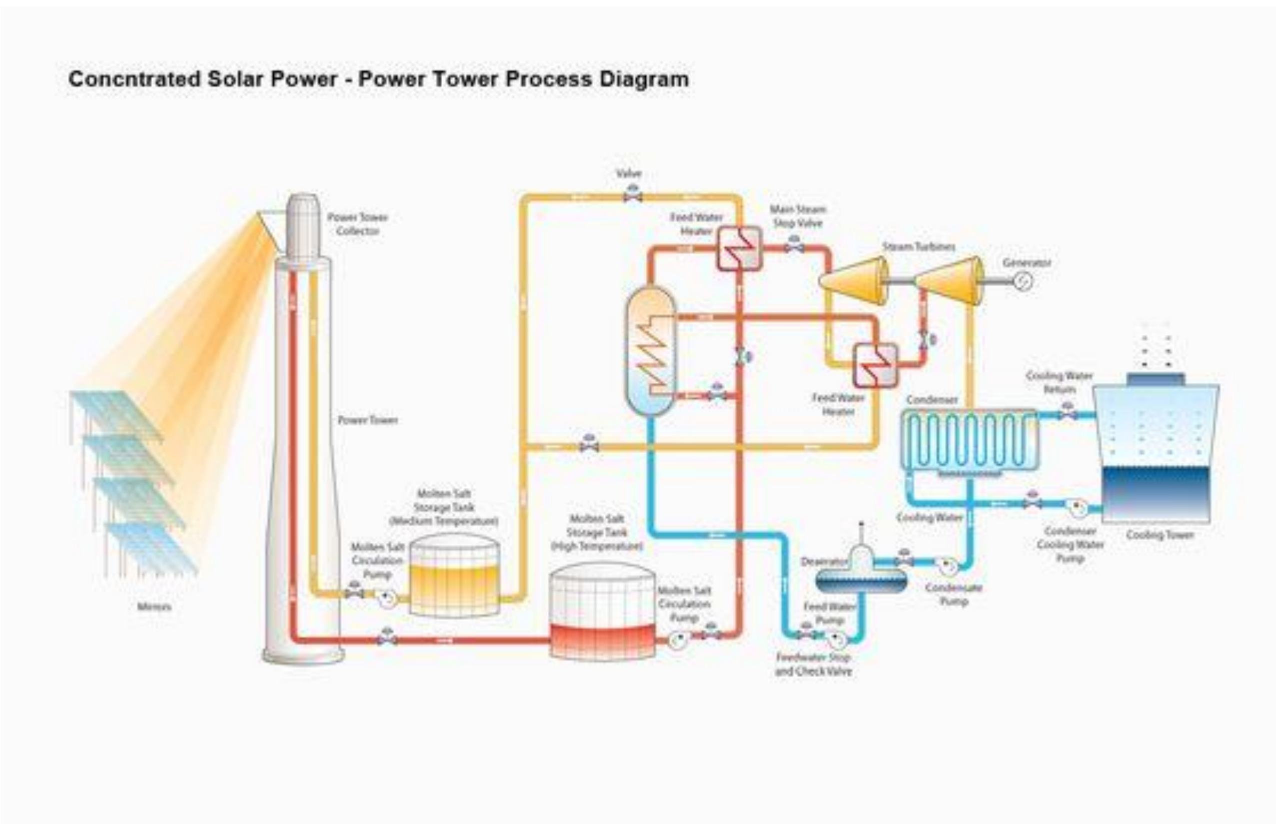
- Ideal for large, utility-scale power plants.

⇒ **Advantages**

- Higher temperatures and efficiency compared to trough systems.
- Better thermal storage capabilities.

⇒ **Disadvantages**

- Complex and costly to build and maintain.
- Requires precise tracking systems for heliostats.



