



A Comprehensive Review of Solar Cooling System

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ABSTRACT

Solar cooling systems offer an ingenious solution to satisfy the world's energy demand while also reducing greenhouse gas emissions. Harnessing solar energy, these systems offer an environmentally friendly alternative to conventional cooling methods that are primarily based on fossil fuels. Solar cooling systems basically work through thermal energy conversion techniques such as absorption or adsorption refrigeration or photovoltaic-driven systems conventional vapor compression cycles [6]. It shows great potential in several climates, especially with high solar radiation. Three major hurdles are improving energy efficiency, reducing initial investment costs, and ensuring year-round operation. This paper reviews the concepts, types and trends of solar cooling systems with special attention on their sustainability and role in energy transition plans.

Keywords: solar heating, sustainable energy, Adsorption, absorption, and refrigeration cooling powered by photovoltaics, environmentally friendly cooling systems, energy conservation, climate-friendly cooling and solar-powered air conditioning.

INTRODUCTION

As the energy consumption continues to increase in the world, the immediate need is to develop pragmatic and sustainable answers to the cooling challenge. Since most of the conventional air conditioners depend upon fossil fuel-based electricity, a large number of them not only consume huge amounts of power during peak demand, but also increase greenhouse gases emissions significantly. Since solar cooling systems utilize free and renewable solar energy as the input for generating cooling, they are a good alternative in this regard. The two advantages are that these systems reduce the carbon footprint of air conditioning and produce renewable energy.

There are two primary categories of solar cooling technologies: thermally-driven and electrically-driven systems. These technologies can be applied through various ways. Absorption and adsorption chillers are examples of thermally-driven systems that generate cooling directly from solar thermal energy without the use of material or chemical refrigerants, many of which are also potent greenhouse gasses. Instead, photovoltaic-driven systems can be integrated with the current cooling segment because they use solar electricity to perform normal vapor compression cycles. These technologies vary from one another in terms of their advantages, uses, and drawbacks, such as cost, scalability, and performance efficiency in various climates.

In areas with strong solar insolation and peak cooling demand—when demand is greatest—solar cooling systems are particularly appealing. However, the primary reasons they are not commonly used include obstacles including the high cost of capital investments, the difficulty of continuously obtaining solar energy, and the complexity of thermal storage solutions. Nevertheless, a number of challenges have to be addressed through ongoing research and development in order to create systems that may be utilized more autonomously and economically.

Based on their fundamentals, categories, and advancements up to this point, it offers a thorough analysis of solar cooling technologies. Our goal is to demonstrate their potential for enabling sustainable refrigeration by examining their operational characteristics, functioning principles, and integration with broader energy systems. Additionally, its economic and environmental implications are examined, emphasizing the contribution of solar cooling systems to energy independence and climate change mitigation.

2. AN OVERVIEW ON SOLAR COOLING SYSTEM

A solar cooling system relies on renewable solar energy, which provides for cooling without the conventional alternatives of air conditioning and refrigeration methods. These systems are particularly valuable in solving the increased global demand for cooling while reducing energy consumption and greenhouse gas emissions. Solar cooling has been gaining prominence in residential, commercial, and industrial applications, especially in regions with high solar irradiance.

