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# A review on the development of photovoltaic/concentrated solar power (PV-CSP) hybrid systems

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ABSTRACT

As an emerging technology, the photovoltaic/concentrated solar power (PV-CSP) hybrid technology is considered as one of the research focuses currently in solar energy field, due to various advantages compared with the PV-alone and CSP-alone technologies. Compared with the PV-alone system, the PV-CSP hybrid system can produce electricity with better power quality. While compared with the CSP-alone system, the cost of power production can be reduced. The overall generating efficiency will also be greatly improved if the PV component and the CSP component of the hybrid system are "compactly" hybridized by PV-topping or spectral beam splitting (SBS) technologies. The development of PV-CSP hybrid systems accelerated in recent years with the increase of maturity of PV and CSP technologies. This paper presents an exhaustive review on the state-of-the-art of the PV-CSP hybrid technologies, including the non-compact hybrid system, the PV-topping hybrid system, the SBS hybrid system, and the hybrid system combining SBS and PV-topping technologies. Recent progresses of the key technologies of the PV-CSP hybrid systems, such as high temperature solar cells, spectral beam filters, and high flux heat exchangers, are generally discussed. After that, the research status and the hybrid system performance are summarized from the literature to provide a global point of view on the PV-CSP hybrid technology. The advantages and limitations of the hybrid technology are also concluded according to the literature reviewed.

## 1. Introduction

Solar energy is one of the most promising renewable energy sources because it is both free and endless. The global solar radiation projected on the earth's surface consists of the direct and the diffuse radiations, and the direct part can be concentrated to achieve a much higher illumination. There are mainly two different technologies for power generation using solar energy. One is the photovoltaic (PV) technology, including the flat-plate PV and concentrated PV (CPV), in which PV cells directly convert solar radiation into electrical energy by the PV effect. The other is the concentrated solar power (CSP) technology, in which solar radiation is firstly concentrated and converted into heat, and then the heat is used to generate power through a power cycle. As aforementioned, the CPV and CSP systems convert the direct part of solar radiation, and the flat-plate PV system converts the global solar radiation (The direct and global solar radiations are usually measured as direct normal irradiance (DNI) and global horizontal irradiance (GHI) for the concentrated and flat-plate type solar converting systems, respectively). At present, the PV technology has been highly commercialized, and the CSP technology is also in rapid development. According to the prediction of International Energy Agency (IEA), by 2030, the global installed capacity of CSP will reach 261 GW [1], and the global installed capacity of PV will reach 1721 GW [2].

As shown in Fig. 1, the CSP technology is usually classified into the solar dish-Stirling technology, the solar tower technology, the solar parabolic trough technology, and the solar linear Fresnel reflector technology in terms of the optical elements employed [1]. Despite the different appearances of equipment, a CSP system typically consists of a solar concentrator system (solar island), a solar receiver system, a thermodynamic cycle power generation system (conventional island), and usually a thermal energy storage (TES) system. In the past decade, the commercialization of CSP technology was successfully pushed forward [3]. CSP plants with solar multiples of 3–5 and TES duration of over 10 h have emerged, such as the Gemasolar solar tower plant (19.9 MW) in Spain [4], the Crescent Dunes solar tower plant (100 MW) in the USA [5]. Generally, the CSP technology has the following characteristics: (i) the heat transfer fluids (HTFs) operate at around 400–600 °C or around 1000 °C, and thus the conventional island of CSP plant shares the same equipment with the fossil thermal power plant; (ii) it produces alternating current (AC) output, which is

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**Nomenclature**

*Symbols*

| | |
|---|---|
| $CR_{PV}$ | concentration ratio of PV |
| $CR_{CSP}$ | concentration ratio of CSP |
| $T_{PV}$ | PV cell temperature |
| $T_h$ | hot end temperature of CSP |
| $\eta_g$ | overall generating efficiency of hybrid system |
| $\eta_{CSP}$ | conversion efficiency of PV subsystem |
| $\eta_{PV}$ | conversion efficiency of CSP subsystem |

*Abbreviations*

| | |
|---|---|
| AC | alternating current |
| ARPA-E | Advanced Research Projects Agency-Energy |
| CAPEX | capital expenditure |
| CF | capacity factor |
| CPC | compound parabolic concentrator |
| CPV | concentrated photovoltaics |
| CR | concentrator ratio |
| CSP | concentrated solar power |
| DA-CPV | dense array concentrated photovoltaics |
| DNI | direct normal irradiance |
| LCOE | levelized cost of electricity |
| FOCUS | Full-Spectrum Optimized Conversion and Utilization of Sunlight |
| GHI | global horizontal irradiance |
| HCPV | high concentrated photovoltaics |
| HTF | heat transfer fluid |
| IEA | International Energy Agency |
| IRR | internal rate of return |
| ISE | Institute for Solar Energy Systems |
| MESSENGER | Mercury Surface, SpaceEnvironment, Geochemistry and Ranging |
| MTSA | Multi Tower Solar Array |
| ORC | organic Rankine cycle |
| PCM | phase change material |
| PPA | power purchase agreement |
| PV | photovoltaics |
| PV/B | photovoltaic/biofuel |
| PV/T | photovoltaic/thermal |
| REIPPP | Renewable Energy Independent Power Producers Program |
| SBS | spectral beam splitting |
| SIC | substrate integrated cooler |
| TES | thermal energy storage |
| TPV | thermophotovoltaics |
| TSC | Total Solar Cogeneration |

of a high power quality and matches the frequency and phase of the existing power grid. In addition, the CSP plants with integration of large scale TES can yield successfully stable and dispatchable power from the intermittent solar energy. As thus, it is expected that the CSP plants would provide flexibility and reliability for the power scheduling, as the mid-merit power plants. Moreover, the CSP plants with cheap TES would play a critical role under the future scenario of high penetration of the renewable energy resources [6].

However, the solar-to-power conversion efficiencies of CSP plants are still low, and the cost of CSP system needs to be reduced significantly. The efficiencies of commercial CSP plants are about: 15–20% for the tower system, 15% for the parabolic trough system, 8–10% for the linear Fresnel system (which is usually much lower than others because of the low optical system efficiency), and 25–30% for the dish system (although the efficiency of dish system is much higher, it is still far from commercialization due to the high cost and unreliability of Stirling engine) [7,8]. The levelized cost of electricity (LCOE) of CSP is about 20 $ct/kWh, and even considering the merits of the dispatchability offered by CSP plants with TES and the increased variable renewable penetration in regional power markets, the LCOE of a current-generation molten-salt power tower plant with 10 h of TES is estimated to be 12 $ct/kWh [6], which is still much higher than that of utility-scale PV (about 8 $ct/kWh [2]). Therefore, there is a great demand to increase the generating efficiency and reduce the LCOE of the CSP technology.

Unlike CSP systems, PV systems use solar cells and directly convert sunlight into electricity without or with only a few moving parts, which makes PV systems much simpler than CSP systems. The PV technology is usually divided into three generations: the first generation of silicon solar cell technology; the second generation of thin film solar cell technology; and the third generation including emerging technologies such as the tandem cell, the quantum well technology, the thermophotovoltaic (TPV) technology, and high concentration PV devices [9]. At present, the first and second generation technologies have been well developed. While among the third generation technologies, the CPV technology which combines the sunlight concentrator and the tandem III-V cell has been driven to actualization and commercialization stages. The multi-junction PV cells can have very high conversion efficiencies in concentrated sunlight. For example, the four-junction cell of Fraunhofer Institute for Solar Energy Systems (ISE) has reached an efficiency record of 46% at 508 suns [10,11]. And the commercially available high concentrated photovoltaic (HCPV) module can operate at 500–2000 suns [12].

