SOLAR THERMAL ENERGY HARVESTING

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Overview

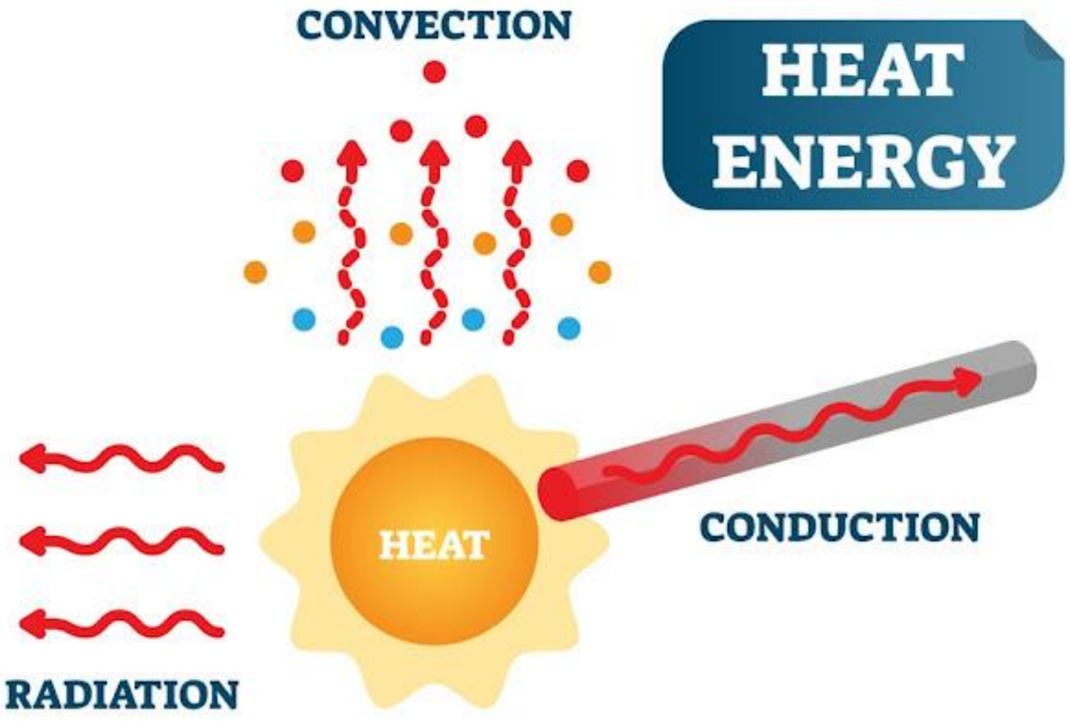
→ cn currently focusing research on this, price expected to go down

- Solar thermal energy utilization has gained significant attention in recent years as a viable option for clean and sustainable energy generation.
- Solar thermal energy can be directly used for heating and cooling applications, as well as for generating electricity through various technologies, such as solar thermal power plants.
- Solar thermal energy is the thermal energy generated by the sun's radiation. The primary mechanisms for harnessing solar thermal energy are through the use of solar collectors, which absorb the sun's radiation and convert it into heat energy.
- In addition to the direct use of solar thermal energy for heating and cooling, researchers have also explored innovative approaches to harness solar thermal energy for electricity generation.

Basics of Solar Energy

- Solar radiation can be classified into different wavelength ranges, including visible light, infrared, and ultraviolet.
- The intensity of solar radiation varies depending on factors such as time of day, location, and weather conditions.
- Solar constant and factors affecting solar irradiance. Solar constant is the amount of solar radiation received per unit area at the top of the Earth's atmosphere, which is approximately 1,366 W/m^2. The amount of solar radiation reaching the Earth's surface is influenced by various factors such as atmospheric composition, cloud cover, and latitude.

Heat Transfer Mechanism



Credit: solnpharma, 2021

Heat Transfer Principles in Solar Thermal Systems

- Heat transfer mechanisms play a crucial role in the design and performance of solar thermal systems.
- **Conduction** is the transfer of heat through a material without the involvement of any bulk motion of the material. An example of a conduction process is the heat transfer through the absorber plate of a solar collector.
- **Convection** is the transfer of heat due to the movement of a fluid, such as air or water. An example of a convection process is the transfer of heat from the absorber plate to the working fluid in a solar collector.
- **Radiation** is the transfer of energy through electromagnetic waves without the need for a physical medium. An example of a radiation process is the absorption of solar radiation by the absorber plate in a solar collector.

Conversion Mechanisms

- The conversion of solar radiation to thermal energy is a fundamental process in solar thermal systems.
- The absorbed solar radiation heats up the absorber surface, which in turn transfers the heat to a working fluid, such as water or air, through conduction and convection.
- The heated working fluid can then be used for various applications, such as space heating, hot water, or electricity generation through a thermal power cycle.

Solar Thermal Energy vs. Photovoltaics

- Solar thermal energy systems and photovoltaic systems are both technologies that harness solar energy, but they **operate on different principles** and have different applications. While solar thermal systems convert solar radiation directly into heat, which can be used for heating, cooling, or power generation, photovoltaic systems convert solar radiation into electricity.
- Advantages of solar thermal systems include higher energy conversion efficiency, the ability to store thermal energy for later use, and the potential for combined heat and power applications.
- Limitations of solar thermal systems include the need for specialized components, such as solar collectors and heat exchangers, and the dependence on the availability of solar radiation.

Applications of Solar Thermal Energy

- Domestic applications: space heating, water heating, and cooling through solar-powered air conditioning systems.
- Industrial applications: process heat for industrial processes, such as drying, pasteurization, and steam generation.
- Power generation applications: solar thermal power plants, which use solar collectors to generate steam that drives a turbine to produce electricity.

Classification of Solar Collectors

- Passive systems: Allow the direct use of solar radiation for heating or cooling without the need for mechanical or electrical devices, such as solar chimneys and solar walls.
- Active systems: Utilize mechanical or electrical devices to collect, store, and distribute solar thermal energy, such as flat-plate collectors, evacuated tube collectors, and concentrating solar collectors.

Flat-Plate Collectors (FPC)

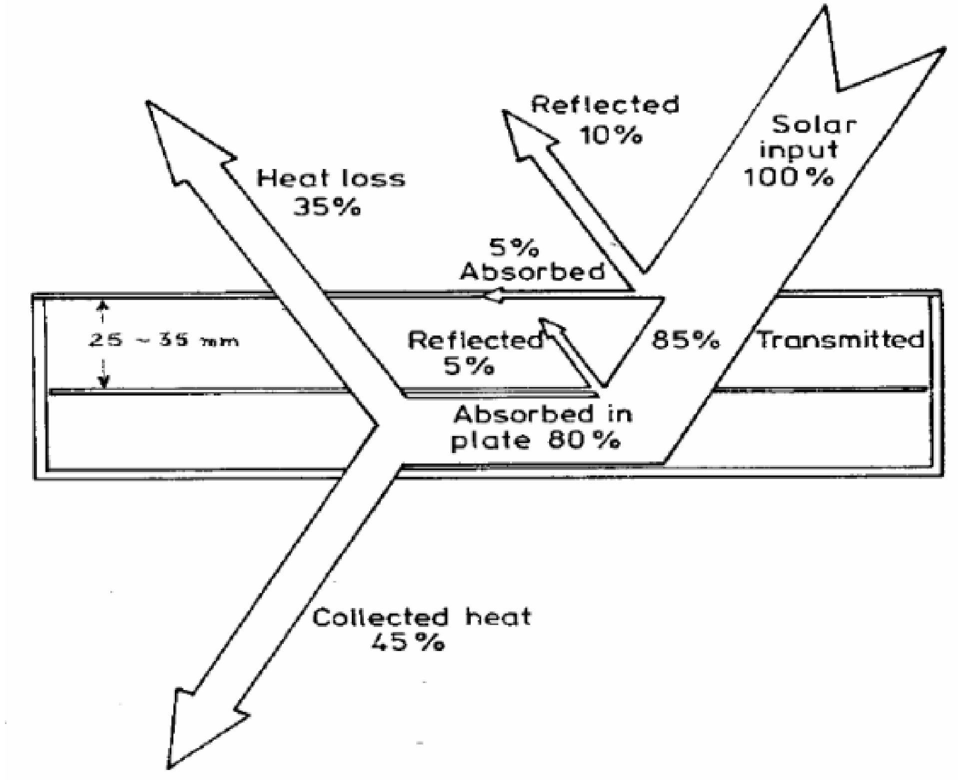
- Flat-plate collectors are the most common type of solar thermal collector, consisting of an absorber plate, a transparent cover, and a heat transfer fluid.
- The absorber plate is responsible for absorbing the incoming solar radiation and converting it into thermal energy.
- The transparent cover, typically made of glass or plastic, reduces heat losses from the absorber plate to the surrounding environment.
- The heat transfer fluid, such as water or a water-glycol mixture, circulates through the collector and carries the collected thermal energy to storage or end-use applications.