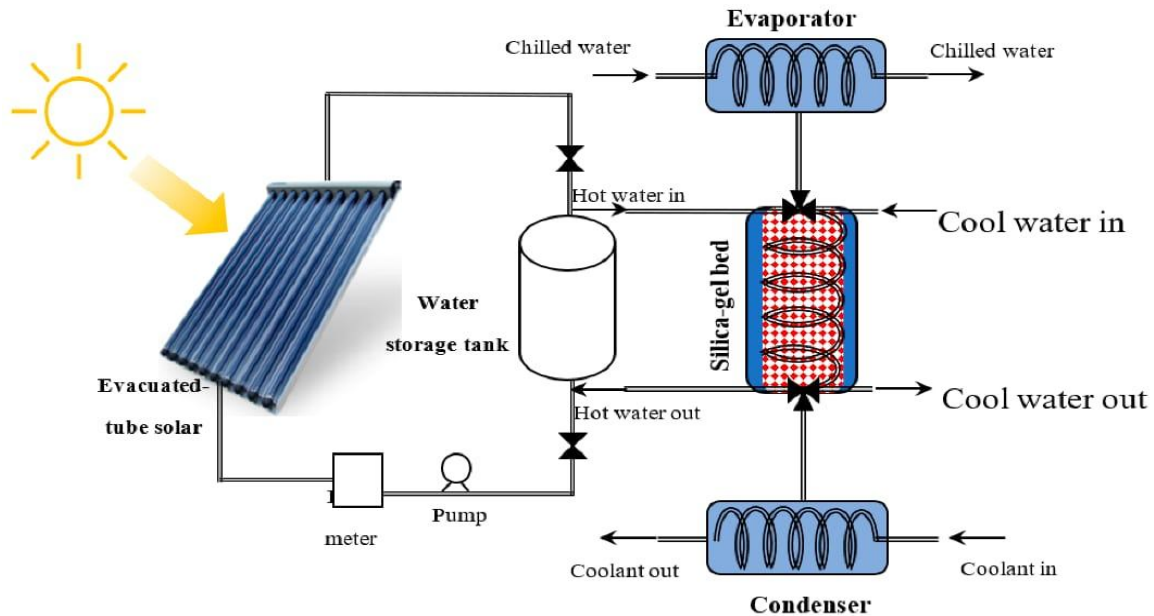


Fig: Performance Analysis of a Solar Cooling System

How Solar Cooling Works: Solar cooling systems capture the sun's energy to energize the cooling process by either thermal or photovoltaic (PV) routes:

Solar Thermal Cooling:

- Solar collectors (flat-plate, evacuated tube, or concentrating) absorb solar heat.
- This solar heat is then transferred to drive thermally activated cooling technologies of which examples include:
- Absorption Cooling: It relies on a working pair, usually water-lithium bromide or ammonia-water, to produce cooling through chemical absorption processes.
- Adsorption Cooling: It utilizes solid desiccants, which include silica gel or zeolite, to adsorb refrigerants under the influence of solar heat.
- Desiccant Cooling: Leveraged solar heat regenerates the moisture-absorbing materials for dehumidification.

Photovoltaic (PV)-Based Cooling:

- Solar panels convert the sunlight into electricity.
- The electricity converts standard electric air conditioners or vapour compression systems.
- Any extra energy can be stored in batteries for usage at non-sunlight hours.

Hybrid Systems: Both types of systems combine to provide maximum efficiency and reliability under varying weather conditions.

2.1 Types of Solar Cooling Systems:

Solar cooling systems are classified as per the standard from which solar energy is collected and converted into a method of providing cooling. Generally, these systems are classified into two types: thermally-driven systems and photovoltaic-driven systems; both working principles are diverse, having their own advantages and disadvantages.

2.1.1 Thermally-Driven Solar Cooling Systems:

a. Absorption Cooling Systems: This system utilizes solar thermal energy to drive an absorption refrigeration cycle and provides sustainable, energy-effective cooling. It is well suited for places that have high solar irradiance and significant levels of cooling.

