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A comprehensive review of solar energy technologies: from photovoltaic cells to hybrid systems

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ABSTRACT
Solar technologies are considered as one of the most promising solutions for sustainable energy supply and reducing dependence on fossil fuels. This review provides a comprehensive classification of solar technologies, including photovoltaic (PV), thermal (thermal) and hybrid (PVT) systems. In this review, the performance, efficiency, advantages and limitations of each of these technologies are analyzed and emerging trends such as the use of nanofluids, advanced selective coatings and phase change materials (PCM) are discussed. The results show that the selection of the appropriate technology strongly depends on the climatic conditions, ambient temperature and the intended application.
Keywords: Solar energy, thermal collectors, photovoltaic cells, evacuated tube collectors, combined PVT systems, nanofluids

1- INTRODUCTION

With the increasing global demand for energy and environmental concerns arising from the consumption of fossil fuels, renewable energies, especially solar energy, have attracted considerable attention. Solar energy is considered one of the cleanest energy sources due to its abundance, accessibility, and the absence of greenhouse gas emissions during operation. Solar technologies are generally divided into two main categories: photovoltaic systems, which convert sunlight directly into electricity, and thermal systems, which capture and use thermal energy from solar radiation. In addition, combined photovoltaic-thermal (PVT) systems have been developed with the aim of simultaneously generating electricity and heat.

2- PHOTOVOLTAIC SYSTEMS

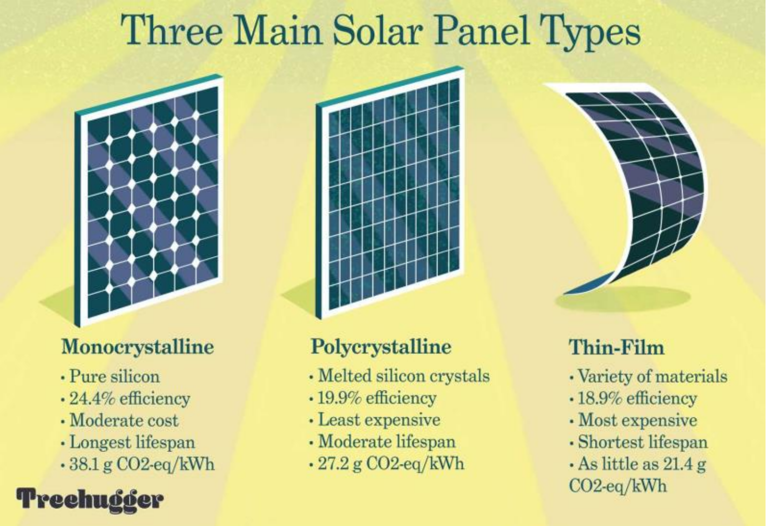
Photovoltaic systems convert sunlight into direct electrical current based on the photovoltaic effect. These systems are divided into different types:

1.1.1 Crystalline Silicon Cells

• Mono-crystalline silicon:High efficiency (20-22%), higher cost

• Polycrystalline silicon:Average efficiency (15-17%), lower cost
Thin-Film Cells
• Including CdTe, CIGS and a-Si technologies
• High flexibility and lower production cost

Perovskite Solar Cells
• Potential efficiency of over 25%
• Low production cost and possibility of manufacturing on flexible surfaces



Types of Solar Panels: Pros and Cons

Fig.1. The three main types of photovoltaic solar panels (Monocrystalline, Polycrystalline, Thin-Film) with a comparison of the efficiency and characteristics of each [1].

3- SOLAR THERMAL SYSTEMS

Flat-Plate Collectors

Flat plate collectors are the simplest and most common type of thermal collector. They consist of an insulated box with a dark absorber plate and copper tubes through which the heat-carrying fluid passes.

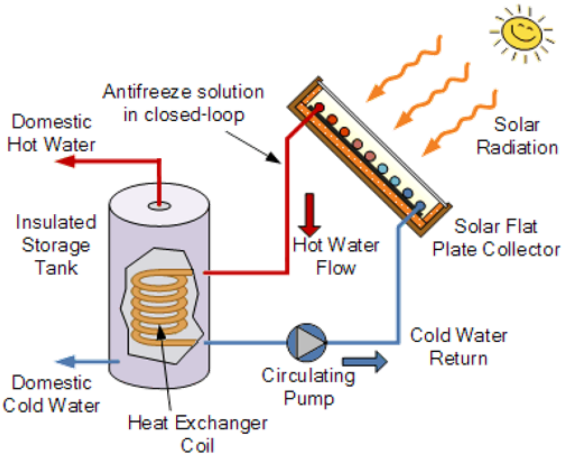


Fig. 2. Schematic diagram of a flat plate collector system including storage tank, circulation pump, heat exchanger and connecting pipes [2].