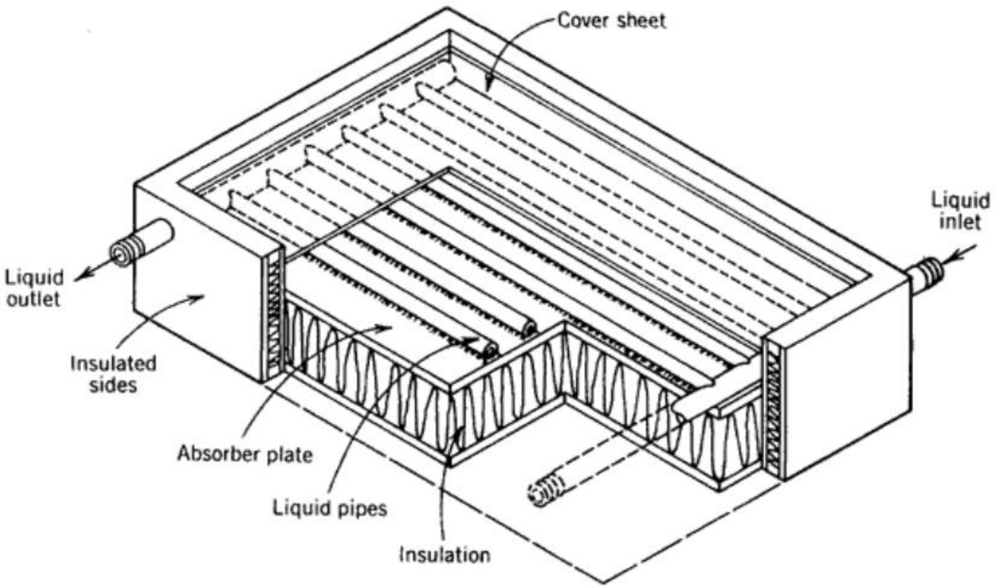
Flat-Plate Collectors (FPC)

- Flat-plate solar collectors are one of the most basic and extensively researched technologies for solar-powered domestic hot water systems. The concept is straightforward: a dark, flat surface absorbs sunlight to capture maximum energy, which is then transferred to water, air, or another fluid for practical use.
- These are the main components of a typical flat-plate solar collector:
  - ❖Black surface - absorbent of the incident solar energy
  - ❖Glazing cover - a transparent layer that transmits radiation to the absorber, but prevents radiative and convective heat loss from the surface
  - ❖Tubes containing heating fluid to transfer the heat from the collector
  - ❖Support structure to protect the components and hold them in place
  - ❖Insulation covering sides and bottom of the collector to reduce heat losses

Flat-Plate Solar Collector

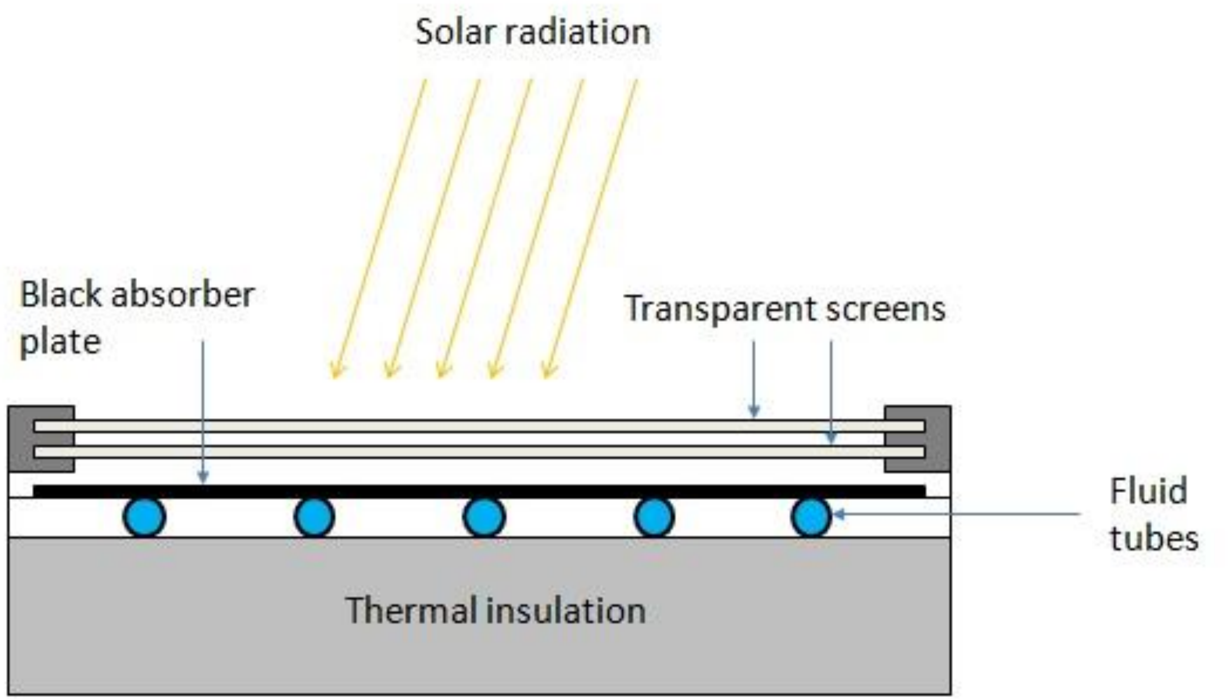
- Consist of tubes carrying a fluid running through an insulated, weather-proof box with a dark absorber material and thermal insulation material on the backside that also prevents heat loss.





Source: Struckmann, 2008 in Analysis of a Flat-plate Solar Collector

Flat-Plate Collectors (FPC)



Schematic of a flat plate solar collector with liquid transport medium. The solar radiation is absorbed by the black plate and transfers heat to the fluid in the tubes. The thermal insulation prevents heat loss during fluid transfer; the screens reduce the heat loss due to convection and radiation to the atmosphere
Credit: Mark Fedkin (modified after Duffie and Beckman, 2013)

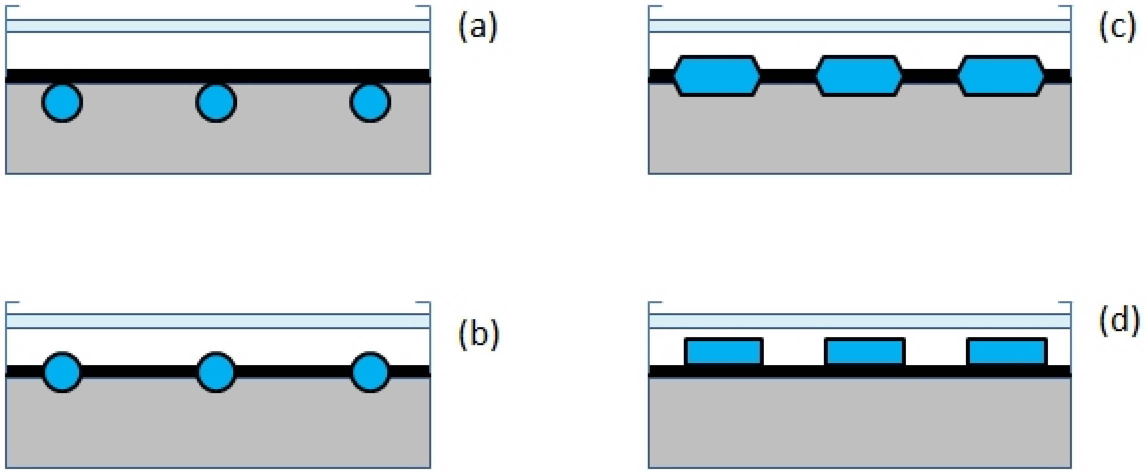
- ❑ Flat-plate collectors can use either liquid or air for heat transport.
- ❑ Water is a common liquid due to its favorable thermal properties:
    - High volumetric heat capacity
    - Incompressibility
    - High mass density, allowing smaller pipes
- ❑ Challenges of using water:
    - It can freeze in winter, potentially damaging the system.
    - Drain-down systems with sensors help prevent freezing but may introduce air pockets, reducing efficiency.