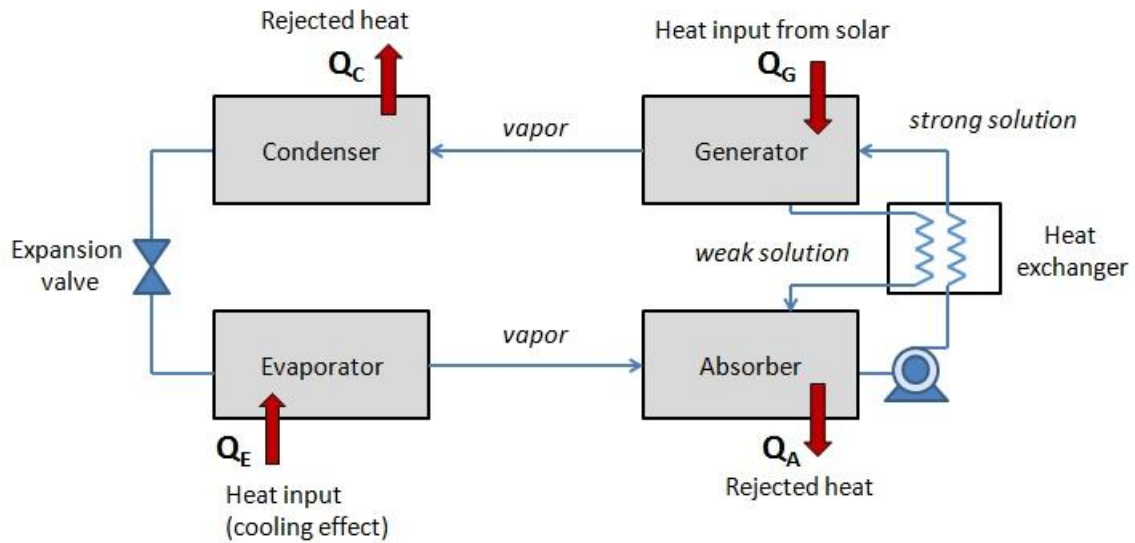


Fig: The working cycle of absorption cooling

1. Working Principle: The system works on an absorption refrigeration cycle, which utilizes the principle of heat for cooling rather than electricity. This mainly deals with the transfer of heat from a refrigerant to an absorbent.

Heat Input (Generator):-

- Solar collectors used to absorb thermal energy, which is then used to heat the generator.
- A solution comprising refrigerant (water or ammonia) and absorbent (lithium bromide or water) in the generator is heated.
- The refrigerant evaporates due to this heat and separates from the absorbent.

Condensation (Condenser):

- In the condenser, the refrigerant vapor is cooled. This causes it to get condensed into a liquid state.
- During condensation, heat is discarded to the environment

Expansion (Expansion Valve): The liquid refrigerant flows through an expansion valve that reduces both its pressure and temperature

Evaporation (Evaporator): The low-pressure refrigerant takes heat from the air or water that needs cooling in the evaporator.

Absorption (Absorber): The refrigerant vapor flows back to the absorber, where it is absorbed again by the absorbent. The cycle continues because the refrigerant-absorbent solution is returned to the generator.

b. Adsorption Cooling Systems: An adsorption solar cooling system utilizes solar thermal energy to power an adsorption refrigeration cycle. The systems are environmentally friendly, highly efficient at low-grade heat utilization, and suitable for areas with high solar irradiance.

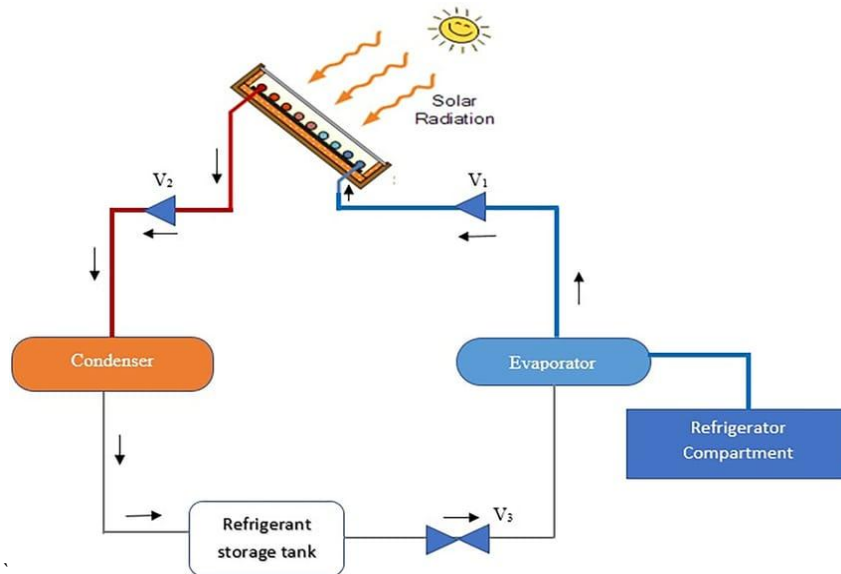


Fig: Schematic diagram of solar adsorption cooling system

1. Working Principle: The working principle of the adsorption solar cooling system is based on a solid adsorbent's physical adsorption-desorption cycle with a refrigerant. Heat caused by the solar energy triggers the said cycle resulting in cooling.