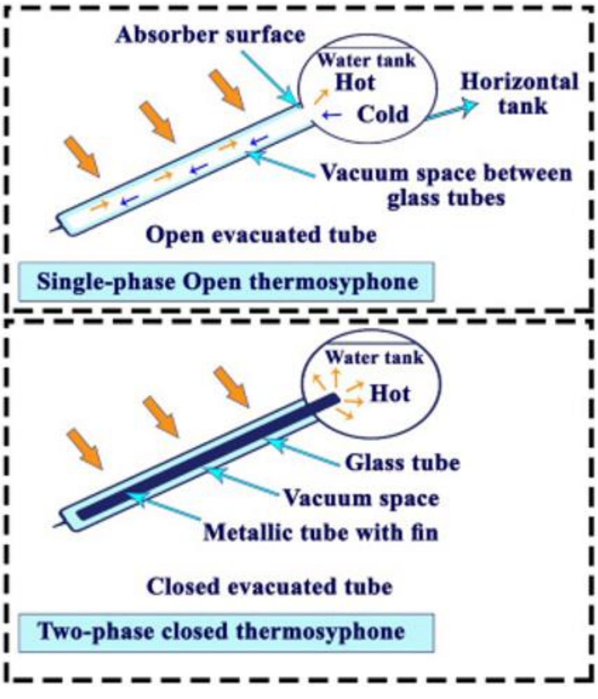
Table 1. Comparison of technical specifications of flat plate and evacuated tube collectors

Characteristic	Flat plate collector	Vacuum tube collector
Absorbent area	90%+ of total area	60-80% of the total area
Low temperature performance	Significant reduction	Maintaining high efficiency
Insulation	Conventional glass and insulation	Vacuum between two layers of glass
Frost resistance	Need for a protective system	Higher natural resistance
Initial cost	Lower	Higher
Useful life	15-20 years	20-25 years

(Source: Taken from comparative studies of thermal collectors [3])

Evacuated Tube Collectors

Evacuated tube collectors (ETSC) consist of rows of double-walled glass tubes with a vacuum between the inner and outer walls. This vacuum minimizes heat loss, especially in low-temperature conditions.



Evacuated Tube Solar Collector - an overview | ScienceDirect Topics

Fig 3. Internal structure of a vacuum tube collector: (top) open vacuum tube with single-phase thermosyphon, (bottom) closed vacuum tube with two-phase thermosyphon [4].

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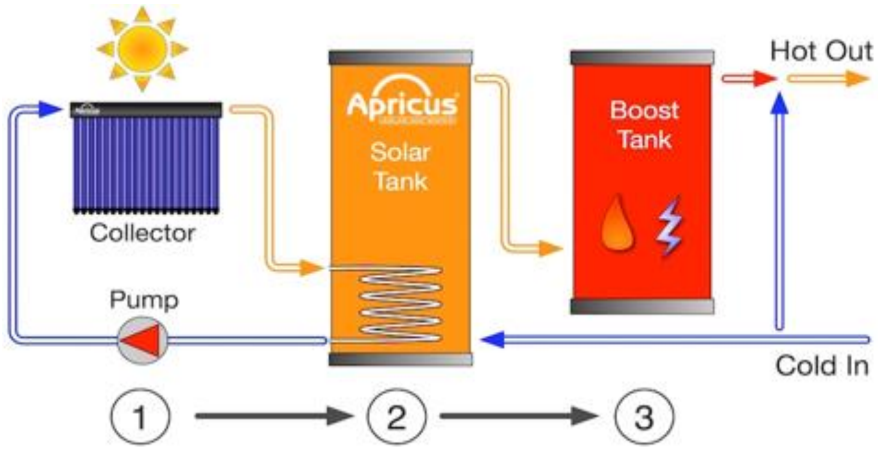
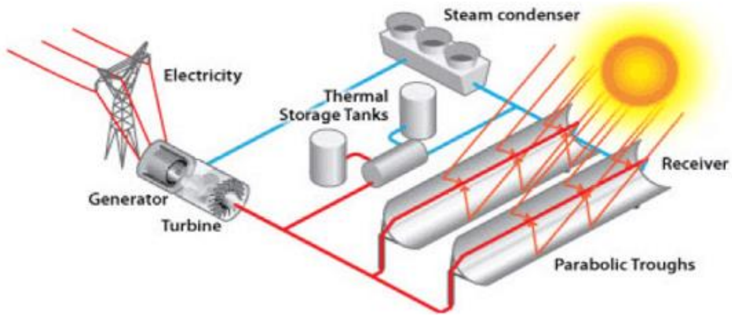