Flat-Plate Collectors (FPC)

- Antifreeze solutions (e.g., ethylene glycol, propylene glycol) are alternatives to water:
  - Require a closed-loop system and proper disposal due to toxicity.
  - Need replacement approximately every five years.
- Air as a transport fluid is suitable for space heating and crop drying: Often requires a fan, though some systems use passive airflow via thermal buoyancy.
- Phase-change liquids (e.g., refrigerants) offer advantages:
  - Do not freeze, avoiding winter-related issues.
  - Can change phase (liquid to gas) with temperature shifts, enabling rapid thermal response.

Flat-Plate Collectors (FPC)

- The key considerations in flat plate collector design are:
  - maximizing absorption,
  - minimizing reflection and radiation losses, and
  - effective heat transfer from the collector plate to the fluids.
- One of the important issues is obtaining a good thermal bond between the absorber plate and the structure containing the heat-transfer fluids.



Various designs of flat-plate collector assembly. Color codes: light blue - glass cover, dark blue - fluid channels, black - absorber material, gray - insulation. Some constructions (b, c) include fluid channels in the absorber plate structure to maximize thermal conductance between the components. Other modifications (a, d) include tubes and channels soldered or cemented unto the Plate.

Credit: Mark Fedkin (modified after Kalogirou, 2009)

Flat-Plate Collectors (FPC)

- In steady state, the useful energy output of the collector is the difference between the absorbed solar radiation and the total thermal losses from the collector.

Useful energy = Absorbed solar energy - Thermal losses

- The thermal efficiency (η) is defined as:

$$\eta = \frac{Q_u}{A_c G_T}$$

- where Q_u is the useful energy/heat output from a collector, G_T is the incident solar radiation flux (irradiance), and A_c is the collector area. The denominator is the total energy input for the collector. G_T is usually measured with a pyranometer or assumptions for a specific location. The collector area is a defined technical characteristic. The main task here is how to estimate the Q_u - the useful energy.

Flat-Plate Collectors (FPC)

- The useful energy, Q_u is

→ ratio / %

$$Q_u = A_c[S - U_L(T_{plate} - T_{ambient})]$$

- where S is the absorbed solar radiation, U_L is the total losses, T_{plate} is the temperature of the absorbing plate, and $T_{ambient}$ is the temperature of the air, and A_c again is the area of the collector surface.

- The absorbed solar radiation, S, is defined as

$$S = (\tau\alpha)_{av} I_T \qquad I_T = I_0 \cdot \cos\theta$$

→ depend on material

- With I_T is the incident solar radiation, $(\tau\alpha)_{av}$ is the product of transmittance of the collector cover and absorptance of the plate averaged over different types of radiation. In fact, $(\tau\alpha)_{av} \approx 0.96(\tau\alpha)_{beam}$ based on practical estimations.

Flat-Plate Collectors (FPC)

- The *heat removal factor*, $\boldsymbol{F_R}$ shows how much energy remains after heat losses to the surrounding due to collector and inlet temperature difference. T_i is the temperature of the input fluid, and T_a is the temperature of the aperture. Therefore, the energy balance equation for the actual system can be written as follows:

$$Q_u = A_c F_R[S - U_L(T_i - T_a)]$$

- The standard approach to evaluating collector performance involves exposing the system to solar radiation, circulating a fluid through it, and recording the inlet and outlet temperatures along with the flow rate. The useful energy gain can then be determined using these experi $Q_u = mC_p(T_o - T_i)$

Flat-Plate Collectors (FPC)

- If the incident radiation on the collector (G_T) and ambient temperature (T_a) were recorded, we can express the useful gain in terms of incident radiation:

$$Q_u = A_c F_R [G_T (\tau\alpha)_{average} - U_L (T_o - T_i)]$$

- The experimental efficiency of the system at each instant of operation can be obtained:

$$\eta_i = \frac{Q_u}{A_c G_T}$$

Flat-Plate Collectors (FPC)

Example 1 : A flat-plate solar collector has the following specifications:

- **Collector area (A_a) = 2.5 m²**
- **Solar irradiance (G_t) = 850 W/m²**
- **Cover transmittance-absorptance product $(\tau\alpha)_{av}$ = 0.90**
- **Overall heat loss coefficient (U_l) = 4.5 W/m²·K**
- **Inlet fluid temperature (T_{in}) = 35°C**
- **Ambient temperature ($T_{am\beta}$) = 20°C**
- **Mass flow rate ($\dot{m}$) = 0.1 kg/s**
- **Specific heat capacity of water (c_p) = 4186 J/kg·K**
- **Heat removal factor (F_r) = 0.85**

Flat-Plate Collectors (FPC)

Questions:

1. Compute the **absorbed solar radiation (S)** using:

$$S = G_T \times (\tau\alpha)_{\mathrm{av}}$$

2. Calculate the **useful energy gain ($\dot{Q}_u$)** using:

$$\dot{Q}_u = A_c \times F_R \times [S - U_L(T_{in} - T_{amb})]$$

3. Determine the **outlet temperature (T_{out})** of the working fluid using:

$$T_{out} = T_{in} + \frac{\dot{Q}_u}{\dot{m}c_p}$$

4. Compute the **thermal efficiency (η)** of the collector:

$$\eta = \frac{\dot{Q}_u}{A_c G_T}$$

Flat-Plate Collectors (FPC)

$$S = G_T \times (\tau\alpha)_{\mathrm{av}}$$

Substituting the values:

$$S = 850 \times 0.90$$

$$S = 765\ \mathrm{W/m^2}$$

The useful heat gain equation is:

$$\dot{Q}_u = A_c \times F_R \times [S - U_L(T_{in} - T_{amb})]$$

Substituting the values:

$$\dot{Q}_u = 2.5 \times 0.85 \times [765 - 4.5(35 - 20)]$$

$$\dot{Q}_u = 2.5 \times 0.85 \times [765 - 67.5]$$

$$\dot{Q}_u = 2.5 \times 0.85 \times 697.5$$

$$\dot{Q}_u = 1481.34\ \mathrm{W}$$

Flat-Plate Collectors (FPC)

The temperature change is given by:

$$T_{out} = T_{in} + \frac{\dot{Q}_u}{\dot{m} c_p}$$

Substituting the values:

$$T_{out} = 35 + \frac{1481.34}{(0.1 \times 4186)}$$

$$T_{out} = 35 + \frac{1481.34}{418.6}$$

$$T_{out} = 35 + 3.54$$

$$T_{out} = 38.54^{\circ} C$$

Flat-Plate Collectors (FPC)

The thermal efficiency formula is:

$$\eta = \frac{\dot{Q}_u}{A_c G_T}$$

Substituting the values:

$$\eta = \frac{1481.34}{(2.5 \times 850)}$$

$$\eta = \frac{1481.34}{2125}$$

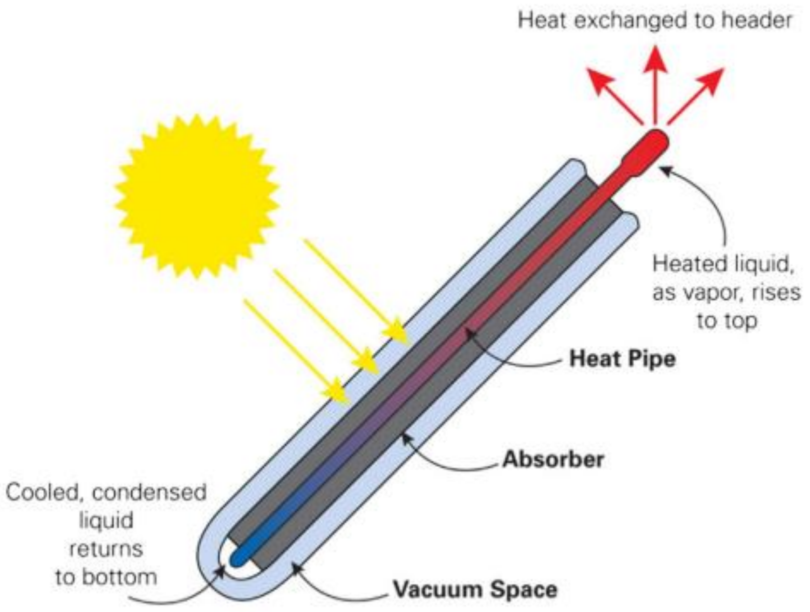
$$\eta = 0.697 = 69.7\%$$

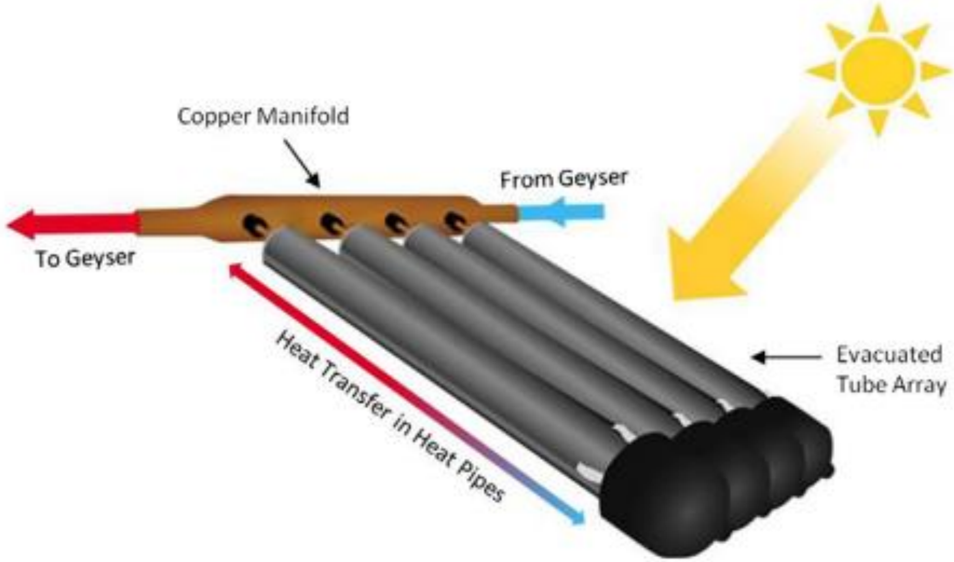
Evacuated Tube Collectors (ETC)

- Evacuated tube collectors are a type of solar thermal collector that use a vacuum-insulated tube to minimize heat losses.
- Inside the evacuated tube, an absorber plate is coated with a selective surface that efficiently absorbs solar radiation and transfers the heat to a working fluid, such as water or a heat transfer fluid.
- Evacuated tube collectors can achieve higher temperatures and have improved efficiency compared to flat-plate collectors, particularly in colder climates, as the vacuum insulation reduces heat losses.

Evacuated Tube Solar Collector

- ETC uses parallel rows of glass tubes, each of which contains either a heat pipe or another type of absorber, surrounded by a vacuum. This greatly reduces heat loss, particularly in cold climates.





Source: Shirazi et. al. , 2018, Solar-powered absorption chillers: A comprehensive and critical review

Concentrated Solar Power (CSP) Systems

- There are three main types of concentrated solar power systems: parabolic troughs, dish systems, and Fresnel reflectors.

  (+)V - through

- Parabolic trough collectors use curved, parabolic-shaped mirrors to concentrate the sun's rays onto a receiver tube, where a heat transfer fluid is heated to high temperatures.
- Dish systems use a parabolic-shaped dish to concentrate the sun's rays onto a receiver, typically a Stirling engine or a thermal receiver.
- Fresnel reflectors use a series of flat or slightly curved mirror strips to concentrate the sun's rays onto a receiver tube, similar to parabolic trough collectors.

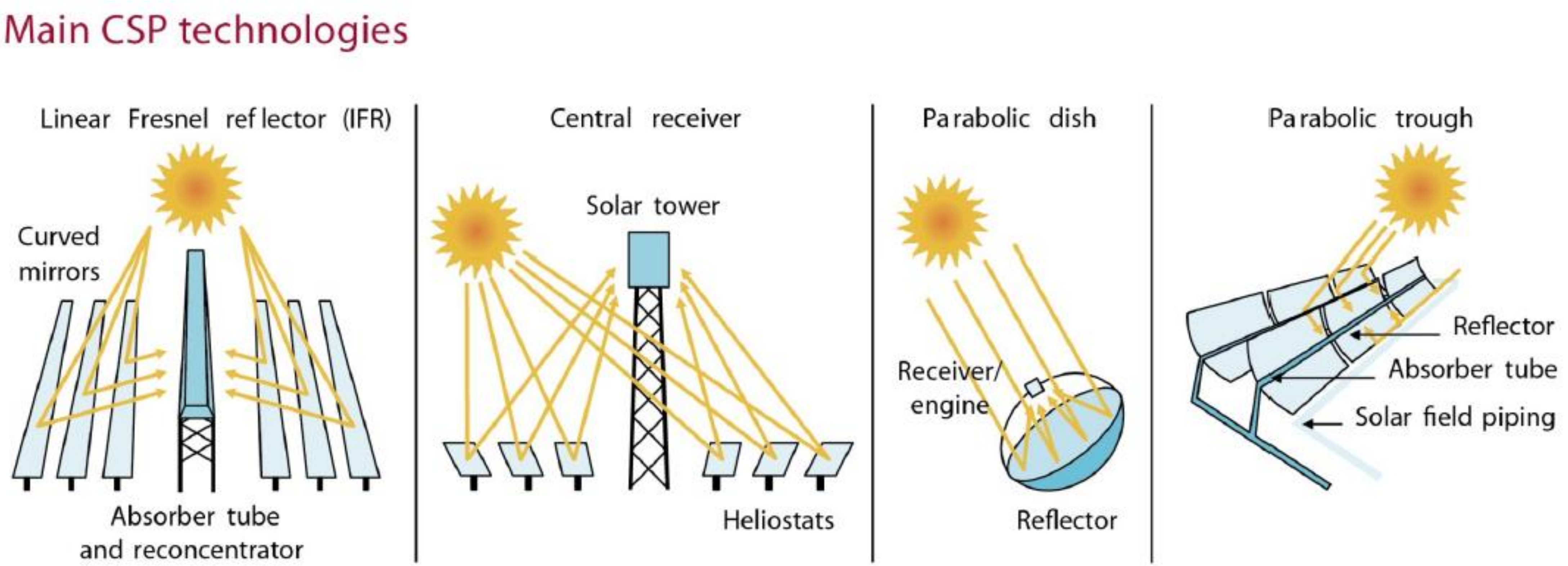
Concentrated Solar Power (CSP) Systems

- Concentrating Solar Power (CSP) plants use mirrors to concentrate the sun's rays and produce heat for electricity generation via a conventional thermodynamic cycle.
- Unlike solar photovoltaics (PV), CSP uses only the direct component of sunlight (DNI) and can provide carbon-free heat and power only in regions with high DNI.

Figure 1 – CSP Parabolic Trough Solar Collectors

Source: IRENA, 2013, CSP Technology Brief

CSP Technologies



IRENA, 2013, CSP Technology Brief

Solar Thermal Application

Figure 4: Marstal Solar District heating plant (33 360 m²), Denmark

Photograph: AltOmSolvarme

Source: IRENA, 2015

Solar Thermal Application

Figure 9: Application of parabolic trough collector in a dairy processing plant in Mexico

Photograph: Inventive Power A.S.

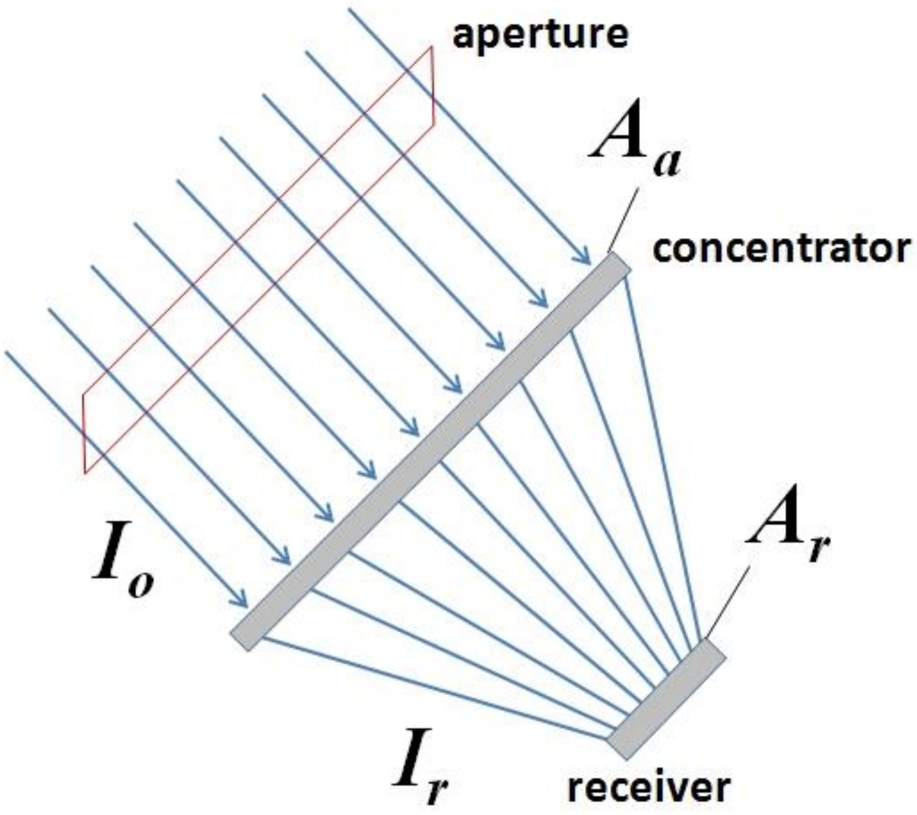
Figure 2: Solar air heating system in textile industry in Vietnam

Photograph: Grammer Solar

Source: IRENA, 2015

Concentrated Solar Power (CSP) Systems

- **Concentration Ratio** (C): Represents how much the incident energy flux (I_o) is optically enhanced on the receiving surface (I_r).
- **Physical meaning**: Indicates the increase in energy density due to light concentration done by focusing incoming energy through an aperture onto a smaller receiver area.
- **Effect**: Higher energy flux on the receiver, improving efficiency.