Adsorption Phase: The refrigerant, (for example water), is adsorbed onto a solid adsorbent, for example silica gel or zeolite. Heat is liberated at this stage, which can be removed to the surroundings.

Desorption Phase: Solar thermal energy heats the adsorbent causing refrigerant desorption as well as separation from the adsorbent. The desorbed refrigerant is collected as vapor.

Condensation Phase: The refrigerant vapor is condensed in a condenser, liberating heat from the surroundings.

Evaporation Phase: Liquid refrigerant passes to an expansion valve that lowers the pressure and temperature of the liquid. In the evaporator, liquid refrigerant absorbs heat from air or water to be cooled producing the cooling effect.

Re-Adsorption Phase: The low-pressure refrigerant vapour return to the adsorbent material, restarting the cycle.

2. Components of an Adsorption Solar Cooling System: Solar Collectors: The solar energy is captured to heat up the adsorbent during the desorption phase. Typically, flat-plate or evacuated tube collectors are used.

- **Adsorber:** It contains the adsorbent material such as silica gel, zeolite where the cycle of adsorption-desorption actually takes place.
- **Condenser:** It condenses the refrigerant vapor into liquid, transferring the heat to the environment.
- **Evaporator:** It absorbs heat from the space or medium that need to be cooled.
- **Expansion Valve:** It reduces the pressure of the refrigerant for cooling.

C. Desiccant-Based Cooling Systems:

Desiccant cooling systems use desiccants to remove moisture from air as part of a cooling process. These often take the form of hybrid systems, combined with solar thermal energy to regenerate the desiccant, offering a completely sustainable and efficient method in which to cool and control humidity, especially in hot and wet climates.

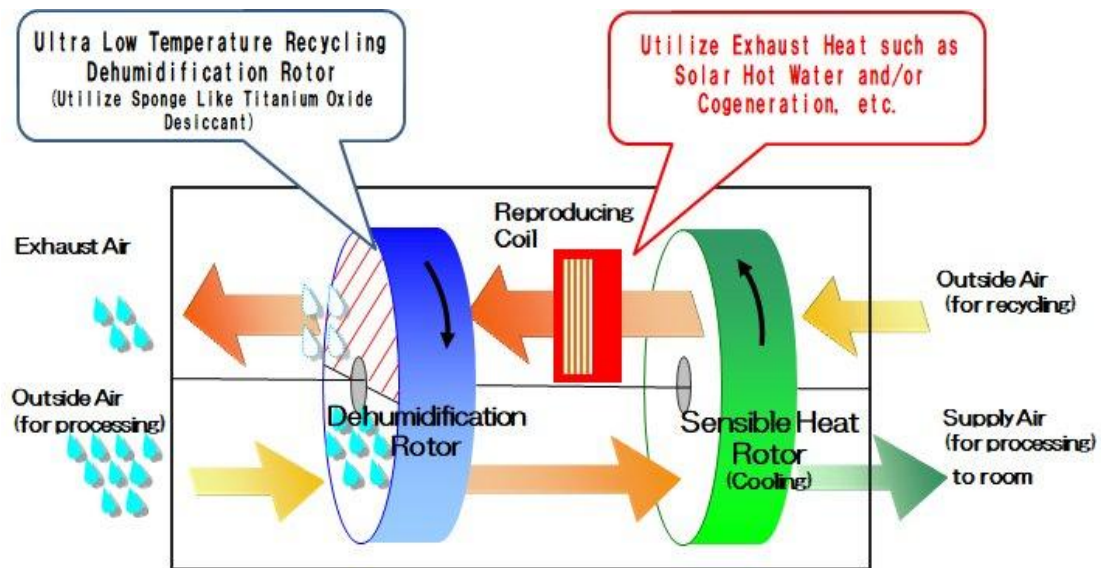


Fig: A review of Desiccant cooling system

1. Operating Principle:

What has been central to a desiccant cooling system is the cycle of moisture absorption and regeneration. The desiccant is regenerated using solar thermal energy, which makes this system relatively independent from the use of traditional sources of power.

