Concentrating Photovoltaic—Thermal Systems

Subjects: Energy & Fuels

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Numerous numerical and experimental studies have been conducted regarding the Concentrated Photovoltaic Thermal (CPVT) system because of its significant potential for efficient conversion of solar energy. The overall efficiency of the CPVT system is strongly dependent on the device, which extracts excess heat from photovoltaic cells. The most efficient cooling technology involves active cooling, which means that heat is collected from the photovoltaic (PV) cell via the forced flow of heat transfer fluid.

concentrated photovoltaic thermal (CPVT) solar energy solar concentration

1. Concentrating Photovoltaic—Thermal Systems

If the heat absorbed by HTF is collected and used for downstream applications, the CPV system becomes Concentrated Photovoltaic Thermal (CPVT) [1]. This installation resolves the drawbacks of photovoltaic–thermal (PVT) and concentrated photovoltaic (CPV) as separate systems, which are: low-temperature heat recovery and waste heat recovery, respectively [2]. A CPVT simultaneously generates both thermal and electrical energy, which means it classifies as a cogeneration unit. The utilization of solar energy is a cascade process [3], which means that the fraction of the solar spectrum with energy close to the band gap of the photovoltaic cells is converted into electricity and then the remaining part of the solar spectrum may be converted into useful heat. Moreover, CPVT can be transformed into a trigeneration or even polygeneration system by installing external devices [4]. Due to the simultaneous generation of various outputs, the total energy efficiency of the CPVT technology is up to 80% [2][5]. The positive and negative impact of high solar energy density and the active cooling of photovoltaic (PV) cells is presented in **Figure 1**.

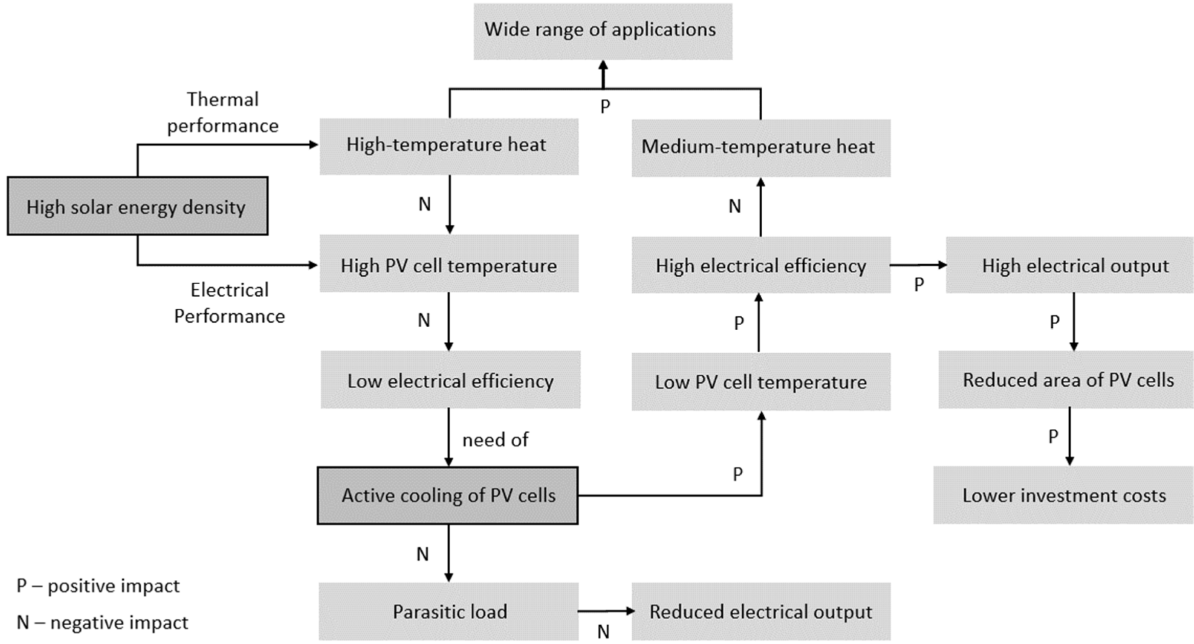

Figure 1. The impact of high solar energy density and active cooling of PV cells on the performance of the CPVT system.

The advantages and disadvantages of CPVT systems are summarized in **Table 1**.

Table 1. Advantages and disadvantages of CPVT systems.