Concentrated Solar Power (CSP) Systems

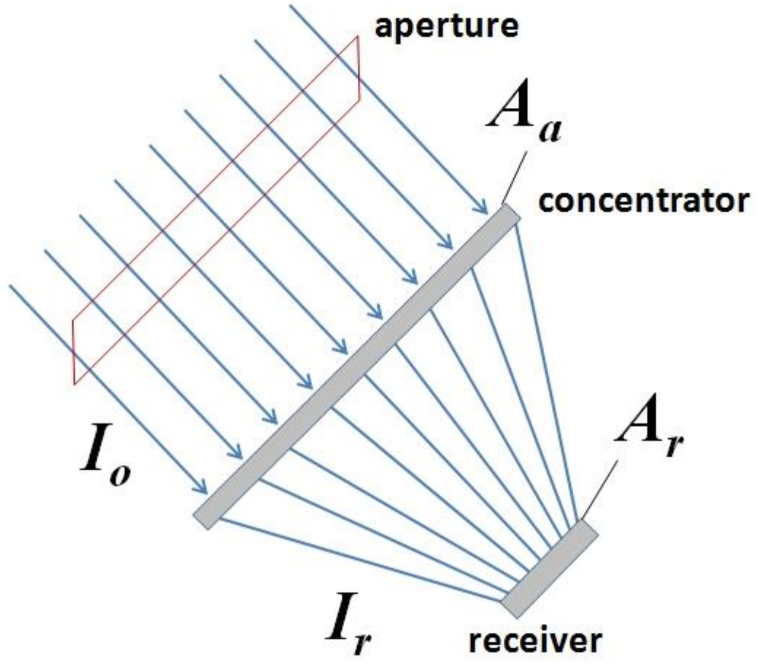
•The **aperture** refers to the area through which **sunlight enters the system** before being focused onto a smaller receiver. It is typically the opening or surface that collects incoming solar radiation, such as:

- ✓ Mirrors or lenses in parabolic troughs, Fresnel lenses, or heliostat fields
- ✓ Reflective surfaces in dish or tower systems

•**Area Concentration Ratio ($\boldsymbol{C_{geo}}$)**: Defined as the ratio of the receiver area to the aperture area $\left(C_{geo} = \frac{A_r}{A_a}\right)$.

•Area Concentration Ratio is also known as the geometric concentration ratio in some sources.

•**It is easy to calculate** since device areas are known and works best when radiation flux is **uniform** across both the aperture and receiver.



Concentrated Solar Power (CSP) Systems

- The concentration ratio can be also represented by the energy flux ratio at the aperture and at the receiver. In this case, it is termed **flux concentration ratio** or **optical concentration ratio** (C_{opt}) and can be directly applied to thermal calculations.

$$C_{opt} = \frac{\text{Average flux over the receiver}}{\text{Flux over the aperture (insolation)}} = \frac{\frac{1}{A_r}\int I_r D A_r}{I_O}$$

- In case the ambient energy flux over the aperture (insolation) and over the receiver (irradiance) is uniform, the geometric and optical concentration ratios are equal $(C_{geo} = C_{opt})$.

Concentrated Solar Power (CSP) Systems

- **Sunlight concentration systems** are classified as:
  - ✓ **Low concentration**: $C < 10$
  - ✓ **Medium concentration**: $10 < C < 100$
  - ✓ **High concentration**: $C > 100$
- **Uniform flux concentrators** (e.g., V-troughs, pyramidal reflectors) have a **single concentration ratio** (C).

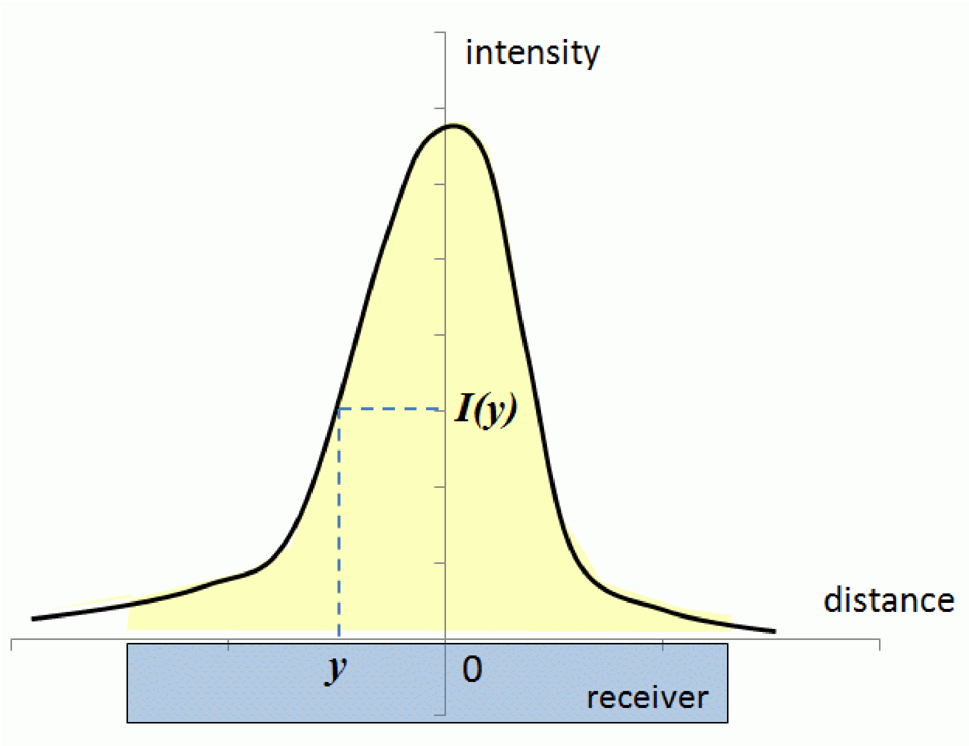
(PDF) Study the performance of V-Trough PV solar system with two axis tracking

Concentrated Solar Power (CSP) Systems

- **Curved reflectors** (e.g., conical, parabolic, spherical) create a **flux distribution** across the receiver, requiring a **local concentration ratio** ($\boldsymbol{C_l}$) to describe performance.

$$C_l = \frac{\text{Local intensity}}{\text{Incident intensity}} = \frac{I(y)}{I_{ap}}$$

- where $I(y)$ is determined for any local position y from the center of the produced image, and I_{ap} is the intensity of the incident radiation at the aperture.



Concentrated Solar Power (CSP) Systems

- In many typical cases of imaging concentrators, the reflectance of the surface (ρ), i.e., the fraction of light radiation reflected from the surface compared to the total incident radiation, is also taken into account. Then the local intensity of the concentrated light, *I(y)*, can be described as follows:

$$I\left(y\right) = I_{ap}\rho C_l$$

Concentrated Solar Power (CSP) Systems

Problem 1: Efficiency of a Parabolic Trough Collector

- A parabolic trough solar collector has an aperture width of **5 meters** and a length of **10 meters**. The system uses a receiver tube with a diameter of **0.1 meters**. The solar irradiance incident on the collector is **800 W/m²**, and the collector operates with an optical efficiency of **70%**.
- **Questions:**
  1. Calculate the **geometric concentration ratio** (C_{geo}) for the system.
  2. Determine the **useful thermal power output** if 80% of the absorbed energy is transferred to the working fluid.
  3. If the working fluid has a specific heat capacity of **4.2 kJ/kg·K** and a mass flow rate of **2 kg/s**, calculate the **temperature increase** of the fluid.
- **Reference:**

✓ Kalogirou, S. A. (2014). *Solar Energy Engineering: Processes and Systems*. Academic Press.