Dehumidification:

- Air laden with moisture is passed through a desiccant (silica gel, lithium chloride, or zeolite).
- The desiccant absorbs moisture in the air, which lowers the humidity of the air.
- The dried air is cooled by an evaporative cooling process, direct or indirect.
- Evaporative cooling utilizes the principle of water evaporation to lower the temperature of air.

Desiccant Regeneration: Solar collectors supply heat to regenerate the desiccant by forcing out the absorbed moisture. The desiccant is now prepared to absorb water once again in the following cycle.

d.Solar Ejector Cooling Systems:

The solar ejector cooling system presents a solar-thermal driven cycle of an ejector-type refrigeration system. This is a very sustainable and low-maintenance cooling alternative, especially for sunny and remote areas. On the grounds of simplicity, use of low-grade heat, and accommodation of natural refrigerants, it becomes attractive for the purpose of eco-friendly cooling.

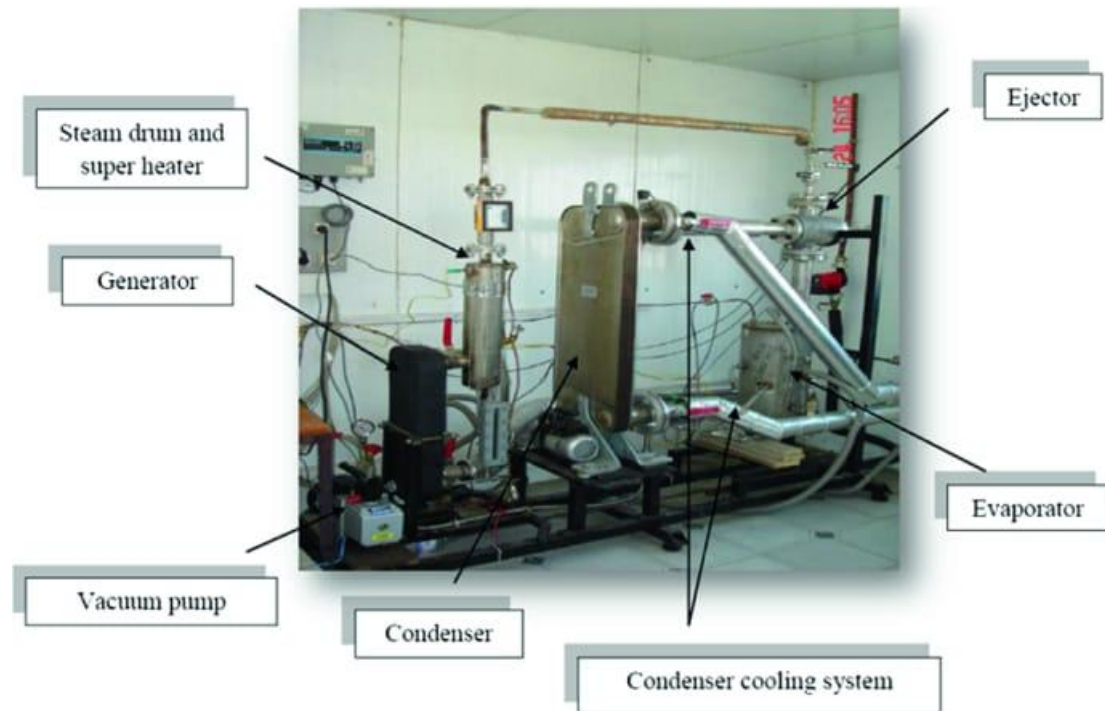


Fig: Design of a solar ejector cooling system

1. Working Principle: The heart of a solar ejector cooling system is the ejector, which is an expander that generates a chilling effect by incorporating a high-velocity fluid jet to entrain a low-pressure fluid. The whole process is powered by solar energy rather than electricity.

- **Solar Heat Collection:** Thermal energy is captured by solar collectors. The thermal energy generates heat inside the generator.
- **Action of Generator:** The generator holds a refrigerant. The solar heat causes a refrigerant to vaporize, producing high-pressure vapor.
- **Ejector Action:** The high-pressure vapor enters the ejector, which it moves with high-velocity through a nozzle. This causes a low-pressure zone that will now entrain refrigerant vapor from the evaporator.
- **Mixing and Compression:** The entrained vapour mixes together with the high-velocity vapour inside the ejector.
- **Condensation:** The combined vapor is condensed to liquid in the condenser, rejecting heat to the environment.