However, the utilization of PV systems is restricted by the instability and intermittent nature of solar radiation. As large scale electric energy storage technologies are still not sufficient to match the market demand, the power from PV has a great impact on the connected grid. Moreover, only photons near the bandgap of solar cells can be converted to power by PV cells, and the majority of solar radiation is converted to heat, which increases the cell temperature and affects the efficiency and longevity of PV systems.

With the above knowledge, it can be found that the features of the CSP technology and the PV technology are complementary to each other. These two systems can be combined together to form a PV-CSP hybrid power generation system. Presently, there are various approaches for the hybridization. For example, a PV system can be used to provide power for a CSP plant as a station-service power; a PV system and a CSP system can be united to provide stable power output for a full day; thermal dissipations of PV cells can be recovered as the thermal energy source of a CSP system; by using the spectral beam splitting (SBS) technology, a PV system can operate at a relatively high efficiency, and a CSP system can simultaneously operate with the unwanted energy of the PV system.

Recently, the PV-CSP hybrid technology has gained increasing worldwide attentions and been placed on the development agenda. The main attractions of the hybrid technology include: (i) the power output characteristics of the CSP system can provide stability in the hybrid system, which is beneficial to the power quality and will reduce the impact of PV system on the grid; (ii) the PV-CSP hybrid systems are also aimed to make full use of solar energy, such as the waste heat recovery of PV cells and the SBS of solar radiation, and thus the overall generating efficiency can be increased and the LCOE may be reduced. These improvements would be helpful to develop large scale solar power plants. In the Solar Thermal Electricity Technology Roadmap of IEA (2014) [1], the PV-CSP hybrid technology has been listed as one of the ten actions and milestones of the CSP technology development.

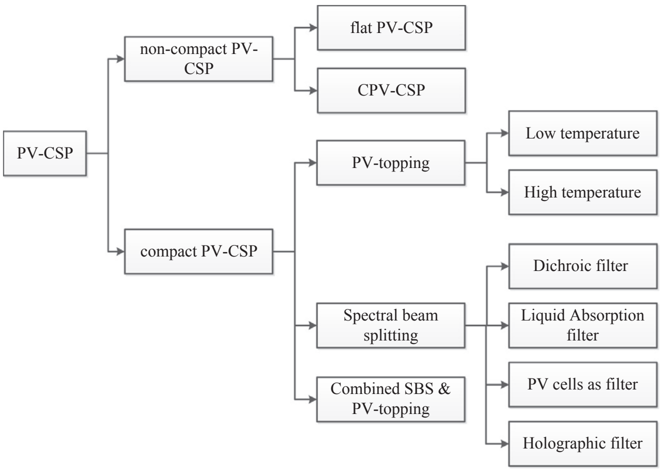


**Fig. 2.** Classification of the PV-CSP hybrid systems.

Although this research field is still in an early stage of development, it is expected that the PV-CSP hybrid technology will be researched in depth, and more commercialized PV-CSP hybrid power plants will be established soon in some regions with suitable solar radiation and weather conditions.

As a currently emerging technology, the development of PV-CSP hybrid systems has not been reviewed yet. The purpose of this article is to summarize the recent research and development progresses of the PV-CSP hybrid systems. The background information and development considerations are given first in Section 1 of this paper. Then an exhaustive coverage of all PV-CSP hybrid studies in the literature or projects is presented in Section 2. In Section 3, the major technical obstacles of PV-CSP hybridization are discussed. In Section 4 and Section 5, we summarize the recent research status and performance characteristics to provide a global point of view, and finally conclude the advantages, constraints, and future prospects of the PV-CSP hybrid technology.

## 2. The PV-CSP hybrid technology

As mentioned above, the PV-CSP hybrid technology involves various kinds of hybridization approaches, and it is helpful to categorize the PV-CSP hybrid technology first. As shown in Fig. 2, according to the essential characteristics of the optical system, the operating temperature and the system integration, the PV-CSP hybrid technology is classified into two types in this paper: the non-compact and the compact PV-CSP hybrid technology. The non-compact PV-CSP technology includes the flat PV-CSP hybrid system and the CPV-CSP hybrid system, while the compact PV-CSP technology includes systems based on three different technologies: the PV-topping technology, the SBS technology, and the combined SBS & PV-topping technology. The state of the art in these PV-CSP hybrid technologies are reviewed as follows.

### 2.1. The non-compact PV-CSP hybrid system

In a non-compact PV-CSP hybrid system, the PV system (including the flat plate PV and the CPV) and the CSP system can operate independently. The hybrid system is integrated together by the electric power dispatching system or the control system, aimed to provide high quality power for the grid or off-grid power demands. The PV system can provide part of the station-service power for the CSP system, and thus the electricity cost of the CSP system could be reduced with the assistance of the PV system. Moreover, a stable power output with an extremely high capacity factor (CF, which is the ratio of average power output to rated power of a CSP plant) can be achieved by this approach [13,14], so that the hybrid system can be used to provide base load power for the grid. As the basis of the non-compact PV-CSP hybrid system, both PV and CSP technologies are matured in recent years, and thus there are only a few technical challenges for this kind of hybridization. Several commercial non-compact PV-CSP hybrid plants are currently planned or under construction. Most of the researches of the non-compact PV-CSP hybrid system are concerned with the dispatching strategy and the economic analysis.

#### 2.1.1. The flat PV-CSP hybrid system

As a pioneer of CSP system, Abengoa s.a. is now constructing a 210 MW flat PV-CSP hybrid power plant, called the Atacama I, at the Atacama Desert of northern Chile [15]. The Atacama I hybrid power plant, composed of a 100 MW flat PV system and a 110 MW tower CSP system with a 17.5-h molten salt TES system, was launched in 2013. After that, another 210 MW hybrid power plant called Atacama II was launched in 2015 [16]. The 110 MW CSP plant of Atacama II is also a solar tower system which will consist of a 250 m solar tower, 11,000 heliostats, and a 15-h molten salt TES system. And the 100 MW PV plant of Atacama II will have 392,000 1-axis tracking monocrystalline silicon modules. It is expected that the Atacama II power plant will produce and directly inject power to the gird 24 h a day.

Abengoa s.a. also proposed a patent on the non-compact flat PV-CSP hybrid system design [17]. For the tower CSP plant with a cavity receiver, the PV system and the auxiliary systems can be placed in the south and north area which is uncovered by the heliostats, to provide electricity for both the grid and the CSP subsystem. The hybrid system

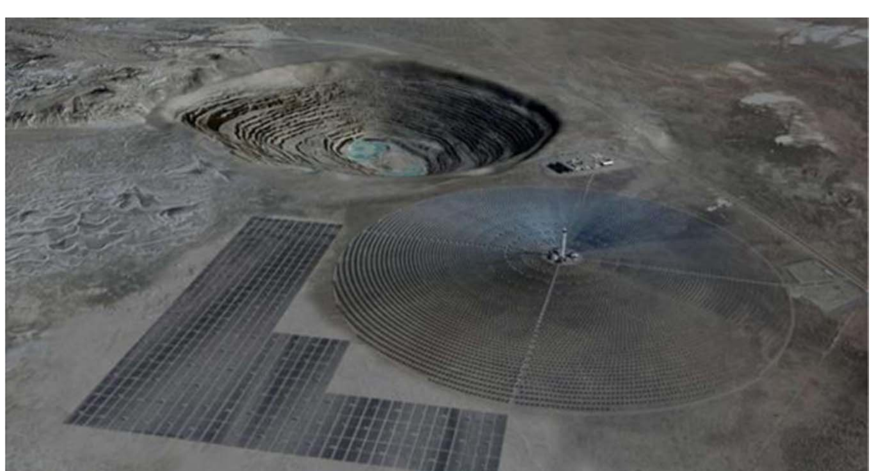

**Fig. 3.** Rendering of the flat PV-CSP hybrid system in northern Chile [18].

could also be equipped with heat exchangers, through which the cooling water of PV subsystem can be used to preheat the heat transfer fluid (HTF) of CSP subsystem, and thus the thermal economic of the hybrid system could be further improved. Besides, the PV modules may further be combined with the heliostat field by mounting the PV cells at the middle or edges of heliostats.