Advantages	Disadvantages
High thermal efficiency	Non-homogenous irradiance distribution
Medium- and high-temperature thermal output	Significant optical losses
High electrical efficiency *	Usage of only direct irradiation
Low elevated temperature of PV cells	Possibility of PV cells overheating/damage
Reduced area of PV cells	High complexity of the system
Lower investment costs in PV cells *	Requirement for active cooling
Wide range of applications	Parasitic load connected with active cooling
Ease of integration with other devices	Limited maximum temperature of HTF
Cogeneration, trigeneration or polygeneration unit	

* In the case of multi-junction solar cells.

Heat harnessed in the CPVT system may find applications in: domestic water preparation [6], fresh water production [7][8][9][10][11], greenhouse heating [12][13], cooling with absorption chillers [14][15][16][17], organic Rankine cycles [18][19][20][21], hydrogen production [19], dyeing in the textile industry [22], solar windows [13] and other building-integrated systems [23]. It should be noted that the CPVT systems operate well in areas where a large amount of direct irradiation is available, i.e., in hot and mixed climate locations. In these locations, solar-driven cooling and air-conditioning systems are especially desirable [24]. The paper [25] presents the concept of a complex polygeneration system based on renewable energy sources, which is dedicated to isolated communities. This setup includes parabolic trough CPVT, PVT collectors, a biomass heater, an absorption chiller, and a desalination system.

Numerous studies have been conducted with regard to the Concentrated Photovoltaic Thermal (CPVT) systems numerically and experimentally because of their significant potential for efficient conversion of solar energy. Available research papers discussed the influence of an optical element, solar cell, heat receiver, HTF, presence of insulation and/or glazing, operating conditions, etc. on the performance of CPVT systems. These review articles summarized the fundamentals, design considerations, current technologies of CPVT systems [26][27], challenges in development [28], thermal management and storage [2], performance assessment, and future directions of CPVT development [29]. In addition, a review of CPVT systems with waste heat recovery (WHR) was carried out in 2017 [3]. Nevertheless, none of the existing articles cover the topic of devices dedicated to heat extraction via active liquid cooling with a special emphasis on their design: shape, material, insulation, etc. Moreover, there is a lack of a comprehensive analysis of the correlation between the characteristics of the heat receiver geometry, used PV cells and the concentrator type. These contents provides a short introduction regarding CPVT systems and their main components is presented to ensure a theoretical background. Regarding the state-of-the-art solutions in the field of heat extraction devices for the active cooling of photovoltaic cells. The available solutions are classified into two main groups depending on the scale of internal channels: macro- and micro-. Each geometry of the heat receiver is juxtaposed with the corresponding concentrating element, photovoltaic cell, concentration ratio, heat transfer fluid, and operating parameters of the specified system.

2. Concentrator

CPVT systems come in many varieties, which mainly differ in the shape and size of the concentrator, which consequently determines the properties of other system components, such as: the cooling system, photovoltaic cells, tracking system, overall operating parameters and the system costs. The main task of the concentrator is to collect incident solar radiation and redirect it to a significantly smaller area. Therefore, the concentrator increases the amount of primary solar energy collected by a receiver and reduces the required area of solar cells [2]. The ratio between the concentrator area and the receiver area is known as the geometrical concentration ratio (CR) [30]. This is a characteristic property of the system that cannot be modified after manufacture. However, the distribution of irradiation over the receiver area is not homogeneous: the heat flux is the highest in the central part of the receiver and decreases closer to the edges. The ratio of the average solar heat flux over the receiver area and the concentrator area is known as optical efficiency [31]. Thus, the total concentrating ability of the system is described by a parameter known as the optical concentration ratio (CRI), which is a result of the multiplication of the geometrical concentration ratio and optical efficiency. The concentration ratio is expressed as the “number of suns”, where 1 sun is equivalent to 1000 W/m^2 [2]. Based on the concentration ratio, the CPVTs can be classified into four groups: low (CR < 10 sun), medium (10 sun < CR ≤ 100 sun), high (100 sun < CR ≤ 2000 sun) or ultrahigh (CR > 2000 sun) [32], as shown in **Table 2**. With increasing CR, the output of thermal and electrical power increases and improves the efficiency of the system. Nevertheless, higher CR raises also numerous limitations. The common problem of high and ultra-high CPVT systems is the non-uniform distribution of irradiance and temperature on the receiver area, overheating of PV cells, and significant and optical losses (such as chromatic aberration). Therefore, a system with high CR requires a highly smooth optical element, efficient cooling device, accurate two-axis solar tracking and sometimes even secondary optics. On the contrary, for CPVTs with low CR, active cooling or tracking is not required because they are the only ones that utilize not only direct solar radiation but even diffuse radiation [2].

Table 2. CPVT classification based on concentration ratio. Prepared on the basis of [4][31].