Evacuated Tube Solar Collectors, Solar Collector - Apricus Solar Water Heater

Fig 4. Diagram of the complete evacuated tube collector system including collector, pump, solar tank and booster tank [5].

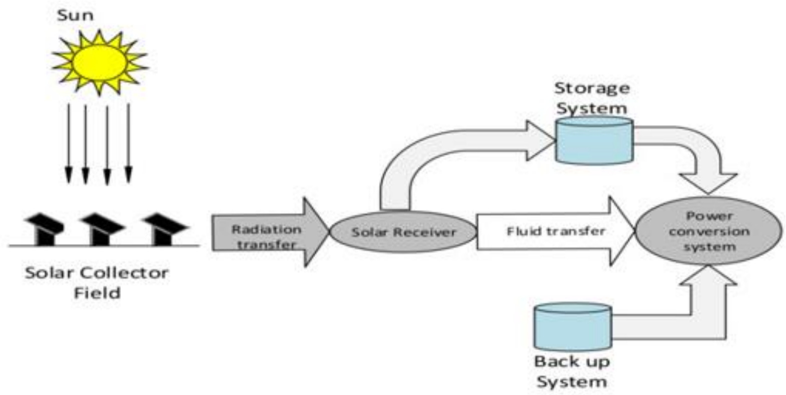
Concentrated Solar Power (CSP) Systems

By concentrating solar radiation at a single point, these systems create high temperatures and use them to produce steam and ultimately electricity.



Linear Concentrator System Concentrating Solar-Thermal Power Basics | Department of Energy

Figure 5. Schematic diagram of a linear concentrator system including the receiving tube, thermal storage tanks, turbine, and generator [6].

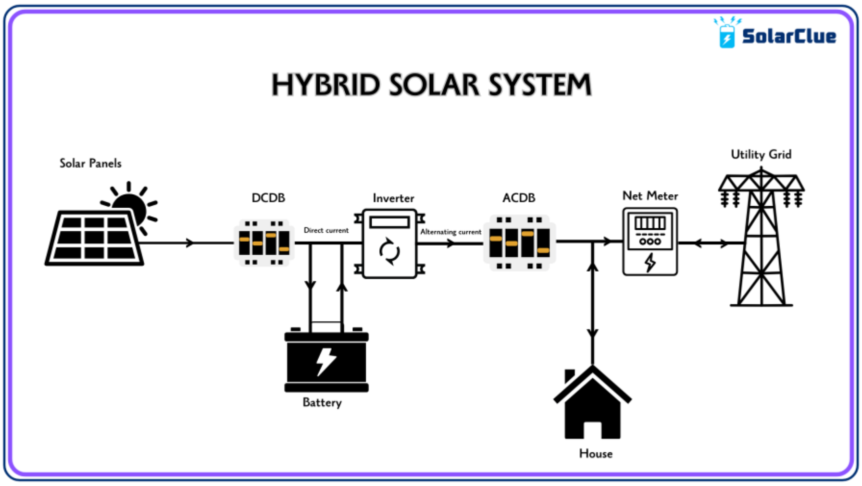


Performance Analysis and Optimization of a Parabolic Trough Solar Power Plant in the Middle East Region

Figure 6. General diagram of a concentrated solar power (CSP) system including the collector field, receiver system, storage system, and power conversion system [7].

4- COMBINED PHOTOVOLTAIC-THERMAL SYSTEMS (PVT SYSTEMS)

PVT systems increase the overall efficiency of the system by combining the simultaneous production of electricity and heat.