In Chile's Atacama Desert, another PV-CSP project called Copiapo [18,19] was put on the agenda since 2015 (Fig. 3), which will include a 130 MW tower CSP plant and a 150 MW PV plant. The project was dominated by SolarReserve, LLC who also has the experience of developing several CSP projects. The project planned to construct a hybrid plant with a molten salt TES system for 14 h, and thus could provide a total of 260 MW, 24/7 base load power for local mining industries.

The 100 MW Redstone CSP plant [20], which is planned to be established in South Africa by SolarReserve LLC, will also be united with the 75 MW Lesedi and the 96 MW Jasper PV plants nearby, forming the world's first combined CSP-PV solar park with a total capacity of 271 MW. The two PV plants have completed their construction in 2014 and are currently in operation. And the Redstone CSP plant, which is a solar tower plant with a 12-h molten salt TES system, is expected to start operation in early 2018.

Hybrid with PV plants can greatly improve the CF of CSP power plants in a cost-effective way. SolarReserve, LLC analysed the combined operation of the PV-CSP hybrid project in Chile's Atacama Desert [13]. If the CSP plant is dispatched in response to the output from the PV plant, the CF of the PV-CSP hybrid system can reach 80–90%, which is much higher than that of conventional CSP plants (between 20% and 50%) and is even comparable to conventional thermal power plants. In addition, with the consideration of seasonal variation, the authors discussed the tilt angle of fixed PV modules and developed new solar resource assessment metrics for the design of the high CF hybrid system.

Except for the aforementioned projects and conceptions, some researchers focused on the economic analysis of the flat PV-CSP hybrid system with TES. Hlusiak et al. [21] established a simulation model according to the meteorological data of Morocco. The economic analysis showed that the PV-CSP hybrid plant is viable to provide electricity following the national electricity demand. Compared with a CSP-alone plant with TES, the LCOE of the PV-CSP hybrid plant can be decreased by 8–13%, ranging from 13.04 to 18.32 €ct/kWh. And the LCOE may be further reduced to 8.8–10.8 €ct/kWh, if the hybrid plant is combined with wind power and batteries.

In KTH Royal Institute of Technology, several technical and economic analyses of utility scale PV-CSP hybrid system were presented. Ramon [22] set up a simulation model based on the monocrystalline silicon PV power plant and the tower CSP plant with molten salt TES. Considering the influences of climate, market and operating strategy, the PV-CSP hybrid plant would be economically feasible if a suitable TES system is employed to match the power consumption during the peak hours. In a typical week of South Africa, under the conditions of the Renewable Energy Independent Power Producers Program (REIPPP) and with fixed/variable demand and current electricity pool prices, the CSP-alone system, the PV-alone system, and the PV-CSP hybrid system showed the best internal rate of return (IRR), the LCOE, and the CF, respectively. The author concluded that the PV-CSP hybrid system is an attractive option in South Africa with the same nominal capacity of the CSP system and the PV system. Based on the model developed previously, Dominio [23] carried out a multi-objective optimization in order to find optimal plant designs for the selected market, which also met intermediate and peak load demand under the REIPPP price scheme. The results showed that both the CSP-alone and the PV-alone plants yield lower average Power Purchase Agreement (PPA) prices and Capital Expenditure (CAPEX) than the PV-CSP hybrid plant. Contrarily, the PV-CSP hybrid system achieves higher values of CF and performs better in meeting the dispatch strategy than the CSP-alone or the PV-alone system. After that, Larchet [14] studied a high CF (over 99%) PV-CSP hybrid plant in the Chilean Atacama Desert. The economies of the PV-CSP hybrid, a CSP-alone plant and a hybrid PV-diesel plant, were compared for the base load requirement. The results showed that the PV-CSP hybrid plant gains a 97% reduction in $CO_2$ emissions compared with the PV-diesel hybrid plant. Furthermore, compared with that of the CSP-alone plant and the PV-diesel hybrid plant, the LCOE of the PV-CSP hybrid plant reduces by 35% and 46%, respectively. The PV-CSP hybridization seems to be a promising technology for such applications.

Most recently, Parrado et al. [24] made a projection of the LCOE of a PV-alone (50 MW), a CSP-alone (50 MW with 15 h TES) and a PV-CSP hybrid (20 MW PV and 30 MW CSP with 15 h TES) plant in Atacama Desert of northern Chile. Due to the huge solar resource available in this region, the PV-CSP hybrid plant was found to be a reliable and clean solution for the large local industries such as the mining industry. The LCOE was calculated according to two scenarios: IEA Blue Map and Roadmap [2,7]. From 2014–2050, according to the

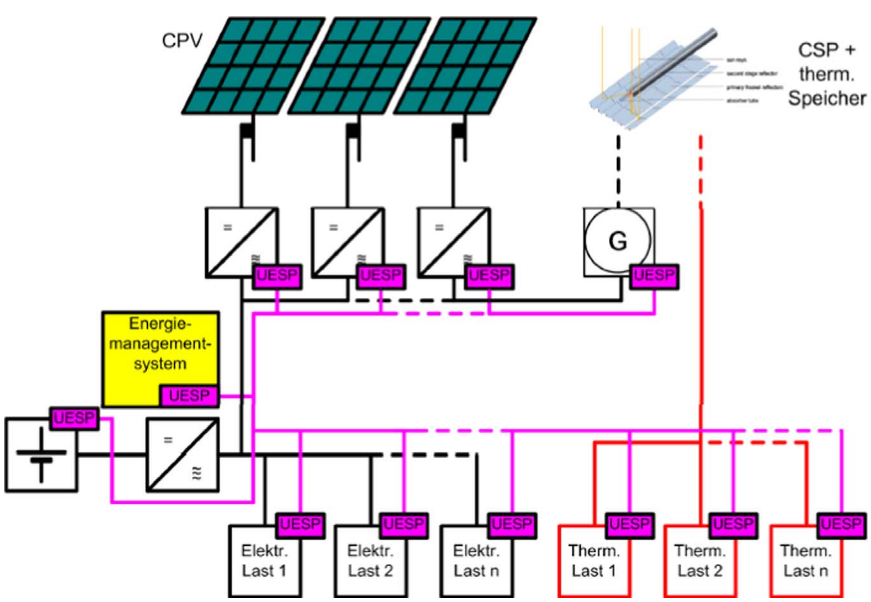


**Fig. 4.** The CPV-CSP hybrid system proposed by ISE for SKA [25].

IEA Blue Map, the LCOE of the PV-CSP hybrid plant would be reduced from 14.69 to 8.57 US$ct/kWh, while according to the IEA Roadmap, it would be reduced from 13.88 to 7.74 US$ct/kWh. Although the LCOE of the PV-CSP hybrid plant may be slightly higher than the lowest LCOE value of PV and CSP, the PV-CSP hybrid plant enables 24/7 power generation and reaches higher CFs than the other two. Therefore, the flat PV-CSP hybrid technology seems to be a feasible option to supply sustainable electricity, stabilize electricity price, and reduce carbon emission in the northern Chile.