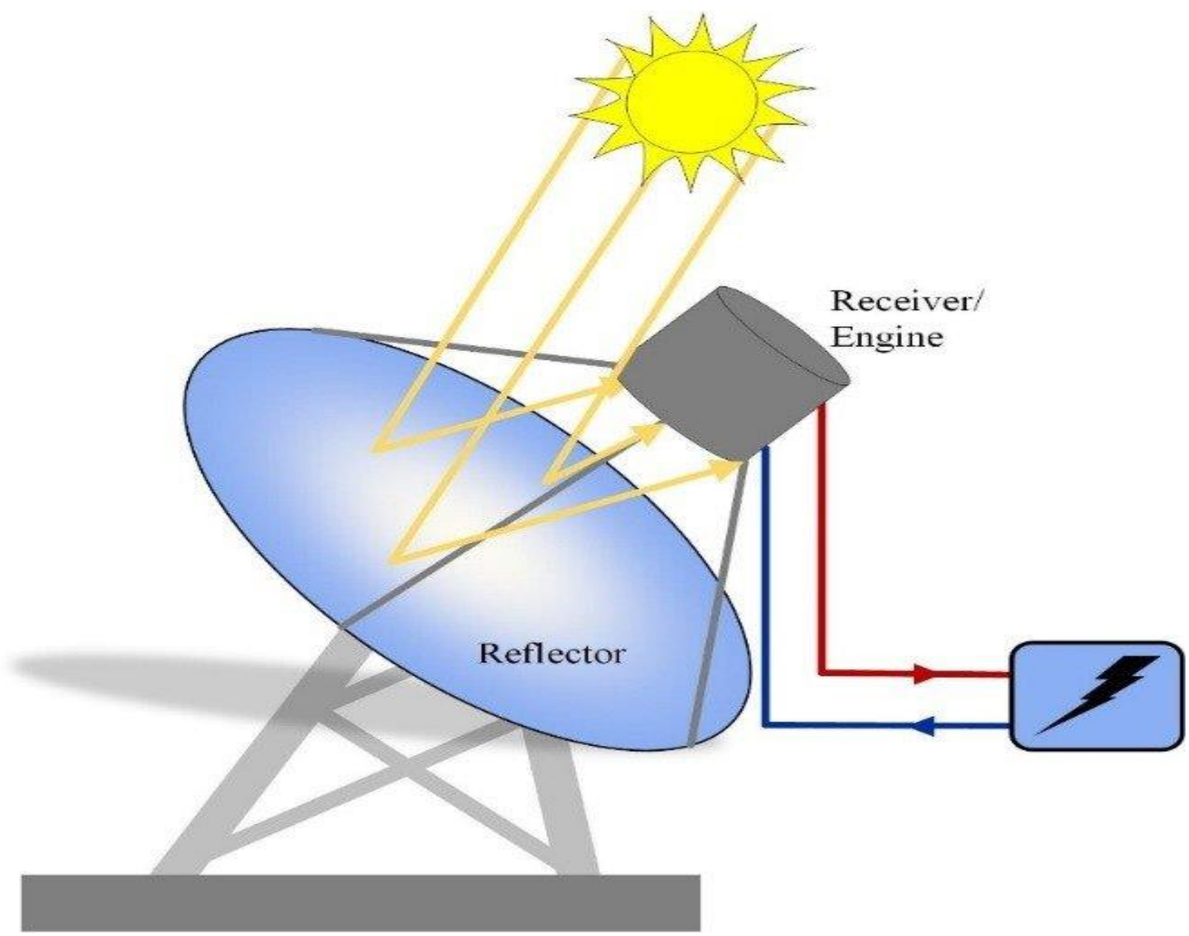
C-Parabolic Dish Systems

⇒ **Description**
- Uses dish-shaped mirrors to focus sunlight onto a receiver at the focal point.
- Typically paired with a Stirling engine or other heat engines.

⇒ **Applications**
- Suitable for smaller, distributed power generation.

⇒ **Advantages**
- High efficiency due to direct energy conversion.
- Modular and scalable.

⇒ **Disadvantages**
- More complex and expensive per unit of capacity compared to other systems.
- Limited commercial deployment.