2. Solar Ejector Cooling System Components: Solar Collectors: flat-plate, evacuated tube, or concentrating collectors supply the thermal energy

- **Condenser:** Condenses refrigerant vapor, rejecting heat to the surroundings.
- **Evaporator:** Takes heat from the air or medium to be cooled.
- **Expansion Valve:** Lowers the pressure of the refrigerant to cool it.

2.1.2 Photovoltaic-Driven Solar Cooling Systems:

PV-driven solar cooling systems make use of the electricity generated from photovoltaic solar panels to operate conventional or specialized cooling appliances such as air conditioners or heat pumps. They are flexible and highly efficient for cooling in regions where sunshine is plentiful, offering a clean source of renewable energy for cooling in place of conventionally driven electric cooling.

1. Principle of Operation: This system harnesses sun energy through PV panels, which converts that energy into electricity. The electricity will power cooling devices either as a direct or hybrid system.

- **Direct System:** PV panels produce electricity to drive coolers through inverter-based air conditioner or a DC-powered chiller. direct delivery of cooling takes place for the sunlight hours.
- **Hybrid System:** Battery storage, which includes addition of excess solar energy to be used during non-sunlight hours for cooling. It can be connected to the grid for backup or sell surplus electricity to the grid (grid-tied systems).

2. Components of a PV-Driven Solar Cooling System:

- **Photovoltaic Panels:** This is a panel that captures sunlight and converts it into electricity.

- **Cooling System:** Direct Current (DC) Air Conditioners: For direct connection to PV panels, enhances efficiency.
- **Inverter Air Conditioners:** High-efficiency models and can be used in grid-tied or off-grid systems.
- **Hybrid Systems:** Can be combined with thermally cooled devices for greater flexibility
- **Extra Inverter:** Converts DC power created by photovoltaic modules into AC which could feed air-cooled systems
- **Battery Storage (Optional):** Store excess energy generated by photovoltaic arrays at peak sunlight and use them during periods of overcast or at night.
- **Charge Controller:** Controls the electrical current flowing from the photovoltaic panels to the batteries and cooling systems to prevent overcharging.

2.1.3 Emerging and Hybrid Solar Cooling Technologies:

Hybrid solar cooling technologies combine novel designs with multi-energy sources to overcome the constraints of conventional solar cooling systems. The goal here is further efficiency enhancement, improved dependability, and reduced environmental damage while keeping the cost-effectiveness in check.

1. New Solar Cooling Technologies:

1.1. Solar Assisted Vapor Compression Cooling:

- **Concept:** Combines solar thermal or photovoltaic energy with conventional vapor compression systems for electricity-saving purposes.
- **Key Features:** Based on solar energy as a preheater or compressor workload reducer.
- **Benefits:** Increased efficiency of the system and energy-saving.
- **Applications:** Residential and commercial cooling

1.2. Solar-Assisted Absorption/Adsorption Cooling with Advanced Materials:

- **Concept:** Design with new types of adsorbents and absorbents based on metal-organic frameworks and composite materials to enhance heat of absorption
- **Key Characteristic:** Higher absorption capacity and regeneration rates.
- **Benefits:** Better cooling efficiency, Smaller and sleeker designs possible.
- **Applications:** Industrial process cooling and distributed cooling systems.

2. Hybrid Solar Cooling Technologies:

2.1. Solar-Geothermal Hybrid Cooling:

- **Concept:** Integration and exploitation of the potential of solar and geothermal heat pumps for increased cooling efficiency.
- **Key Characteristics:** solar power can be used to drive or pre-heat the geothermal fluid.
- **Advantages:** very efficient, especially in areas of high solar and good geothermal potential.
- **Applications:** cooling of huge buildings and industries.

2.2. Hybrid Solar PV-Thermal Cooling:

- **Concept:** Integrate photovoltaic panels into solar thermal collectors in order to exploit both electrical and thermal energy.
- **Key Features:** PV panels produce power for cooling applications.
- **Advantages:** Maximum possible solar energy is exploited, Efficiency of the overall system is improved.
- **Applications:** Residential, Commercial and industrial cooling.