### 2.1.2. The CPV-CSP hybrid system

CPV modules may also be used in the non-compact PV-CSP hybrid system. The ISE Institute of Fraunhofer provided a solution to provide 100% clean energy for the Square Kilometer Array (SKA) radio telescope project, which was based on the non-compact CPV-CSP hybrid system [25]. As shown in Fig. 4, a CPV system and a linear Fresnel CSP system are combined in the conceptual design, and lithium batteries and redox flow batteries for electricity storage are simultaneously used. Except for generating power for SKA, the system can also provide heat with the help of the CSP system.

In order to reduce the high cost of overlarge area of traditional mirror fields of CSP plants, Platzer [26] from ISE suggested to use the low-cost PV system to deal with the power demand during the daytime, and to use the CSP system to generate power with the stored thermal energy. Under this operating strategy, both the scale of the CSP system and the price of the steam turbine and other equipment can be reduced. A simulation model was set up based on a CPV plant and a parabolic trough CSP plant with 12 h TES. The results showed that for a total capacity of 50 MW, the CF of the hybrid system reaches over 50%. The operation duration of the hybrid system is over 7300 h/year and the LCOE can be reduced to 0.124 €/kWh, which is much better than the CSP-alone system of 5880 h/year and 0.152 €/kWh. Meanwhile, the schedulability of the plant could be substantially improved because of the TES.

Recently, a pilot CPV-CSP hybrid plant [27] was under construction in the industrial district of Ottana, Italy. As shown in Fig. 5, the hybrid power plant was based on a 600 kWe CSP plant and a 400 kWe CPV plant. The CSP plant employed linear Fresnel reflectors as the concentrator, thermal oil as the HTF, a two-tank direct TES with a capacity of about 15 MWht, and an organic Rankine cycle (ORC) module for power generation. The CPV plant employed dual axis tracking 3-junction PV modules as the converter, and sodium-nickel batteries with a capacity of 430 kWhe. This facility can provide ancillary services at distribution level. It was aimed to demonstrate the possibility of producing electricity with desired power profiles according to the weather forecast. Two different energy management strategies, including a deterministic approach and a stochastic approach (to take into account the uncertainties in weather forecast for the optimal energy management), were developed to maximize the power production of the hybrid plant [28]. The stochastic approach instead of the deterministic one allows to achieve a more robust power profile. Using the energy management strategy based on the stochastic approach, an improvement of about 3–5% of the yearly power production is expected compared with the deterministic approach. The energy management strategy, characterized by different degrees of integration (named fully integrated and partially integrated), was also analysed and compared by the authors [29]. The results demonstrated that the fully integrated solution is better in annual energy production and duration hours with fixed power outputs. The dispatchability features of the CPV-CSP hybrid plant strongly depend on the capacity of the two energy storage systems, especially on the TES system. The storage system of the hybrid plant should be carefully optimized to fit the desired power output curves.

## 2.2. The compact PV-CSP hybrid system

Besides the non-compact PV-CSP hybrid method, the PV and CSP systems can also be integrated more “compactly” with the consideration of the different energy conversion methodologies of PV and CSP technologies. Roughly speaking, photons with energy lower than the

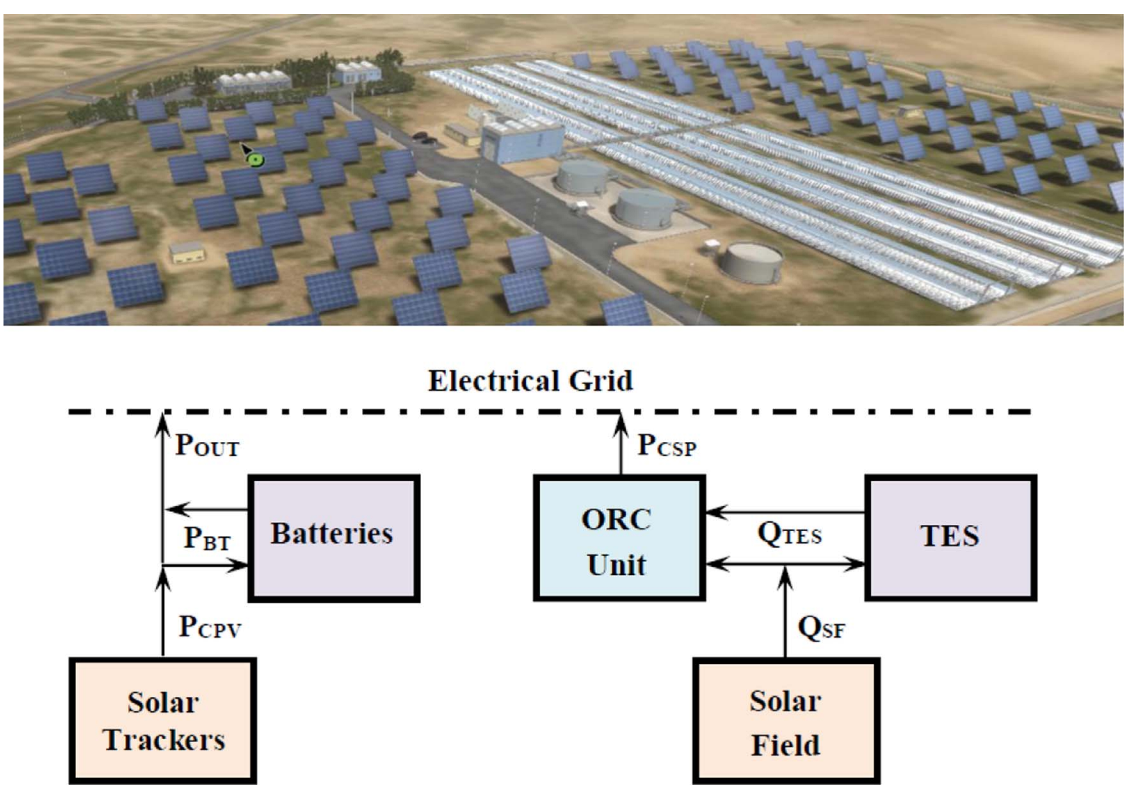


**Fig. 5.** The pilot CPV-CSP hybrid system under construction in Italy [27,28].

bandgap of PV cells are transmitted and converted into heat in the substrate of cells, while photons with energy over the bandgap of PV cells can be partly converted into electricity by the PV process, and the other part is dissipated as heat by the thermalization process. As a consequence, the incident solar energy of PV cells can be only partly converted to electricity, and there is room to combine with other technologies to improve the overall conversion efficiency.

The compact PV-CSP hybrid system is aimed to make full use of solar energy, which is the same with other solar hybrid technologies such as the PV/biomass, the PV/thermoelectric and the PV/thermal (PV/T) hybrid technologies. Moreover, the compact PV-CSP hybrid system can also be considered as a special application of PV/T which uses the thermal energy for power generation. The basic "compact" hybridization methods of PV-CSP system, including the PV-topping method and the SBS method, were developed in the researches of PV/T hybrid systems in the 1970 s and 1980 s, as reviewed by Chow [30] and Mojiri et al. [31]. The development of the compact PV-CSP hybrid technology is highly related to the PV/T technology since then.