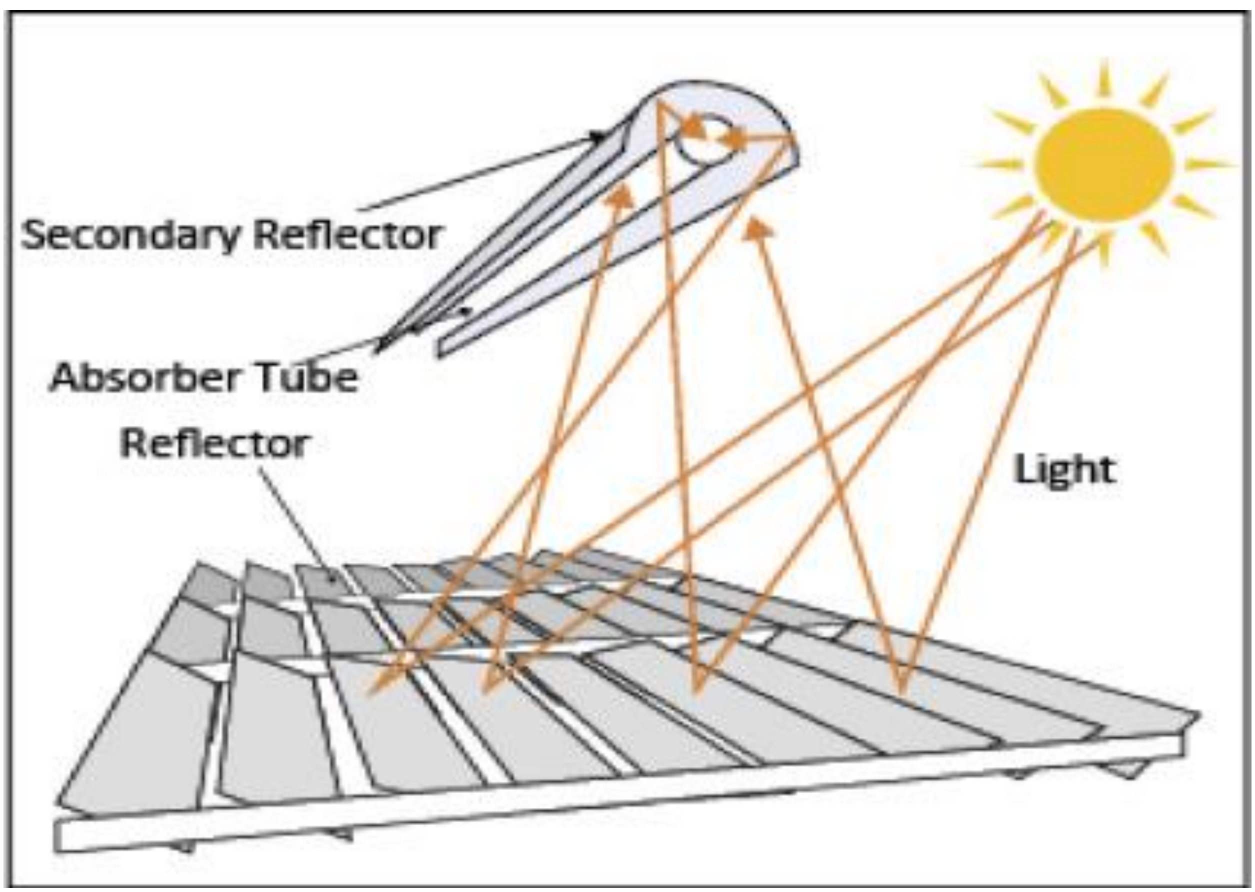
D-Linear Fresnel Reflector Systems

⇒ **Description**
- Uses flat or slightly curved mirrors to focus sunlight onto a fixed receiver.
- Functions similarly to parabolic trough systems but with simpler design.

⇒ **Applications**
- Suitable for medium-scale power generation.

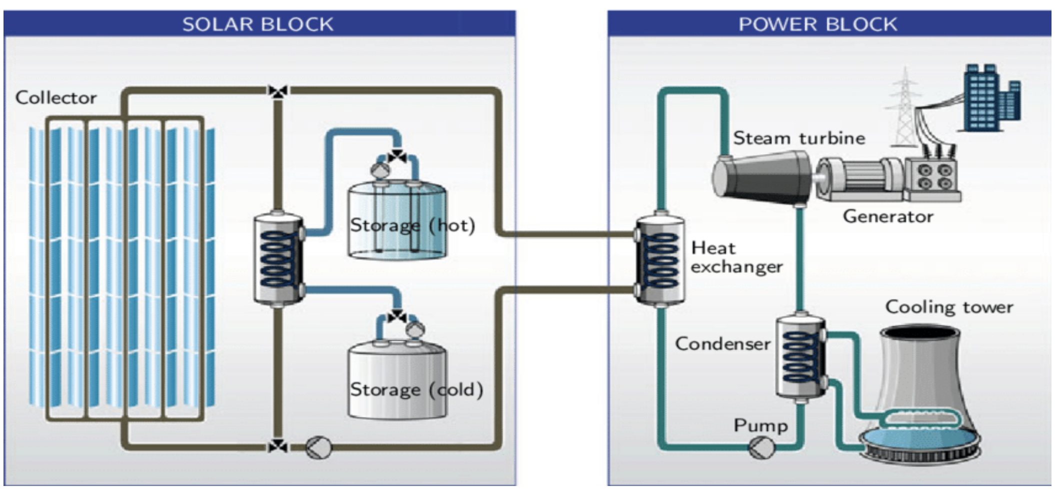
⇒ **Advantages**
- Lower cost and simpler construction compared to parabolic troughs.
- Easier to integrate with existing industrial processes.

⇒ **Disadvantages**
- Lower efficiency compared to parabolic trough and power tower systems.
- Requires more land area for the same power output.



3. Key Components of Solar Thermal Power Plants

- **Solar Collectors and Reflectors**
  - Concentrate solar radiation to achieve high temperatures.
  - Types include parabolic troughs, heliostats (for power towers), and dishes.
- **Heat Transfer Fluid (HTF)**
  - Medium that absorbs and transports heat from the collector to the steam generator.
  - Common HTFs include synthetic oils, molten salts, and pressurized steam.
- **Steam Generation System**
  - Converts the thermal energy from the HTF into steam.
  - The steam is used to drive turbines.
- **Turbine and Generator**
  - **Steam Turbines**
    - Converts the thermal energy of steam into mechanical energy.
  - **Generator**
    - Converts mechanical energy from the turbine into electrical energy.
- **Thermal Energy Storage (TES)**
  - Stores excess thermal energy for use during periods without sunlight.
  - Types of storage include sensible heat storage (using materials like molten salts) and latent heat storage (using phase change materials).



Structure of a concentrating solar thermal power plant. In the solar block, large mirrors collect rays of sunlight and concentrate them on an absorber pipe. The concentrated heat of the sun is used to heat a transfer fluid, usually thermal oil. The hot fluid is either sent to the power block, where in a heat exchanger hot steam is generated from liquid water, or its energy is stored in a molten salt storage for later use after sun-set. In the power block the vapour streams through the turbine to power its blades so that the generator generates electricity.