Concentrated Solar Power (CSP) Systems

Known Data:

- **Aperture width** = 5 m
- **Aperture length** = 10 m
- **Receiver diameter** = 0.1 m
- **Solar irradiance (I_0)** = 800 W/m^2
- **Optical efficiency (η_0)** = 70% = 0.7
- **Heat transfer efficiency** = 80% = 0.8
- **Specific heat capacity (c)** = 4.2 kJ/kg·K = 4200 J/kg·K
- **Mass flow rate ($\dot{m}$)** = 2 kg/s

Concentrated Solar Power (CSP) Systems

- **Geometric Concentration Ratio (C_{geo})**

$$C_{\text{geo}} = \frac{A_a}{A_r}$$

Where:

- $A_a = \text{aperture area} = \text{width} \times \text{length} = 5 \times 10 = 50\ \text{m}^2$
- $A_r = \text{receiver area} = \pi d L = \pi(0.1)(10) = 3.14\ \text{m}^2$

$$C_{\text{geo}} = \frac{50}{3.14} = 15.92$$

Concentrated Solar Power (CSP) Systems

- **Useful Thermal Output (U_L)**

$$U_L = \dot{Q}_s = \eta_0 \times A_a \times I_0 \times \text{heat transfer efficiency}$$

$$\dot{Q}_s = 0.7 \times 50 \times 800 \times 0.8$$

$$\dot{Q}_s = 22,400 \text{ W} = 22.4 \text{ kW}$$

Concentrated Solar Power (CSP) Systems

- **Temperature Increase of the Fluid (ΔT)**

$$\Delta T = \frac{\dot{Q}_s}{\dot{m}c}$$

$$\Delta T = \frac{22,400}{(2 \times 4200)}$$

$$\Delta T = \frac{22,400}{8400} = 2.67^{\circ}\mathrm{C}$$

Thermal Energy Storage (TES) Systems

- Thermal energy storage is a critical component of solar thermal systems, allowing the collected heat to be stored and used when needed.
- Sensible heat is the energy stored by increasing the temperature of a material without changing its phase.
- Latent heat is the energy released or absorbed by a material during a phase change, such as the melting or solidification of a phase-change material.
- Sensible heat storage systems store thermal energy by raising the temperature of a storage medium, such as water, rock, or molten salt.
- Latent heat storage systems use phase-change materials that store energy during the phase change between solid and liquid, or liquid and gas.
- Thermochemical storage systems store energy through reversible chemical reactions, which can provide high-density and long-term storage.

Advanced Materials for Solar Thermal Harvesting

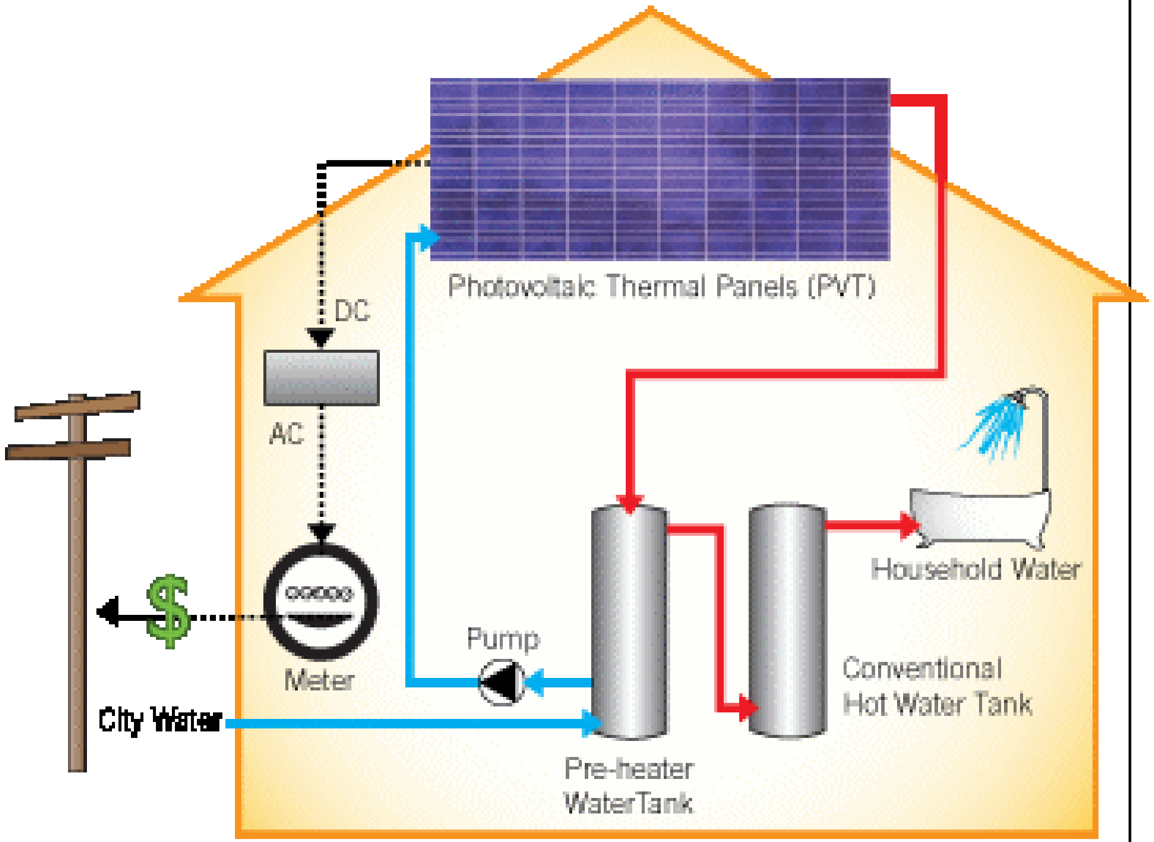
- Advanced materials play a crucial role in improving the efficiency and performance of solar thermal harvesting systems.
- Selective absorber coatings: These coatings are designed to maximize the absorption of solar radiation while minimizing thermal radiation losses, leading to higher operating temperatures.
- Phase-change materials: These materials can store and release large amounts of thermal energy during their phase change, providing efficient thermal energy storage.
- Thermal insulation materials: Advanced insulation materials, such as aerogels and vacuum insulation panels, can reduce heat losses and improve the overall efficiency of solar thermal systems.
- Thermal storage materials: Novel thermal storage materials, including molten salts and phase-change materials, can enhance the energy storage capacity and operating temperatures of solar thermal systems.

Hybrid Solar Systems

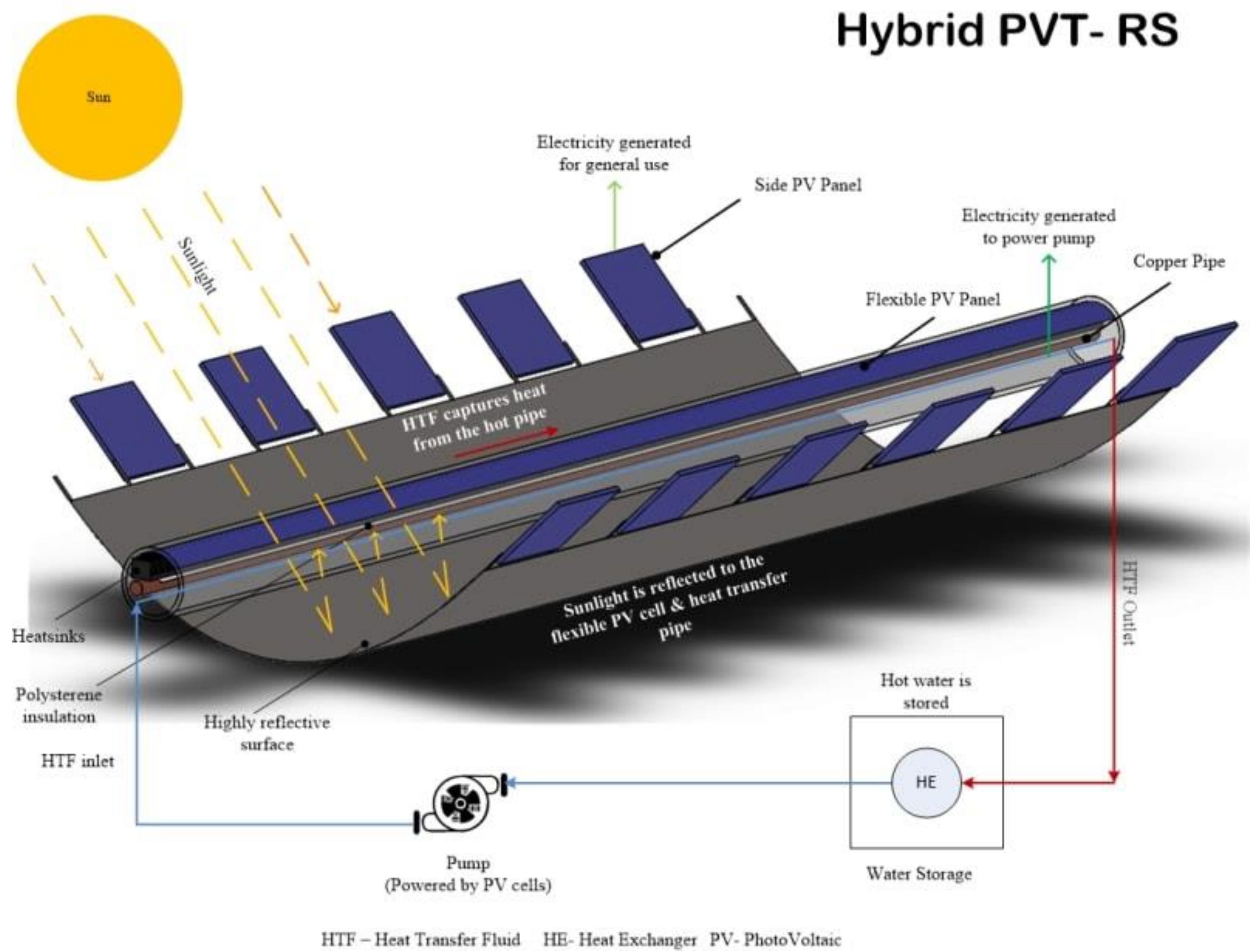
- Hybrid solar systems combine solar thermal and photovoltaic technologies to harness both thermal and electrical energy from the sun.
- In a hybrid system, the solar thermal collector is used to generate heat, while the photovoltaic system generates electricity.
- The thermal energy collected can be used for various applications, such as space heating, water heating, and industrial processes, while the electricity generated can be used to power the system itself or fed into the grid.
- Hybrid systems can improve the overall efficiency and performance of solar energy conversion by utilizing both thermal and electrical outputs.