The compact PV-CSP hybrid system can be classified into three different ways according to the different hybridization approaches. The first is the PV-topping technology, which generates power by using the PV system as the topping cycle and the CSP system as the bottoming one. The second is the SBS technology, which splits the spectral beam of solar radiation to directly convert the visible light to electricity in PV cells and to convert the near-infrared or ultra-violet light to heat at high temperatures for power generation in CSP systems. The third is the combined SBS & PV-topping technology, in which both the dissipated heat and the unwanted solar radiation of PV cells are absorbed and are then used to drive a heat engine for power generation. The compact PV-CSP hybrid system not only inherits the advantages of the non-compact one which can achieve high CF and good power quality, but also drastically improves the overall generating efficiency. However, there are much more technical challenges compared with the non-compact PV-CSP hybrid system, and no projects or prototypes of the compact PV-CSP have been reported until now.

According to the three different hybrid methods, the compact PV-CSP hybrid technologies are reviewed and discussed in the following part.

#### 2.2.1. The PV-topping PV-CSP hybrid system

In the PV-topping PV-CSP hybrid system, the dissipated heat of PV cells is recovered to generate power through the CSP system. In such a system, the solar cells are simultaneously used as the thermal receiver and the PV converter. Besides, solar radiation is usually concentrated to reduce the use of expensive solar cells, and to achieve a higher hot end temperature. In this configuration, the overall generating efficiency may be sharply improved since the topping PV cycle and the bottoming CSP cycle are combined.

Presently, the development of the PV-topping PV-CSP hybrid system faces many challenges, primarily due to the limitation of the PV operating temperature. The bandgap of solar cells decreases with the temperature, which leads to the photoelectric performance degradation at high temperatures (a negative power temperature coefficient). For instance, the limiting operating temperature of crystalline silicon cells at which the electrical efficiency drops to zero is 270 °C [32], and the GaAs cells are usually not capable of operating over 400 °C [33]. In reality, because of the temperature limitation of the electrodes and welding material, the operating temperatures of Si and GaAs solar cells are usually no more than 80 °C and 120 °C, respectively. Under this temperature restriction, the hot end temperature of the bottoming cycle would be low and thus the power generation efficiency is also limited. Thus, the development of the PV-topping hybrid system depends on the breakthrough of two techniques: one is the low temperature power generation technology, and the other is the high temperature PV cells. Therefore, theoretical researches of this field mainly focus on two directions: the low temperature and the high temperature.

*2.2.1.1. Low temperature PV-topping PV-CSP hybrid systems.* The low temperature wasted heat from the CPV cells can be collected to generate electricity by low temperature power generation methods such as ORC, constituting the CPV-ORC hybrid power system. According to results from the present theoretical researches, the absolute generating efficiency could be improved by 6–16% compared to the PV-alone system.

As shown in Fig. 6, Ji et al. [34] proposed a CPV-ORC system with a phase change material (PCM) TES system, two stage compound parabolic concentrators (CPCs) and two stage evaporators. The hybrid system uses amorphous silicon solar cells as the receiver and HCFC114 as the ORC working fluid, of which the evaporating temperature is 78 °C. The accumulator battery and tracking system are not required in the system, so that the cost can be reduced. The calculation results showed that the overall generating efficiency of the system achieves 13.37%. A further analytical study from Li et al. [35] on this system replaced HCFC114 to HCFC123, of which the evaporating temperature is 118 °C. The generating efficiency of the hybrid system is expected to be 13.1%, which is nearly doubled over the PV-alone system (7.27%) of the same receiver area, also indicating that the hybrid CPV-ORC power generation is promising.

Zhang et al. [36] proposed a high concentrated photovoltaic-microscale organic Rankine cycle (HCPV-MORC) system based on a microchannel evaporator and a microchannel condenser. As shown in Fig. 7, the system includes a screw expander, a gear pump and a recuperator. Three different working fluids, R134a (tetrafluoroethane), R245fa (pentafluoropropane) and R365mfc (pentafluorobutane), were compared at the evaporating temperatures of 85 °C, 120 °C and 140 °C, respectively. When the condensing temperature is 30 °C and the HCPV heat flux is 694.94 kW/m$^2$, the system efficiencies for the three working fluids are 39.8%, 43.7% and 44.15%, respectively. For the hybrid system using R245fa, when the HCPV cell temperature increases from 40 °C to 126 °C, the HCPV efficiency is decreased by 4.6% but the MORC contributes to additional 13.4% efficiency. A net 8.8% increase of the overall generating efficiency could be achieved. It can be concluded that the increase of power output from the ORC system is much larger than the decrease of power output from the PV system when the PV temperature increases, and thus the high operating temperature has a positive influence on the generating efficiency of the hybrid system.

Besides, Zhao et al. [37,38] also discussed a CPV-ORC system with R245fa. The CPV subsystem consists of a glass cover, PV panels, a thermal absorber, and insulation layers. The analysed results of the ORC subsystem showed that the thermal and exergy efficiencies of the ORC subsystem could be improved with a heat regenerator at the

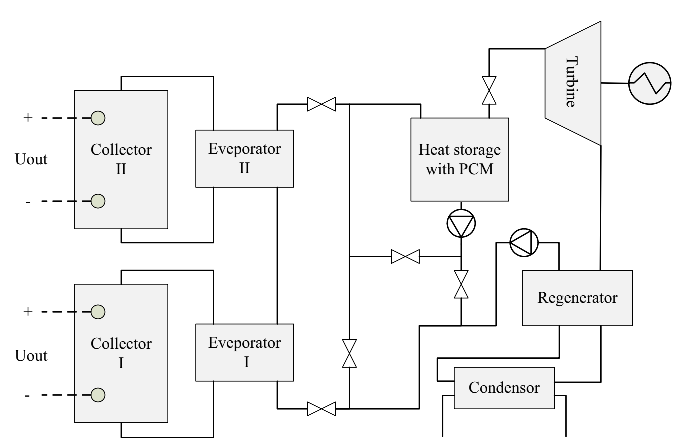


**Fig. 6.** The CPV-ORC hybrid system with a PCM TES [34].

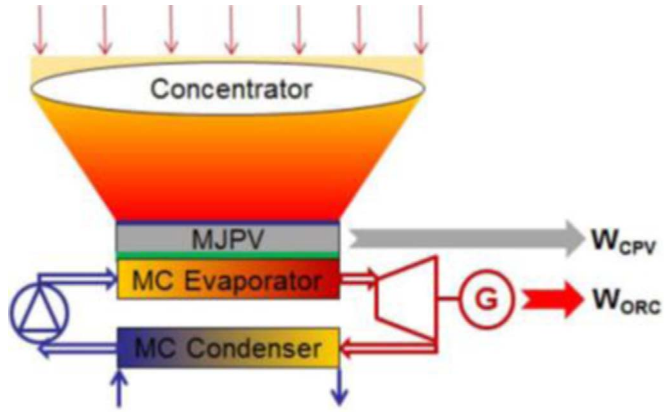


**Fig. 7.** The CPV-ORC hybrid system combining a microchannel evaporator and a microchannel condenser [36].

exhaust of the expander, since the high temperature of the exhaust vapour is used to pre-heat the liquid HTF from the pump. But further discussions on the efficiency of the CPV-ORC hybrid system were not presented in the article.