4. Thermal Energy Storage

Energy storage has become an important part in renewable energy technology systems such as solar systems. Thermal energy storage (TES) is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation. TES systems are used particularly in buildings and industrial processes. Advantages of using TES in an energy system are the increase of the overall efficiency and better reliability, but it can also lead to better economics, reducing investment and running costs, and less pollution of the environment and less carbon dioxide (CO_2)]. Solar thermal systems, unlike photovoltaic systems with striving efficiencies, are industrially matured, and utilise major part of sun's thermal energy during the day. Yet, it does not have enough (thermal) backup to keep operating during the low or no solar radiation hours. TES is becoming particularly important for electricity storage in combination with concentrating solar power (CSP) plants where solar heat can be stored for electricity production when sunlight is not available. New materials are selected, characterised, and enhanced in their thermo-physical properties to serve the purpose of a 24 h operation in an efficient TES system.

- Importance of TES
    - Provides a solution for the intermittency of solar power.
    - Enables continuous power generation even when the sun is not shining.
    - Enhances the reliability and dispatchability of solar thermal power plants

Three key benefits of thermal energy storage

Thermal energy storage can:

- Reduce peak demand and level demand by storing energy when there is less demand and releasing when there is high demand.
- Reduce CO_2 emissions and costs by making sure energy is used when it is cheaper and there is more renewable energy in the mix.
- Increase the overall energy efficiency of energy systems.
- Thermal energy storage is also a key part of peak shaving systems, where off-peak power is used to drive heat pumps that can produce heat or cold produced by cheaper electric power and waste heat from industrial sources in order to balance energy system loads.

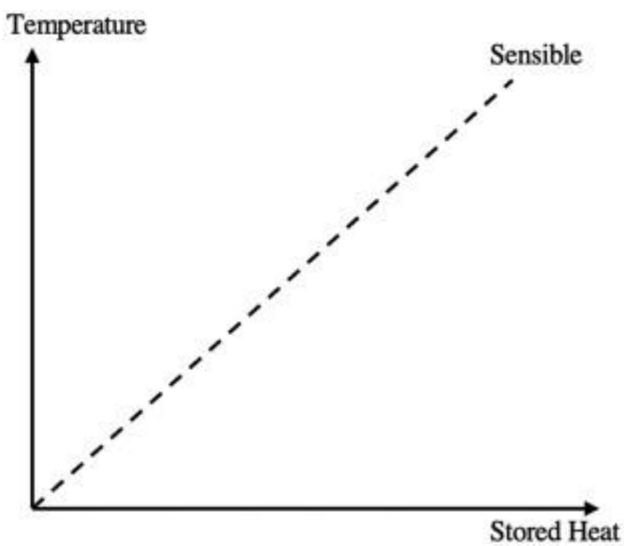
Types of Thermal Energy Storage

- **Sensible Heat Storage**
    - Uses materials that store heat by increasing temperature.
    - Common materials include molten salts, water, and concrete

Sensible heat storage is a relatively mature technology that has been deployed in a wide range of high-temperature industrial applications. For liquid sensible heat storage media, materials with low melting temperatures, high decomposition temperatures and low costs are preferred; on the other hand, the melting and decomposition temperatures do not need to be considered for solid sensible heat storage media. A comprehensive performance evaluation is necessary for sensible heat storage, covering technical, economic and life cycle issues, in order to achieve the best overall performance. In high-temperature industrial applications, special attention should be paid to the coupling problem between sensible heat storage and specific target systems. Further studies on material development, system optimization and other aspects are still needed to improve large-scale applications of sensible heat storage in various industrial settings.

A theoretical analysis of waste heat recovery technologies

Sensible heat storage is one of the most common applications due to its feasibility and simplicity. The mechanism is based on heat that is charged into the system to modify the temperature of a storage medium without changing its phase.



shows the relationship between the stored heat capacity and the temperature which can be a linear relationship. The absorption and release occurs via radiation, conduction, and convection. Sensible heat storage often has a low energy density and prone to thermal energy runaway [].

- ## Latent Heat Storage
  - Utilizes phase change materials (PCMs) that store and release heat during phase transitions.
  - Offers higher energy density compared to sensible heat storage.

The use of a latent heat storage system using Phase Change Materials (PCM) is an effective way of storing thermal energy (solar energy, off-peak electricity, industrial waste heat) and has the advantages of high storage density and the isothermal nature of the storage process. It has been demonstrated that, for the development of a latent heat storage system, choice of the PCM plays an important role in addition to heat transfer mechanism. The information on the latent heat storage materials and systems is enormous and published widely in the literatures.

Capacity of latent heat storage

Latent heat storage stores heat in a storage medium in the form of potential energy between the particles of the substance. The conversion between the heat and the potential energy within the substance involves a phase change – thus heat storage occurs without significant temperature changes in the storage medium. The capacity of latent heat storage can be determined by the following:

$Q = m\,\gamma$

where γ is latent heat in kJ/kg. The thermal storage density of the storage medium can be expressed as below,

$Q/V = \rho\,\gamma$

Since the latent heat of a substance is much greater than the specific heat of the same substance, latent heat storage can store the same amount of heat in a much smaller volume. This is a significant advantage of latent heat storage systems.