3. BENEFITS AND CHALLENGES

3.1 Benefits:

1. Green House Emissions Lowered:

- Green house emissions: Solar cooling can decrease the reliance on fossil fuels considerably thereby reducing the carbon emissions.
- Natural Resources Usage: Some systems like absorption and adsorption contain eco-friendly refrigerants, which decreases the environmental footprint.

2. Energy Saving:

- Low Installation and Operating Expenses: Solar energy is free and accessible making the economics of electricity or fuel usage very low.
- Peak load shifted: The system runs during sunny periods when the cooling demand is normally at its highest.

3. **No Fossil Fuels:** Energy Independence: Solar cooling is independent of the traditional energy grids, thus fit for off-grid or remote use.

3.2 Challenges:

1. High Initial Costs:

- Installation Expenses: Solar panels, thermal collectors, and other components require significant upfront investment.
- Advanced Materials: Technologies like adsorption systems or hybrid configurations can further increase costs.

2. Weather Dependency:

- Reliance on Sunlight: Performance is directly tied to solar radiation, making the system less effective in regions with inconsistent sunlight.
- Seasonal Variability: Efficiency can drop during cloudy or winter months without adequate storage solutions.

3. Space Requirements:

- Collector Size: Large collectors are required for solar thermal or PV panels, and these may not be accessible in many locations.
- Infrastructure Requirements: Installation on rooftops or open ground requires structural and environmental considerations.

4. ADVANTAGES AND LIMITATIONS

4.1 Advantages of Solar Cooling Systems:

1. Environmental Benefits:

- Reduced Carbon Footprint: Solar cooling systems significantly cut greenhouse gas emissions by using renewable energy.
- Eco-Friendly Refrigerants: Many systems use natural refrigerants (e.g., water, ammonia), reducing ozone depletion and global warming potential.

2. Energy Efficiency:

- Renewable Energy Use: Solar cooling harnesses solar energy, a sustainable and inexhaustible resource.
- Peak Load Reduction: Performs best during sunny periods, aligning with peak cooling demands, thereby reducing strain on power grids.

3. Cost Savings:

- Lower Operation Expenses: Since the installation period, solar cooling systems use free solar energy and, therefore, save on electricity and fuel.
- Long-term Cost Saving: The long-term cost savings in utility bills therefore pays off the investment made at hand.

4. Flexibility:

- Wider Application: It is applicable in residential, commercial, and industrial cooling purposes
- Hybrid Integration: Solar cooling can easily integrate with other forms of renewable technologies, including geothermal or wind.

4.2 Limitations of Solar Cooling Systems:

1. High Initial Costs:

- Installation Cost: Sunny panels, collectors, and specialized cooling components are costly in initial stages
- Advanced Technological Systems: Technologies such as adsorption cooling with good grade materials increase the investment levels.

2. Dependence on Weather:

- Uncertainty of Sunlight: Efficiency is much more dependent on the intensity of solar radiation.

- Seasonal and Geographic Limitations: Inefficient during rainy or winter seasons without backup systems.

3. Space Requirements:

- Huge Installation Areas: Solar thermal collectors or PV panels occupy a considerable amount of space that cannot be possible in densely populated regions.
- Structural Limitations: Rooftop-mounted devices must have adequate structural strength.

4. Efficiency Issues:

- Low COP: Compared with other conventional systems, most solar cooling systems run with lower coefficients of performance (COP).
- Losses of Energy: Inefficiencies in conversion and losses due to heat can completely demolish the potential performance of a system.

5. APPLICATION EXAMPLES

Many residential, commercial, and industrial applications have already been made operational with solar cooling systems. Some of the notable examples are as follows:

5.1 House Cooling:

- Example: Solar Absorption Cooling for a Home in Spain
- System Type: Solar absorption cooling with flat-plate solar collectors .
- Description: A house was using a solar thermal system integrated with an absorption chiller to produce cooling for hot summer days in southern Spain .
- Result: 40% savings on electricity, Low peak load sensitivity on the power grid.