Ju et al. [40] proposed a novel CPV-CSP hybrid system aimed to increase the HTF operating temperature and thus improve the conversion efficiency of the PV-topping PV-CSP hybrid system. As shown in Fig. 8, with consideration of the non-uniform energy flux distribution of the spot concentrating system such as heliostats and parabolic dishes, an annular CSP thermal receiver is mounted surrounding the dense array CPV (DA-CPV) modules and the evaporative cooling subsystem on the backside. Because the mismatch loss would be very large in interconnected solar cells of different concentration levels, only the solar radiation in the core region with high and relatively uniform energy flux is received by the DA-CPV modules. The remaining peripheral solar radiation with low energy flux is received by the thermal receiver, and then used to superheat the evaporated working fluid from the evaporative cooling subsystem. As the operating temperature of the working fluid could be much higher, the CSP system can generate power by various thermodynamic cycles. Based on this CPV-CSP hybrid system design, Han et al. [39] developed an analytical model for the system performance analysis. Using InGaP/GaAs/Ge three-junction solar cells and R134a as the ORC working fluid, the overall generating efficiency can be increased from 28.4% of the conventional CPV-alone system to 44% of the hybrid system at 500 suns. At ultra-high concentration ratio of 2000 suns, the overall generating efficiency would still be 36.8%. The results demonstrated that the novel hybrid system is a viable solution for hybrid solar power generation with relatively high efficiencies.

Not only the overall generating efficiency of the system can be improved by using the ORC as the bottoming cycle, the economics of the CPV-ORC hybrid system may also be improved. Kosmadakis et al. [41] carried out a feasibility study on a miniature CPV-ORC hybrid system of kW level. The studied system consists of CPC collectors, silicon solar cells and an ORC system with R245fa (evaporating temperature 130 °C) as the working fluid. The results indicated that the average generating efficiency increases to 11.83% compared with 9.81% of the CPV-alone system. An annual simulation showed that the generated power is 3735.8 kWh and 6339.4 kWh for the CPV-alone system and the CPV-ORC hybrid system, respectively. Even when the operating temperature of PV cells is lowered to 40 °C, the annual efficiency of the CPV-alone system (6.56%) is much lower than that of the hybrid system (10.52%) at the same environmental and operating conditions. Besides, from the economic point of view, the CPV-ORC hybrid system also performs better than the CPV-alone system. The annualized costs of electricity production of the CPV-ORC hybrid system and the CPV-alone system are 0.113 €/kWh and 0.147 €/kWh, respectively. The hybrid system has a larger net present value and a shorter pay-back-period during its economic life cycle.

However, there are still arguments on the benefit of efficiencies and costs of the CPV-ORC hybrid system. In the research of Orosz [42], a CPV-ORC hybrid system of medium temperature (200 °C) was theoretically and experimentally investigated for small-scale power plants serving remote areas. Properties of Evergreen c-Si cells and Uni-Solar a-Si tandem cells were measured under different temperatures and concentration ratios, and then used to optimize the CPV-ORC hybrid system by the Max/Min genetic search algorithm. The results showed that there is a strong correlation of efficiency with an increased operating temperature in both the CPV-ORC and the CPV-alone scenarios. The generating efficiency of the CPV-ORC system is slightly higher than that of the CPV-alone system, but neither of them has dominant advantages. The economic analysis also indicated that the CPV-ORC system proposed in the research could not reduce the costs.

According the opinion of Calise et al. [43], the CPV-ORC hybrid system was not economically better than the CPV/thermal (CPV/T)-alone system. The possible future commercialization of the CPV-ORC system highly depends on the reduction of the ORC capital costs. The authors' CPV-ORC hybrid system was developed based on a CPV/T system consisting of a parabolic dish concentrator and a planar receiver with triple-junction silicon solar cells. A dynamic simulation model was developed in TRNSYS, considering detailed components characteristics and weather conditions. The overall generating efficiency of the CPV-

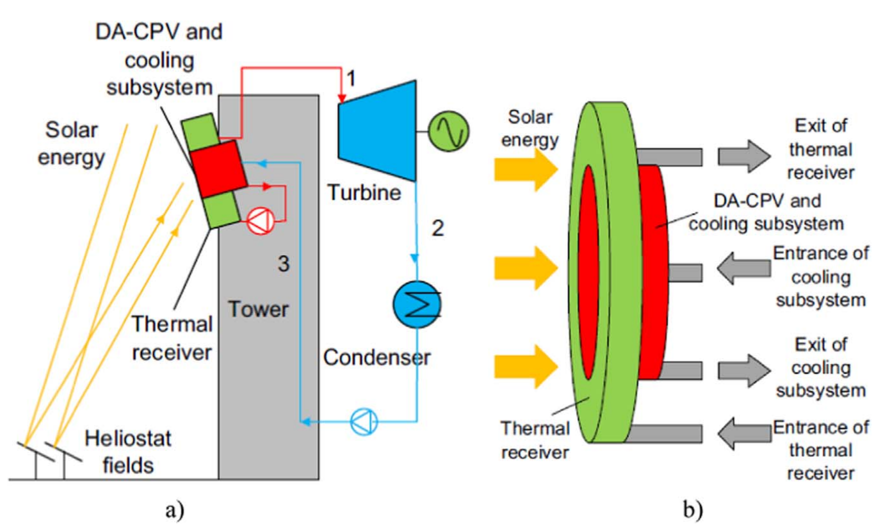


**Fig. 8.** The CPV-CSP hybrid system with an external thermal receiver: a) the system schematic; b) the solar receiver [39].

ORC hybrid system is 41.6%, which is 8% higher compared with the CPV/T-alone system. However, for a 20-year project, the capital cost of the CPV-ORC system is about 18% higher than that of the CPV/T-alone system. Thus, the capital cost of the ORC system couldn't be paid back by its additional electricity production.

As mentioned above, the economics of the CPV-ORC hybrid system is a controversial issue. However, it is obvious that all these researches on the costs of the CPV-ORC hybrid system are still rough. Detailed economic analysis is necessary so that a more reliable and clearer viewpoint can be obtained. Although the CPV-ORC hybrid system seems probably to be not cost-effective at present, some developers showed their interests on this technology. A commercially available PV-topping system called FourFold™ was under development by Focused Sun [44,45], and it could be built in a low-cost modular way to provide power for a 100 kW to 10 MW micro-grid. Each module of FourFold™ used four linear Fresnel mirrors to concentrate sunlight onto the absorber with linearly arranged PV cells. Mineral oil flowed through the absorber, cooled the PV cells and rose to a temperature of 100–300 °C. Moreover, the gained thermal energy could be stored or used to generate power by a thermodynamic cycle such as Kalina cycle and ORC. The reported generating efficiency of the PV modules was about 18%, and a total of up to 75% of the incoming energy could be harnessed.

*2.2.1.2. High temperature PV-topping PV-CSP hybrid systems.* For the PV-topping hybrid system, the Carnot efficiency of the bottoming power cycle increases monotonically with the receiver (solar cell) temperature [46]. But on the contrary, as the solar cell temperature increases, the efficiency of solar cells reduces, and the convective and radiative heat losses from the thermal receiver (for a PV-toping system, it is the solar cells) increases [47]. These two facts lead to tough physical and engineering challenges for the development of the PV-topping hybrid system, especially for the high temperature PV-topping hybrid system. To date, there are only two individual researches principally discussing the efficiency and application prospects of the high temperature systems.