Latent heat storage

Latent heat storage system commonly employs phase change materials (PCMs) during energy containment. PCMs have the potential for energy absorption as well as energy release which involves physical state change. In LHS system, heat containment process takes place during the phase change that occurs over a relatively stable temperature and corresponds proportionally to the fusion heat of substance. The PCMs portrays itself as materials that display elevated energy containment as well as maintaining a uniformed temperature throughout the process. The LHS capacity can be calculated by using the following equation

(6.8) $Qs=m[cps(tm-ti) + f\Delta q+cpl(ti-tm)$

Where

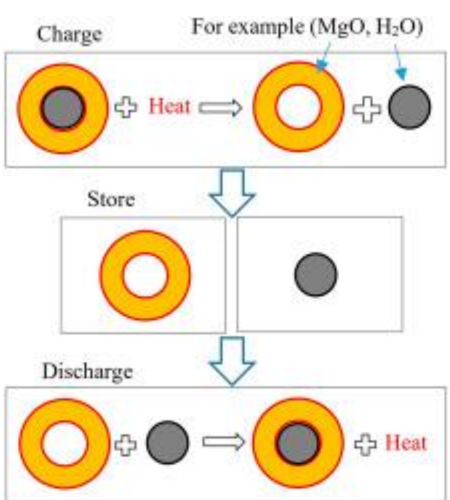
Q_s is storage capacity (J)
t_m is the melting temperature (°C)
m is the mass of material (kg)
C_{ps} is the specific heat of solid phase kJ / (kg ·K)
C_{pl} is the Specific heat of liquid phase kJ / (kg ·K)
f is the melt fraction
Δq is the latent heat of fusion (J)

- **Thermochemical Storage**
  - Involves chemical reactions that absorb and release heat.
  - Provides long-term storage with high energy density.

Thermochemical heat storage works on the notion that all chemical reactions either absorb or release heat; hence, a reversible process that absorbs heat while running in one way would release heat when running in the other direction. Thermochemical energy storage stores energy by using a high-energy chemical process. Heat is applied to material A during the charging process, resulting in the separation of two portions, B and C. The resulting reaction products are readily isolated and kept until the discharge procedure is required. The two portions B and C are subsequently combined under optimal pressure and temperature conditions, resulting in the release of energy. Heat losses from storage units are limited to sensible heat effects, which are often negligible in comparison to the heat of reaction. The thermal breakdown of metal oxides has been researched for energy storage applications. These reactions may be advantageous since the emitted oxygen could be reused or disposed of and the oxygen from the atmosphere could be utilized in the reverse operations. Potassium oxide decomposes at temperatures between 300°C and 800°C while releasing 2.1 MJ/kg of heat in the process, whereas lead oxide, on the other hand, decomposes at temperatures between 300°C and 350°C, releasing 0.26 MJ/kg of heat in the process .

Solar-energy-driven desalination cycle with an energy storage option: Proposed thermal energy storage material reaction

The THS process can be expressed as A + heat ↔ B + C, where A is thermochemical material, and B, C are reactants. The reactants B and C are hydroxide and water, respectively. The three main processes involved in THS system are (i) charging, (ii) storage, and (iii) discharging, as illustrated in .



5-Efficiency solar power system

The efficiency of a concentrating solar power system will depend on the technology used to convert the solar power to electrical energy, the operating temperature of the receiver and the heat rejection, thermal losses in the system, and the presence or absence of other system losses; in addition to the conversion efficiency, the optical system which concentrates the sunlight will also add additional losses.
Real-world systems claim a maximum conversion efficiency of 23-35% for "power tower" type systems, operating at temperatures from 250 to 565 °C, with the higher efficiency number assuming a combined cycle turbine. Dish Stirling systems, operating at temperatures of 550-750 °C, claim an efficiency of about 30%.[Due to variation in sun incidence during the day, the average conversion efficiency achieved is not equal to these maximum efficiencies, and the net annual solar-to- electricity efficiencies are 7-20% for pilot power tower systems, and 12-25% for demonstration-scale Stirling dish systems.

Theory[

The maximum conversion efficiency of any thermal to electrical energy system is given by the Carnot efficiency, which represents a theoretical limit to the efficiency that can be achieved by any system, set by the laws of thermodynamics. Real-world systems do not achieve the Carnot efficiency.

The conversion efficiency η of the incident solar radiation into mechanical work depends on the thermal radiation properties of the solar receiver and on the heat engine (e.g. steam turbine). Solar irradiation is first converted into heat by the solar receiver with the efficiency $\eta_{Receiver}$ and subsequently the heat is converted into mechanical energy by the heat engine with the efficiency $\eta_{mechanical}$, using Carnot's principle. The mechanical energy is then converted into electrical energy by a generator. For a solar receiver with a mechanical converter (e.g., a turbine), the overall conversion efficiency can be defined as follows:

$$\eta=\eta_{optics}\cdot\eta_{receiver}\cdot\eta_{mechanical}\cdot\eta_{generator}$$

where η_{optics} represents the fraction of incident light concentrated onto the receiver, $\eta_{receiver}$ the fraction of light incident on the receiver that is converted into heat energy, $\eta_{mechanical}$ the efficiency of conversion of heat energy into mechanical energy, and $\eta_{generator}$ the efficiency of converting the mechanical energy into electrical power. $\eta_{receiver}$ is: $\eta_{receiver} = \frac{Q_{absorbed} - Q_{lost}}{Q_{incident}}$

with $Q_{incident}$, $Q_{absorbed}$, Q_{lost} respectively the incoming solar flux and the fluxes absorbed and lost by the system solar receiver.