Concentration CR [sun]	Low <10	Medium 10–100	High 100–2000	Ultra-High >2000
Concentrator	Compound Parabolic V-trough	Linear Fresnel Reflector Parabolic Trough Linear Fresnel Lens	Parabolic dish Central Receiver System Fresnel Lens Non-imaging dish concentrator	Parabolic dish+ Compound Parabolic Central Receiver System+ Compound Parabolic Fresnel Lens+ Compound Parabolic Non-imaging dish concentrator+ Compound Parabolic
Irradiation utilization	Direct/Partially diffusive	Direct	Direct	Direct
Cooling requirement	Passive	Passive/Active	Passive/Active	Active
Tracking	No/Maybe	Yes	Yes	Yes

When taking into consideration the concentrator geometry, the solar radiation may be focused onto a focal line or focal point. The linear focus CPVTs are using compound parabolic reflector, parabolic trough mirror, linear Fresnel reflector, linear Fresnel lens, etc. and they operate with a single-axis tracking mechanism, which rotates the construction around its focal axis [2]. The compound parabolic collector (CPC) uses parabola-shaped mirrors to focus solar radiation onto a relatively wide linear receiver to reach the two focal lines. CPC is a low-concentration technology with CR < 5, which generates medium temperature heat and may be used even without a tracking system [33]. The parabolic trough collector (PTC) also uses linear parabolic optics but in the form of a single reflector. A linear receiver is placed lengthways on the focal line, and it has a rectangular, triangular, or less often a circular or semicircular cross-section [34]. PTC is the most popular and, simultaneously, the most mature solar concentrating technology [35][36]. In the Linear Fresnel Reflector (LFR), narrow flat mirrors, which consist of chains of prisms, are placed in rows, close to ground level. They follow the Sun's movement always in the east–west plane and focus the solar radiation onto a long, downward-facing, stationary receiver placed above them. The CR usually ranges between 10 and 40. LFR technology is characterized by simplicity of operation and low maintenance costs [37]. Moreover, Fresnel lenses are lightweight and easy to produce at a low cost [38][39].

The point-focus CPVTs are using a parabolic dish collector, spot Fresnel lens, etc. and they operate with a double-axis tracking mechanism. The solar dish collector (SDC) uses a parabolic dish mirror, which concentrates the solar radiation onto a receiver located at the focal point of the system. The receiver may take different shapes such as: cylinder, hemisphere, conic, etc. SDC achieves CR above 100 and this technology is undergoing rapid development [2]. Generally, point-focus systems are able to generate high-temperature heat and can be easily integrated with micro-gas turbines, Stirling engines, etc. [4][40][41] instead of PV cells. Spot Fresnel lenses have circular rows of prisms instead of parallel ones as in the case of linear reflectors [42]. Optical elements for concentrating systems were widely discussed in [43].

3. Photovoltaic Cells

The type of photovoltaic cell applied in the CPVT system depends mainly on the concentration ratio and thermal management system [32]. Because of the high irradiance intensity on the surface of the PV cell, there is a high probability that the photovoltaic cell will operate under adverse operating conditions. Hence, the photovoltaic parameters should be characterized by low-temperature coefficients and the material itself should be highly resistant to thermal damage. The most popular crystalline silicon cells are considered suitable for CPVT systems with a low and medium concentration ratio (CR < 100). Studies [44][45] show that the single-crystalline silicon solar cell works optimally under CR = 4. For a higher CR, the decrease in temperature efficiency is compensated by a lower investment cost. The most technologically advanced multi-junction photovoltaic cells operate efficiently only with high concentration ratios (C > 100) [46][47].

When considering an arrangement of solar cells, they could be classified as single-cell, linear, and densely packed cells [48]. A single cell is easy to cool because it does not occupy significant space. The drawback is that a single cell is not capable of generating a significant amount of energy. On the contrary, linear and densely packed PV cells allow high electrical output. However, concentrated irradiation can vary on the surface of PV cells, so the non-uniform temperature would limit the electrical performance of the entire system [49].

4. Heat Extraction Device

The heat receiver is the main element of the thermal management system in the CPVT system. It is widely known that the efficiency of PV cells decreases not only as a result of the high operating temperature but also as a consequence of the non-uniform temperature distribution over the PV cells. Therefore, a heat receiver is placed in CPVT systems mainly to increase the efficiency of the photovoltaic cell and to reduce thermal stress [50]. Nevertheless, the receiver should simultaneously produce heat with as high a temperature as reasonably possible, widening its range of applications. Generally, the usage of the collected heat contributes to an increase in the total conversion efficiency of the CPVT system. The most efficient, active cooling systems require pumping power, which as a parasitic loss should be kept to a minimum. Finally, to reduce the manufacturing and maintenance costs, the heat receiver should be characterized by relatively simple geometry and reliable operation under concentrated solar radiation [51]. In CPVT systems, a type of heat extraction device depends mainly on the geometry of the optical element, concentration ratio, the number and dimensions of the PV cell, the specific requirements regarding the temperature of the PV cell, and the weather conditions (harsh or mild). In systems with line focus, the heat receiver is usually in the form of a line pipe, whereas for point-focus systems, the geometry is more compact.