Vorobiev et al. [48,49] discussed two different types of hybrid system with PV cells and a heat engine or a thermoelectric generator. Fig. 9b shows the schematic of the high temperature PV-topping type hybrid system. High-efficiency solar cells, including GaAs single-junction and multi-junction cells (24% and 30% at 50 suns, respectively), were selected to accommodate the high temperature operating condition. A calculation for the temperature range of 300–600 K showed that the overall generating efficiency will be over 40% for an appropriate temperature difference of 200–300 K between the cold and the hot ends of the heat engine.

In 2014, an ARPA-E project named "Full-Spectrum Optimized Conversion and Utilization of Sunlight (FOCUS)" [50] was launched to find a cost-competitive way to combine the advantages of the PV and the CSP system. The technical approaches of this project were the SBS and high temperature PV-topping. 13 sub-projects of FOCUS were concentrated on the key problems of hybridization such as beam splitting liquids or mirrors, thermochemical energy storage for super-critical $CO_2$ cycle, high temperature solar cells and hybrid converters. As the leader of ARPA-E FOCUS, Branz et al. [33,51] investigated the hybrid system to give a guidance for the system development. Compared with the PV-alone or the CSP-alone system, the hybrid system may achieve much higher energy and exergy efficiencies. Assuming that the dispatchable electricity has an extra 50% value over the non-dispatchable one, the value of electricity produced by the hybrid system is over 30% higher than that of the CSP-alone or the CPV-alone system. For the high temperature PV-topping hybrid system principally investigated, the ideal exergy efficiency could be more than 60% when solar cells are operating at a concentration of 100 suns and a temperature of 200–600 °C, and the estimated practical generating efficiency is about 40% (Fig. 10). The results also indicated that the proportion of dispatchable electricity output is more than 50% of the total power output when the solar cell temperature is over 400 °C, which is of a high value of electricity as mentioned before.

*2.2.2. The spectral beam splitting (SBS) PV-CSP hybrid system*

As the spectral response of solar cells is highly related to the bandgap, the SBS technology provides another promising way of PV-CSP hybridization. For example, the spectral response of a silicon cell is ranged from 600 to 900 nm. The spectrally separated radiation of this wavelength range is directed to the solar cells, so that the useless radiation is reduced, and a lower operating temperature and a higher conversion efficiency are achievable for the solar cells. When adopting the SBS technology, the efficiency of silicon cells can exceed 40–50% [52], which is much higher than that of the cells under full-spectrum radiation. Moreover, the working fluid temperature of the CSP system will no longer be limited by solar cells, and the below bandgap radiation is redirected to the thermal receiver of the CSP system. This technology was initially discussed in the late 1980 s for aerospace exploration. Regarding the conspicuous advantages mentioned above, this type of PV-CSP hybrid system has gained attentions of many researchers in recent years. Nevertheless, because of the high complexity of the system, there is also no prototype-level research on the SBS PV-CSP hybrid system until now. More experiments and prototypes are necessary to provide a fundamental basis for the system development. The researches on this kind of PV-CSP hybrid system are summarized as follows according to the types of the spectral beam filters, including the dichroic filter, the absorptive liquid filter, the hologram filter, and the PV cell itself as a solid absorptive filter.

*2.2.2.1. The dichroic filter.* The dichroic filter, or the interference filter, including the multilayer dielectric filter and the rugate filter, is widely employed for SBS devices. The dichroic mirrors are usually high efficiency, low-cost, easily-fabricable and non-degradable filters that fit well with the PV-CSP technology. A multilayer dielectric filter consists of a series of different dielectric layers with alternately high and low refractive indexes. While the refractive indexes in a rugate filter are varied continuously. The rugate filter performs better because no obvious optical losses occur on sidebands. However, the cost of rugate filter is expensive because of the precise refractive index control during fabrication, and the durability of the rugate filter is still a problem because of the thin film layer. As a result, most of the researchers adopted the multilayer dielectric filter in the investigations, and this kind of filter can be easily integrated with different types of CSP concentrators including the linear-focusing concentrators (parabolic troughs and linear Fresnel reflectors/lenses) and the point-focusing concentrators (parabolic dishes and heliostat arrays).

Izumi et al. [53] proposed several possible hybrid solar collector

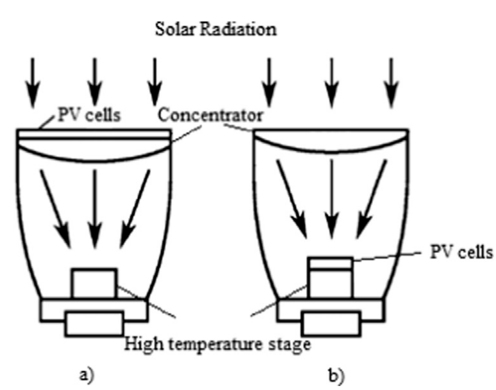


**Fig. 9.** Two PV-CSP hybrid systems: a) using PV cells as the filter; b) PV-topping [48].

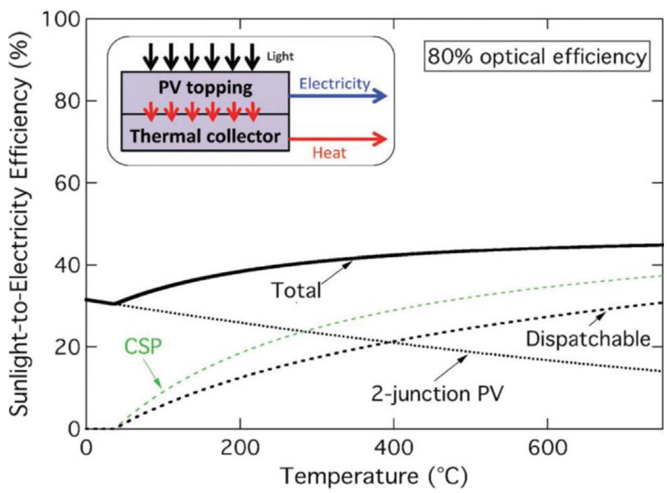


**Fig. 10.** Estimated practical electrical efficiency of the PV-topping hybrid system: PV subsystem efficiency (black, dotted); CSP subsystem efficiency (black, dashed); total efficiency (black, solid); and CSP-alone system efficiency (green, dashed) [33]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

configurations of CPV/T and CPV-CSP hybrid systems in a patent. The author adopted a similar design concept as the Total Solar Cogeneration (TSC) [54–56]. As shown in Fig. 11, the optical concentrators such as Fresnel lens and parabolic trough are combined with the aluminium film coated spectral filter (cold mirror coating). The liquid with a low boiling point is heated to a high temperature in the vacuum tube thermal receiver first, and then used for power generation. Meanwhile, the low temperature water from the cooling system of PV modules can be used for domestic hot water or greenhouses.

As shown in Fig. 12, Liu et al. [57] investigated a CPV/T system with a 2-axis tracking and a compacted Fresnel reflector, which was designed aiming at a better solar energy utilization and a less land area occupation. A secondary reflector under the thermal receiver was adopted to avoid the light spillage. Benefiting from the spectral beam splitter, the PV cell temperature and the hot end temperature of the thermal system would not affect each other. The authors also discussed the prospects of this CPV/T system combined with a heat engine (to be a CPV/CSP hybrid system). When the operating temperature of the working fluid is over 300 °C, and the PV operating temperatures are 25 °C and 50 °C, the overall generating efficiencies achieve 26.6% and 25.6%, respectively, which are much higher than that of the conventional CPV system.