The conversion efficiency $\eta_{mechanical}$ is at most the Carnot efficiency, which is determined by the temperature of the receiver T_H and the temperature of the heat rejection ("heat sink temperature") T_0,

$\eta_{Carnot} = 1 - \frac{T_0}{T_H}$

The real-world efficiencies of typical engines achieve 50% to at most 70% of the Carnot efficiency due to losses such as heat loss and windage in the moving parts.

Ideal case[edit]

For a solar flux I (e.g. $I = 1000 W/m^2$) concentrated C times with an efficiency η_{Optics} on the system solar receiver with a collecting area A and an absorptivity α:

$Q_{solar} = ICA$,

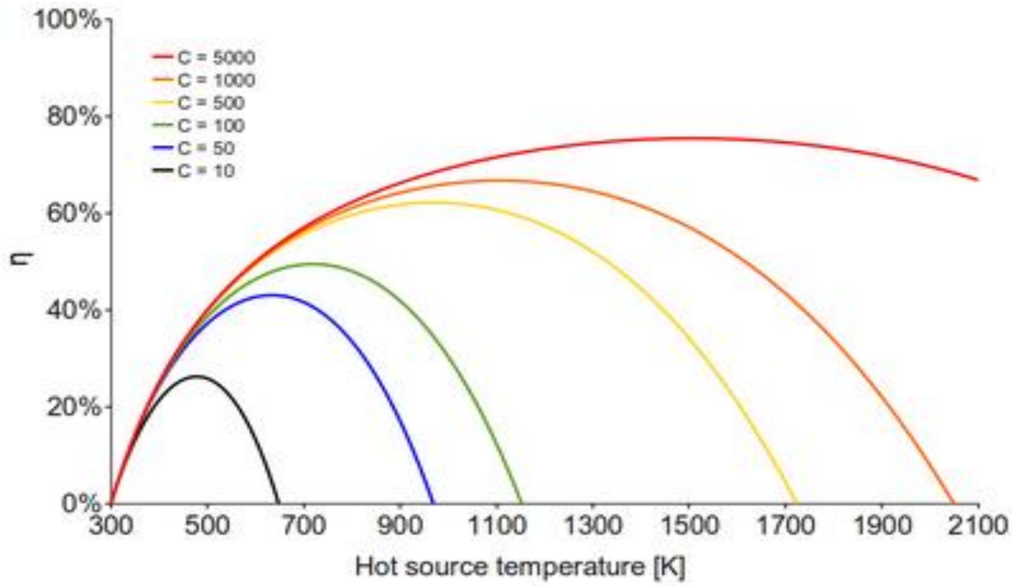
$Q_{absorbed} = \eta_{optics} \alpha Q_{solar}$,

For simplicity's sake, one can assume that the losses are only radiative ones (a fair assumption for high temperatures), thus for a reradiating area A and an emissivity ϵ applying the Stefan–Boltzmann law yields:

$Q_{lost} = A \epsilon \sigma T_H^4$

Simplifying these equations by considering perfect optics (η_{Optics} = 1) and without considering the ultimate conversion step into electricity by a generator, collecting and reradiating areas equal and maximum absorptivity and emissivity (α = 1, ϵ = 1) then substituting in the first equation gives

η=(1−$\sigma TH4IC$)·(1−$T0TH$)



The graph shows that the overall efficiency does not increase steadily with the receiver's temperature. Although the heat engine's efficiency (Carnot) increases with higher temperature, the receiver's efficiency does not. On the contrary, the receiver's efficiency is decreasing, as the amount of energy it cannot absorb (Qlost) grows by the fourth power as a function of temperature. Hence, there is a maximum reachable temperature. When the receiver efficiency is null (blue curve on the figure below), T max is: Tmax=($IC\sigma$)0.25

There is a temperature T opt for which the efficiency is maximum, i.e.. when the efficiency derivative relative to the receiver temperature is null:

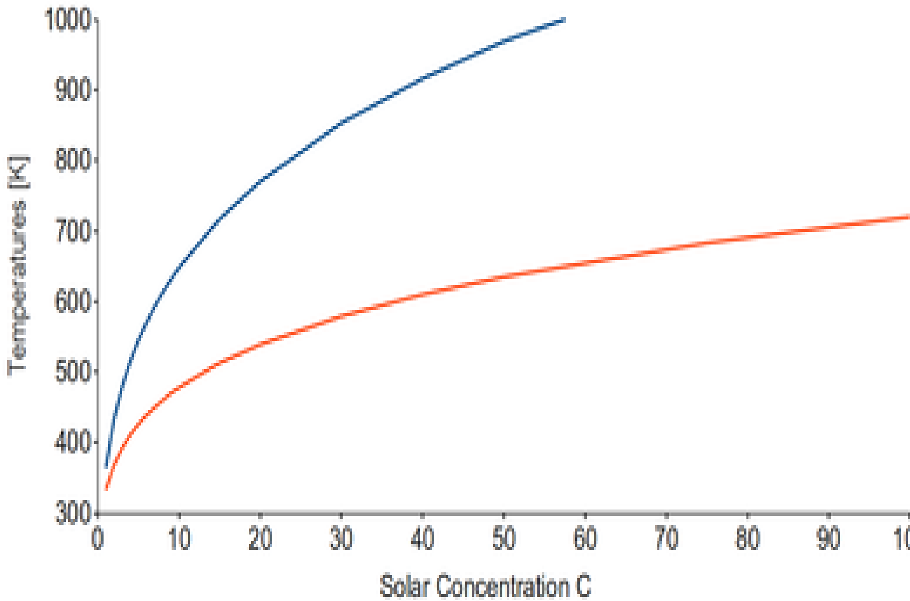
(T opt) = 0

$d\eta dTH$ Consequently, this leads us to the following equation:

$Topt$5−(0.75 T0)Topt4−$T0IC4\sigma$=0

Solving this equation numerically allows us to obtain the optimum process temperature according to the solar concentration ratio C (red curve on the figure below)

C	500	1000	5000	10000	45000 (max. for Earth)
Tmax	1720	2050	3060	3640	5300
Topt	970	1100	1500	1720	2310

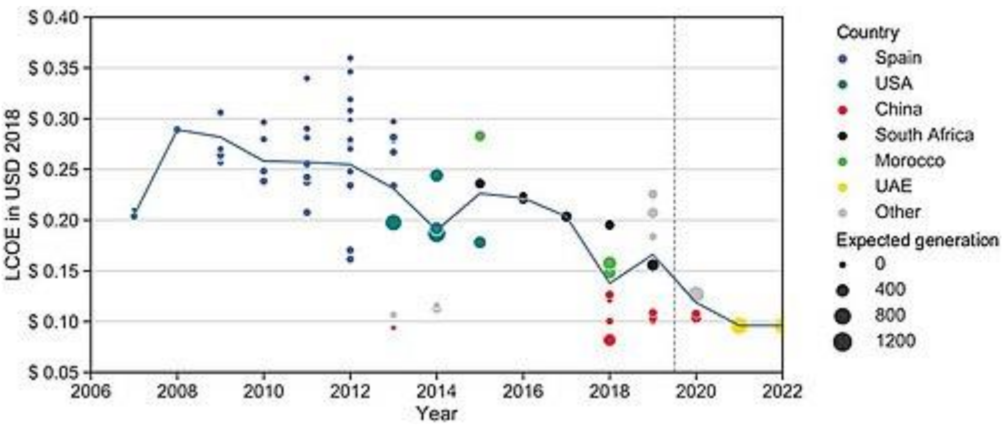


Theoretical efficiencies aside, real-world experience of CSP reveals a 25%–60% shortfall in projected production, a good part of which is due to the practical Carnot cycle losses not included in the above analysis. Also, a realistic approach of concentrating systems taking into account more characteristics of the system can be found in Ref. [89].

\Cost and value[edit]

Bulk power from CSP today is much more expensive than solar PV or Wind power, however when including energy storage CSP can be a cheaper alternative. As early as 2011, the rapid decline of the price of photovoltaic systems lead to projections that CSP will no longer be economically viable.[90] As of 2020, the least expensive utility-scale concentrated solar power stations in the United States and worldwide are five times more expensive than utility-scale photovoltaic power stations, with a projected minimum price of 7 cents per kilowatt-hour for the most advanced CSP stations against record lows of 1.32 cents per kWh[91] for utility-scale PV.[92] This five-fold price difference has been maintained since 2018.[93]

Even though overall deployment of CSP remains limited in the early 2020s, the levelized cost of power from commercial scale plants has decreased significantly since the 2010s. With a learning rate estimated at around 20% cost reduction of every doubling in capacity [94] the cost were approaching the upper end of the fossil fuel cost range at the beginning of the 2020s driven by support schemes in several countries, including Spain, the US, Morocco, South Africa, China, and the UAE:



CSP deployment has slowed down considerablas most of the above-mentioned markets have cancelled their support,[95] as the technology turned out to be more expensive on a per kWH basis than solar PV and wind power. CSP in combination with Thermal Energy Storage (TES) is expected by some to remain cheaper than PV with lithium batteries for storage durations above 4 hours per day,[96] while NREL expects that by 2030 PV with 10-hour storage lithium batteries will cost the same as PV with 4-hour storage used to cost in 2020.[97]

Combining the affordability of PV and the dispatchability of CSP is a promising avenue for high capacity factor solar power at low cost. Few PV-CSP plants in China are hoping to operate profitably on the regional coal tariff of US$50 per MWh in the year 202

6-Applications and Case Studies

*.Gema solar Plant, Spain

description A 19.9 MW power tower plant with a molten salt storage system.

- Can generate electricity 24/7 due to its thermal storage capabilities.

- Impact
  - Demonstrates the potential of solar thermal energy to provide continuous power.
  - Serves as a model for future solar thermal projects.

Design and specifications

The plant is of the SOLAR POWER TOWER type CSP and uses concepts pioneered in the solar one and solar tower demonstration projects, using molten salt as its heat transfer fluid and energy storage medium. Originally called Solar Tres, it was renamed Gema solar.