Case Studies on Technology Implementation

- Example 1: A commercial building (Sârbu & Sebarchievici, 2018) that utilizes a hybrid solar system to meet its heating, cooling, and electricity demands.
- The building is equipped with a rooftop panel and a solar thermal system that provides Domestic Hot Water (DHW) and space heating.



Credit: Boss Solar Toronto



Credit: Rikesh Ramsurn

Case Studies on Technology Implementation

- Example 2: An industrial facility that combines a parabolic trough solar thermal system with a PV array to generate both thermal and electrical energy.
- The thermal energy is used for process heating, while the electricity is used to power the facility and feed into the grid.

Efficiency and Loss Mechanisms

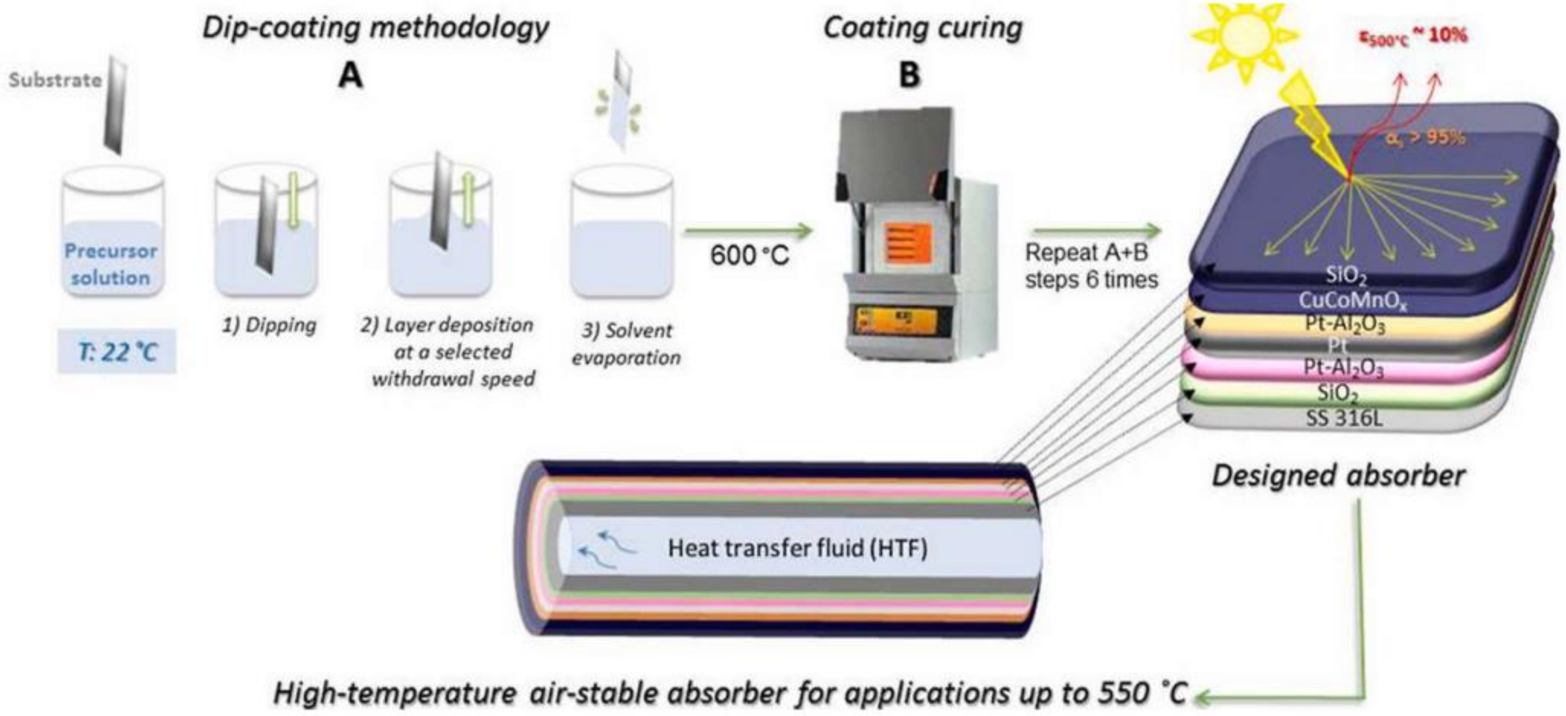
- Efficiency of a solar thermal system is influenced by several loss mechanisms, including:
- Optical losses: reflection, absorption, and scattering of solar radiation in the collector components.
- Thermal losses: heat losses through the collector walls, piping, and storage.
- Material and system integration challenges: degradation of materials, corrosion, and thermal stresses.

Innovations in Solar Thermal Design

- Advances in materials science and engineering have led to the development of innovative solutions to improve the efficiency and performance of solar thermal systems:
- Nano-coatings: Selective absorber coatings with nanostructured surfaces can enhance solar absorption and reduce thermal radiation losses.
- Selective surfaces: Advanced selective surfaces with high solar absorptance and low thermal emittance can significantly improve the efficiency of solar thermal collectors.
- Advanced concentrators: Novel concentrator designs, such as compound parabolic collectors and Fresnel lenses, can increase the concentration ratio and reduce optical losses.

Innovations in Solar Thermal Design

Solar Thermal Selective Coating



Credit: Zayed, 2024

Role of Artificial Intelligence in Solar Thermal Systems

- Artificial intelligence and machine learning techniques are being increasingly applied to solar thermal systems to improve their performance and efficiency.
- Predictive modelling and optimization: AI algorithms can be used to optimize the design, sizing, and control of solar thermal systems based on various parameters, such as climate, building loads, and energy demand.
- Real-time control and monitoring: AI-powered control systems can adjust the operation of solar thermal systems in real-time, ensuring optimal performance and energy efficiency.
- Fault detection and diagnostics: AI algorithms can be used to identify and diagnose faults in solar thermal systems, enabling proactive maintenance and improved reliability.

Cost-Effectiveness and Scalability

- The levelized cost of electricity of a solar thermal system is in the range of $0.05 to $0.15 per kWh, making it a cost-effective option for industrial and commercial applications.
- The scalability of solar thermal systems is a key factor in their widespread adoption, with the ability to install large-scale systems for utility-scale power generation or smaller systems for distributed applications.