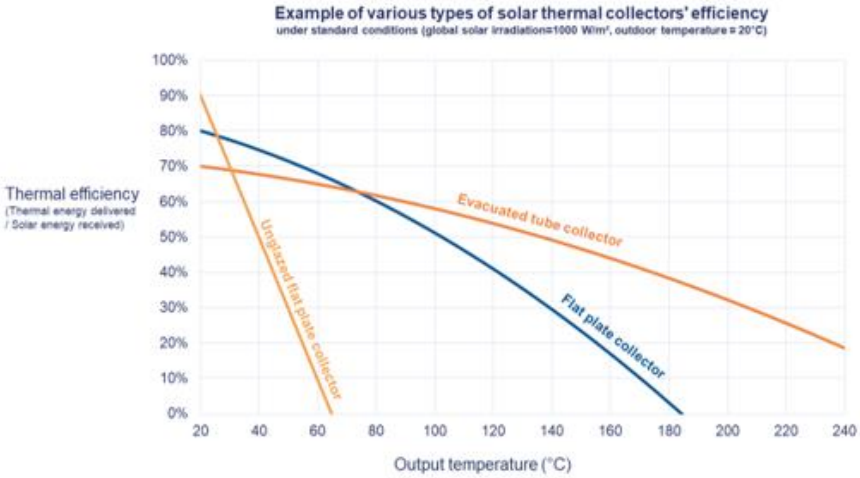


Hybrid Solar System Diagram

Figure 7. Diagram of a hybrid solar system including solar panels, battery, inverter, net metering system, and grid connection [8].

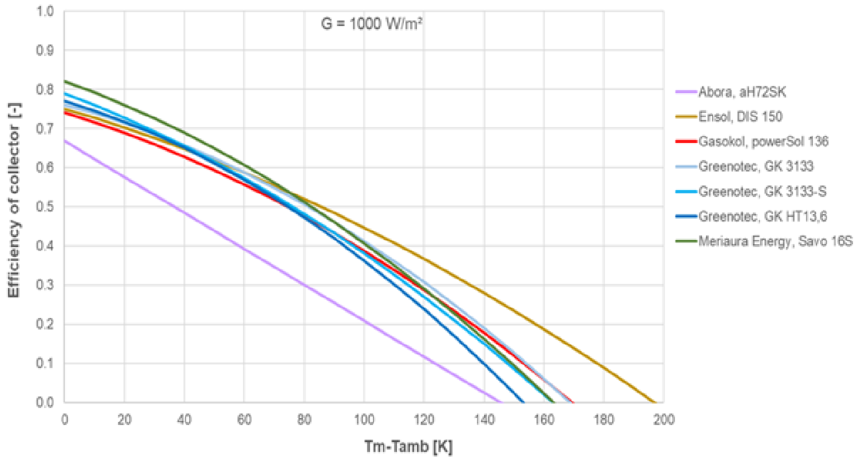
5- RESULTS

3-1. Comparison of efficiency in different climatic conditions



Temperature Different Types Of Solar Thermal Collectors Technical And Efficiency-Oriented Comparison Of Solar Collectors

Figure 8. Comparison chart of thermal efficiency of flat plate, evacuated tube and uncoated flat plate collectors at different outlet temperatures [9].



Technical and efficiency-oriented comparison of solar collectors for district heating Solarthermalworld

Figure 9. Efficiency chart of different types of thermal collectors (Abora, Ensol, Gasokol, Greentec) in terms of the difference between average and ambient temperatures [10].

Table 2. Efficiency of thermal collectors at different ambient temperatures

Ambient temperature (°C)	Vacuum tube efficiency	Flat panel performance	Economic winner
0	High - Reduce heat loss	Low-High High dissipation	Vacuum tube
25	Comparable	Comparable	Flat panel (cost)
50	Maintaining efficiency	Decreased efficiency	Vacuum tube

(Source: Experimental data and comparative simulations [11])

3.2. Economic analysis

Based on available data, the payback period for various systems is as follows:

• Cold climate (like Minnesota):Vacuum tube ~12 years, flat plate ~13 years
• Temperate climate:Vacuum tube ~13 years, flat plate ~11 years
• Warm and sunny climate:Vacuum tube ~12.5 years, flat plate ~9 years

6- CONCLUSION

Solar technologies offer a wide range of solutions for sustainable energy supply. The findings of this review show that:

1. Vacuum tube collectorsThey perform better in cold climates with diffused radiation.
2. Flat plate collectorsThey are more economically efficient in warm, sunny climates.
3. PVT systemsThey have high potential for simultaneous use of electricity and heat.
4. The use of nanofluids, advanced selective coatings, and PCMs can significantly increase the efficiency of these systems.

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