The project, which has received a subsidy of five million euros from the European Commission and a loan of 80 million euros from the European Investment Bank, makes use of the Solar Two technology tested in Barstow, California, but is approximately three times the size. It makes use of several advances in technology after Solar Two was designed and built.

Gema solar is the first commercial solar plant with central tower receiver and molten salt heat storage technology. It consists of a 30.5-hectare (75-acre) solar heliostat aperture area with a power island and 2,650 heliostats, each with a 120-square-metre (1,300 sq ft) aperture area and distributed in concentric rings around the 140-metre-high (460 ft) tower receiver. The total land use of the Heliostats is 195 hectares (480 acres.

The most innovative aspects of the plant, which belongs to the company Torresol Energy, are its molten salt receiver, its heliostats aiming system and its control system. In addition, its storage system allows it to produce electricity for 15 hours without sunlight (at night or on cloudy days). This storage capacity makes its solar power manageable so that it can be supplied based on demand. The plant has already been able to supply a full day of uninterrupted power supply to the grid, using thermal transfer technology developed by SENER.

Gema solar, with its 19.9 MW of power, can supply 80 GWh per year — enough to supply power to 27,500 homes. The plant has been operational since May 2011. Its official launch was held in October 2011.[1]

*Ivanpah Solar Power Facility, USA

- Description
  - One of the largest CSP plants in the world, with a capacity of 392 MW.
  - Uses power tower technology with over 170,000 heliostats.
- Impact
  - Showcases the scalability and effectiveness of power tower systems.

Contributes significantly to renewable energy generation in California

The Ivanpah system consists of three solar thermal power plants on 3,500 acres (1,400 ha) of public land near the California–Nevada border in the Southwestern United States.[] Initially it was planned with 440 MW gross on 4,000 acres (1,600 ha) of land, but then downgraded by 12%. It is near Interstate 15 and north of Ivanpah, California.[] The facility is visible from the adjacent Mojave National Preserve, the Mesquite Wilderness, and the Stateline Wilderness.[18] It is also very visible from the Primm Valley resort area to the northeast.

Fields of heliostat mirrors focus sunlight on receivers located on centralized solar power towers. The receivers generate steam to drive specially adapted steam turbines.

For the first plant, the largest-ever fully solar-powered steam turbine generator set was ordered, with a 123 MW Siemens SST-900 single-casing reheat turbine.[] Siemens also supplied instrumentation and control systems.[20] The plants use BrightSource Energy's "Luz Power Tower 550" (LPT 550) technology[21] which heats the steam to 550 °C directly in the receivers.[22] The plants have no storage.[23]

Final approval for the project was granted in October 2010.[24] On October 27, 2010, Governor of California, Arnold Schwarzenegger, Interior Secretary Ken Salazar, and other dignitaries gathered in the Mojave Desert to break the ground for the construction.[8]

7. Advantages and Disadvantages of Solar Thermal Electricity

- Advantages
-
- Renewable and Sustainable
- Astral thermal power uses an abundant and inexhaustible energy source.
- Energy Storage
- Thermal storage systems enable consistent power generation.
- Scalability
- Suitable for a range of applications from small-scale to large-scale power plants.
- Environmental Benefits
- Reduces greenhouse gas emissions and reliance on fossil fuels.

- Disadvantages

- High Initial Costs
- Significant upfront investment required for plant construction.
- Land Use
- Requires large land areas for collector fields.
- Complexity
- High-temperature systems require sophisticated technology and maintenance.
- Weather Dependency
- Performance is dependent on direct sunlight, affecting output during cloudy or rainy days.

8. Future Prospects and Innovations

- Technological Advancements
- Improved Materials
- Development of advanced materials for collectors, HTFs, and storage to enhance efficiency and reduce costs.
- Hybrid Systems
- Integration with other renewable technologies, such as PV and wind, to create hybrid systems that improve reliability and efficiency.
- Advanced Control Systems
- Utilization of AI and IoT for optimized system monitoring and performance.
- Policy and Market Trends
- Government Incentives
- Policies promoting renewable energy adoption, including tax credits, subsidies, and feed-in tariffs.
- Market Growth
- Increasing global demand for clean energy solutions driving the expansion of the solar thermal market.
- Challenges and Barriers
- Cost Reduction
- Continued efforts to lower the capital costs of solar thermal systems.
- Public Awareness
- Increasing awareness of the benefits and potential of solar thermal electricity.
- Infrastructure Integration
- Enhancing infrastructure to support large-scale solar thermal installations and grid integration.

9. Conclusion

- **Summary**
  - Solar thermal energy provides a viable and sustainable solution for electricity generation.
  - Ongoing technological advancements and supportive policies are key to overcoming current challenges and maximizing the potential of solar thermal power.
- **Outlook**
  - With continued innovation and increasing emphasis on renewable energy, solar thermal technology is poised to play a significant role in the transition to a low-carbon future.

- Collaborative efforts among governments, industries, and research institutions are essential to drive further development and deployment of solar thermal power plants.

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  - National Renewable Energy Laboratory (NREL) (https://www.nrel.gov/)
  - International Renewable Energy Agency (IRENA) (https://www.irena.org/)

- **Books**

Power Plant Instrumentation and Control Handbook: A Guide to Thermal Power Plants