Environmental Impact

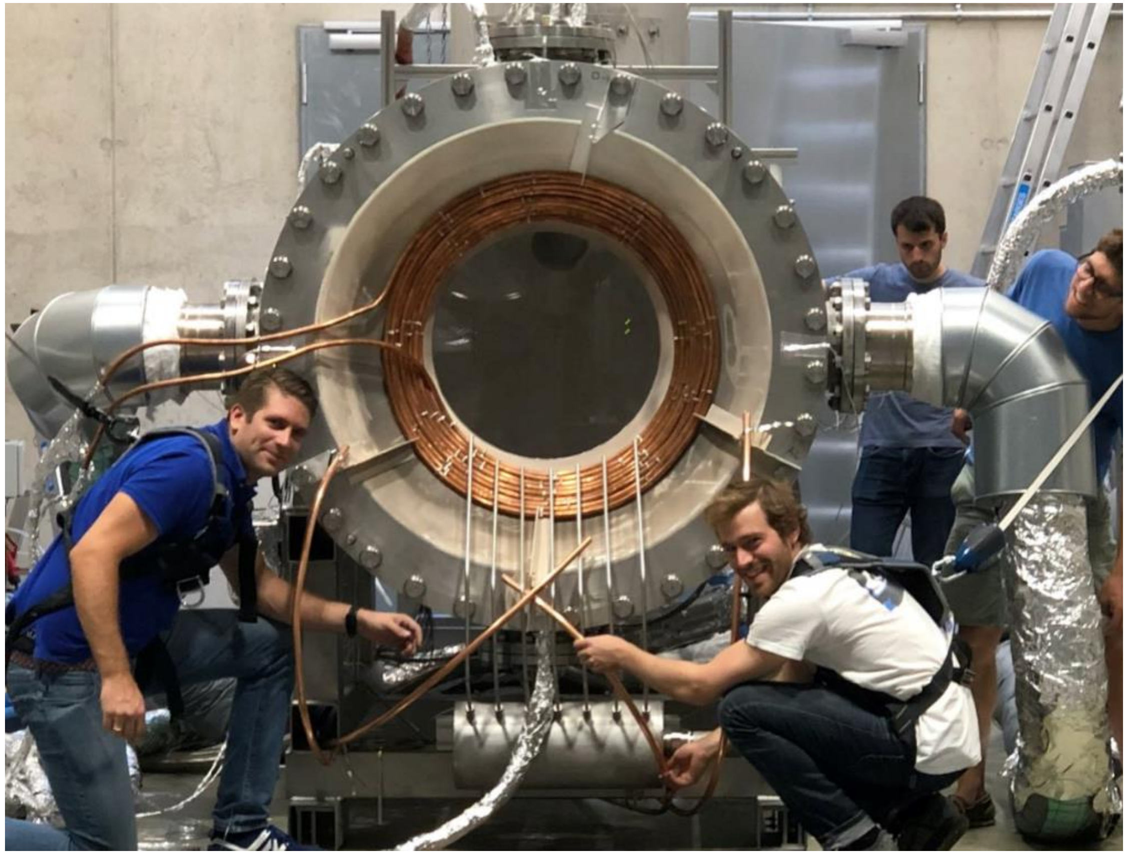
- Solar thermal systems offer significant environmental benefits, including:
  - Reduced carbon emissions: Solar thermal systems displace the use of fossil fuels, leading to a lower carbon footprint compared to conventional heating and cooling systems.
  - Sustainable resource utilization: Solar thermal systems rely on renewable solar energy, reducing the dependency on finite fossil fuel resources.
  - Life-cycle assessment: Comprehensive life-cycle assessments of solar thermal systems demonstrate their superior environmental performance, taking into account the entire lifecycle from manufacturing to decommissioning.

Emerging technologies

- Emerging technologies in the solar thermal field include:
  - Solar fuels: The production of high-temperature solar thermal energy can be used to generate solar fuels, such as hydrogen and synthetic fuels, through thermochemical processes.
  - Thermophotovoltaics: The integration of solar thermal collectors with thermophotovoltaic cells can enable the simultaneous generation of both thermal and electrical energy.
  - Advanced thermal storage: Innovative thermal energy storage technologies, such as molten salt and phase-change materials, can improve the dispatchability and grid integration of solar thermal systems.

Solar fuels

- Solar thermal energy provides the heat for thermochemical reactions to produce new compounds such as green hydrogen or sustainable aviation fuel.



Thermochemical reactor designed for Synhelion's jet fuel production

Credit: Kraemer, S. , 2023

Integration with Energy Systems

- Integration of solar thermal systems into smart grids: Solar thermal systems can be integrated into smart grid infrastructure, enabling real-time optimization, demand-side management, and grid flexibility.
- Multi-energy systems: Solar thermal systems can be combined with other energy technologies, such as photovoltaics, wind power, and energy storage, to create integrated multi-energy systems that provide a diverse range of energy services.

Integration with Energy Systems

- Smart Thermal grids → for district hot water

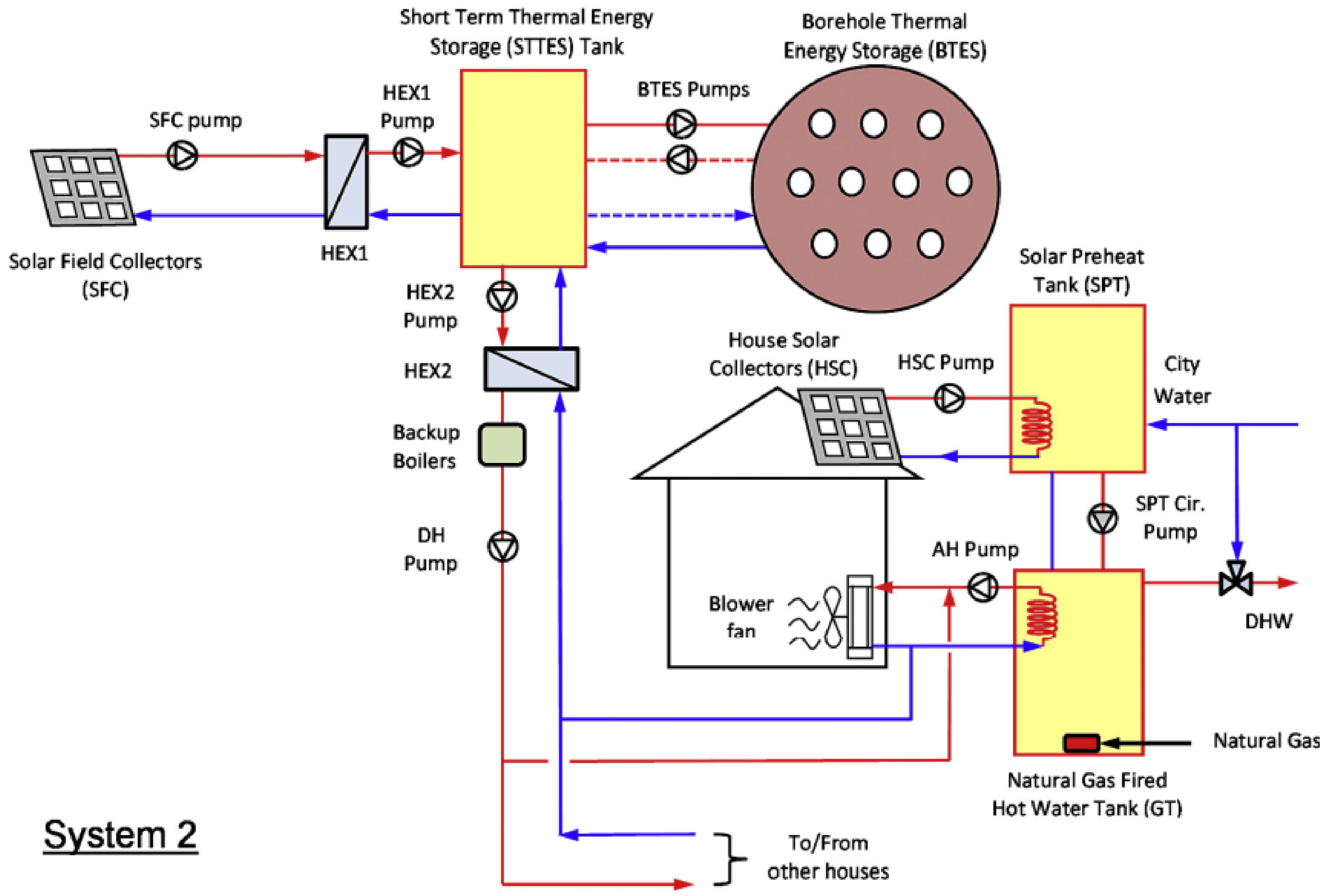


Fig. 2. Schematic of alternative system (system 2) for case study.

Credit: Yang et. al., 2017

Research Frontiers

- Research in the field of solar thermal energy is ongoing, with key focus areas including:
  - Improving collector and receiver performance through advanced materials and design.
  - Developing efficient and cost-effective thermal energy storage solutions
  - Enhancing the integration of solar thermal systems with buildings and energy grids
  - Exploring novel applications and hybrid systems, such as solar fuels and thermophotovoltaics
  - Advancing simulation and optimization tools for system design and control

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