5.2 Cooling in a Commercial Building:

- Case study: Office Building in Singapore
- System type: Hybrid solar PV and Solar cooling system.
- Description: A commercial office built rooftop photovoltaic panels and solar thermal collectors to power a hybrid cooling system. The system relies on solar power in driving adsorption chillers to cool the air.
- Result: Saves 60% of its energy during peak sunlight hours.

5.3 Industrial Applications:

- Case Study: Dairy Plant in India
- System Type: Solar-assisted vapour absorption cooling .
- Description: A dairy plant at Gujarat, India continued to store milk at low temperatures with a solar thermal absorption cooling system.
- Output: Operated with only an input of electrical energy, using solar heat.

6. RESULT AND DISCUSSION

6.1 Performance Analysis:

6.1.1 Energy Density

Conclusion:

The solar powered cooling systems, absorption and adsorption chiller, generally offer efficiencies that can increase up to 50-70% depending upon the local solar radiation and system configuration.

A photovoltaic-driven system can provide direct electrical energy to an air-conditioning or refrigeration system that would have a coefficient of performance (COP), which generally ranges between 3-6, depending upon the system.

Discussion:

The efficiency of solar cooling systems depends on the amount of solar energy received and the ability of the system to convert that energy into a cooling effect. The solar thermal systems usually perform better during periods when the sun continues shining brightly; during overcast conditions or in sites with minimal solar radiation, their efficiency is reduced.

PV-run systems are usually much more flexible since they can generate electricity to activate cooling systems even when there is partial sunlight incidence, though these would depend on the temperature and solar intensity.

6.1.2 Cooling Capacity:

Results:

Solar absorption systems typically have small to medium commercial building cooling capacities or residential cooling applications. Consider the flexibility of cooling capacity with respect to hybrid solar thermal and PV integration in hybrid systems, which may depend on the buildings' sizes in terms of such cooling capacities.

Discussion:

Their cooling capacity would depend on several factors such as the size of the solar collector area, efficiency of the chiller, and the demand for cooling. Hybrid systems are more apt at variable climate conditions and larger buildings because they can harness both strengths of solar thermal and PV technologies. Standalone systems might offer performance drops for off-peak seasons.

6.2 Economic and Environmental Impact:

6.2.1 Cost Analysis

Outcome:

The installation of the entire solar cooling system comprising the solar collectors, absorption chillers, and/or PV panels is highly capital-intensive compared with the standard cooling system.

The return on investment of solar cooling systems is relatively high in sunny regions. Energy saving can offset initial capital costs in 5-10 years.

Discussion:

Higher capital costs pay for themselves by significant savings in energy costs and environmental benefits, especially in regions where the cooling demand is high. Government incentives and even subsidies on renewable energy projects improve the economic viability of these systems.

One major problem is that there is a very high upfront investment, discouraging its use in regions with low sun or the energy price is much lower.

6.2.2 Environmental Benefits

Results:

Solar cooling systems also significantly contribute to reducing greenhouse gas emissions. For instance, in the Middle East region or southern Europe, a solar cooling system can annually decrease CO₂ by up to 10-15 tons of greenhouse gas emissions.

Natural refrigerants-based systems, such as ammonia or water in absorption chillers show less harm to the environment than traditional cooling systems with synthetic refrigerants that have a high GWP.

Discussion:

The environmental benefits of the solar cooling system are potent and strong as they reduce the intake of fossil fuels and reduce carbon emissions. On top of that, using green refrigerant further enhances the appealing feature of these systems as solutions for sustainable cooling.

Although such systems reduce the environmental impact associated with their whole lifecycle, manufacturing and disposal of system components, such as solar panels, must also be considered in a lifecycle analysis of these systems.

7.CONCLUSION

It is in this regard that solar cooling systems are considered the new frontier in helping the world in addressing its rising demand for cooling in order to solve its energy and environmental problems. Because the system relies on renewable solar energy, cutting dependence on fossil fuels becomes a critical part of the reduction in greenhouse gas emissions. It is, therefore, in these kinds of applications that the introduction of solar cooling technologies may possess a significant avenue to successful sustainable cooling in homes, businesses, and industries.

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