Despite the design of the heat extraction device, the HTF that flows through it plays a significant role. For active cooling, the most popular HTFs are air, water, nanofluids, and oils [52]. Air and water are widely available, inexpensive, and environmentally friendly fluids. Since air has a low heat capacity, water is preferred for cooling purposes. However, in some situations, the use of pure water is limited, and it can be mixed with glycols or nanofluid particles [53]. Water-nanofluid solutions are capable of more intensive heat transfer due to their enhanced heat capacity, improving both thermal and electrical efficiency. The higher the concentration of nanoparticles, the higher the viscosity and consequently the higher the pumping power [54]. To reduce this problem, a study on hydrophobic coatings for microchannel heat sinks was conducted, and the results obtained confirmed a reduction in pressure drop of 17% [55]. In addition, the usage of nanofluids may lead to corrosion of aluminum channels due to the pH of the fluid [56]. Another possibility is to use diathermic oil, especially in installations that work in high-temperature polygeneration systems. Oils also provide an excellent alternative for installations, where water usage is restricted. On the other hand, oils are characterized by high thermal inertia [2]. There are also hybrid solar systems that simultaneously use two heat transfer fluids. The studies presented in [57] showed that the usage of air and water in the PVT system allowed for improving its overall efficiency during the winter months. The advantages and disadvantages of liquid heat transfer fluids are presented in **Table 3**.

Table 3. Advantages and disadvantages of liquid coolants used in CPVT systems. Prepared on the basis of [2][58].

Heat Transfer Fluid	Advantages	Disadvantages
water	High heat capacity and thermal conductivity Widely available and inexpensive Environmentally friendly	Upper temperature limit 100 °C Lower temperature limit 4 °C Causes corrosion in hydraulic system Threat of Legionnaires disease
nanofluids	Enhanced thermal conductivity Higher thermal efficiency than water	Bad performance in turbulent flows Higher pressure drop than for water Causes corrosion Higher costs
diathermic oil	High working temperatures (>100 °C) Enhanced thermal efficiency	Significant thermal inertia Reduced thermal conductivity Higher pressure drop than for water Not safe for environment

Depending on the temperature of HTF, the extracted heat may be used in various applications, as shown in **Figure 2**. The low-temperature heat is suitable for domestic applications: water or space heating. When the system operates at higher temperatures (close to 100 °C), it is possible to couple the CPVT system with absorption chillers, ORC cycles or desalination units (membrane distillation requires temperatures from 60 to 90 °C). Higher temperatures can provide heat for industrial processes. Highly efficient absorption chillers operate at temperatures in the range of 80–160 °C. The optimal operating temperature for the CPVT system depends on its main application and the possibilities of heat utilization in specified cases [59][60].

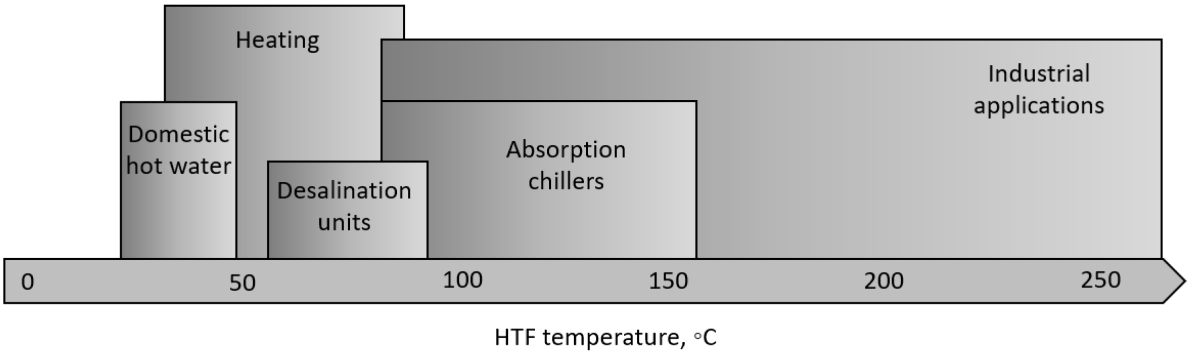

Figure 2. Applications of heat extracted from CPVT system depending on its temperature.

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