Supported by the ARPA-E FOCUS project, Sharp Lab of America Inc. developed a parabolic trough CPV-CSP hybrid system based on the combined PV-topping concept [58]. As shown in Fig. 13, a hyperbolic dichroic mirror was employed for spectrum splitting. The radiation of 500–900 nm is concentrated to a secondary concentrator and then refocused on the 2-J III-V solar cells. The other part of radiation is transmitted through the filter and absorbed by a high temperature thermal receiver on the focal line of the parabolic trough. Demonstrated annual efficiency of the PV cells is over 50% in the wavelength range, while the collected heat in the CSP system is used for thermal storage to improve the dispatchability of the hybrid system. The annualized electricity output of the hybrid system is about 650 kWh/m$^2$. Besides, an experimental research [59] supported by ARPA-E also showed that the SBS technology would help the HTF of the CPV/T system (which combines the vacuum tube thermal receiver and spectral selectivity GaAs cells paved internal CPC secondary reflector) to achieve a high temperature of around 400 °C, which is also suitable for power generation.

Shou et al. [60] analysed a dish CPV-CSP hybrid system with a multilayer dielectric filter as shown in Fig. 14. The reflected sunlight from the parabolic dish can be separated by a $TiO_x/SiO_2$ filter consisting of 42 front layers, a substrate and 36 back layers. The incident energy loss is about 3% in the filter, which reflects 600–1050 nm radiation to silicon solar cells and transmits 400–600 nm and 1050–2500 nm radiation to the thermal receiver of a Stirling engine. When the solar cells are operating at 87 suns and the Stirling engine is operating at 600 suns and 750 K, the overall generating efficiency of the hybrid system is 28%. A 4% and 3% improvement could be achieved compared with the CPV-alone system and the CSP-alone system, respectively.

Two optional configurations of the tower CPV-CSP hybrid system with hyperboloidal reflectors and dielectric filters were proposed by Yogev et al. [62] and Segal et al. [61], providing a feasible approach to deploy large scale grid-connected solar power plant. Fig. 15a shows the first case, in which the hyperboloidal reflector itself is a dielectric filter. An asymmetric heliostat field surrounds a tower of 130 m, and reflects the sunlight to the filter. Part of the solar radiation is transmitted through the filter and concentrated to the PV array on the focal point, while the rest part is reflected to the thermal receiver with CPC secondary concentrators near the ground. In the second case as shown in Fig. 15b, the hyperboloidal reflector is a regular mirror reflecting the sunlight toward the ground. A paraboloidal filter is arranged between the hyperboloidal reflector and the ground CPCs, which reflect the sunlight of desirable wavelength to the PV arrays at the lateral direction. The generated thermal energy of the two configurations is used to generate electricity by Rankine-Brayton combined cycles or to drive chemical processes. At the design point, the CPV-CSP hybrid system receives 55.6 MW solar radiation, which can generate 6.5 MWe from the PV and 11.1 MWe from the combined cycle of CSP. The overall generating efficiency is expected to be about 32%.

Another instance of the tower CPV-CSP hybrid system is shown in Fig. 16, which was designed for the Multi Tower Solar Array (MTSA) [64] with mono-crystalline Si cells and a Brayton gas turbine. At the PV cell operating temperature of 60 °C and the concentration ratio of 500 suns, 40% of the incident power is converted by the PV-subsystem with

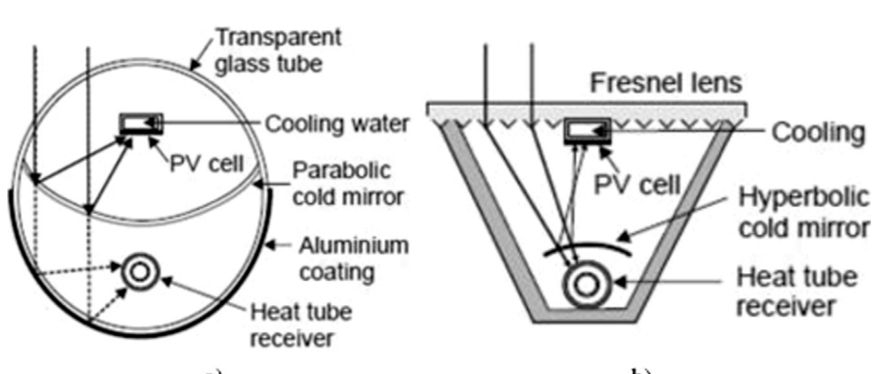


**Fig. 11.** Possible designs of CPV-CSP hybrid systems, a) with a parabolic trough concentrator, b) with a linear Fresnel lens [53].

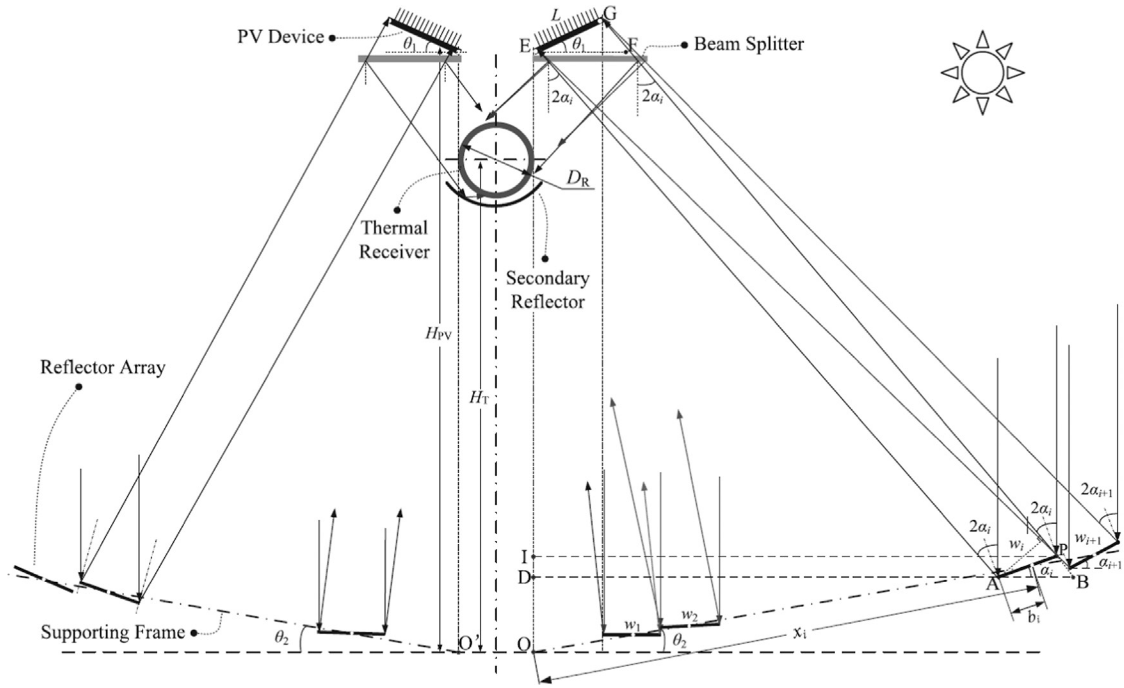


**Fig. 12.** The CPV-CSP hybrid system with a compact linear Fresnel reflector [57].

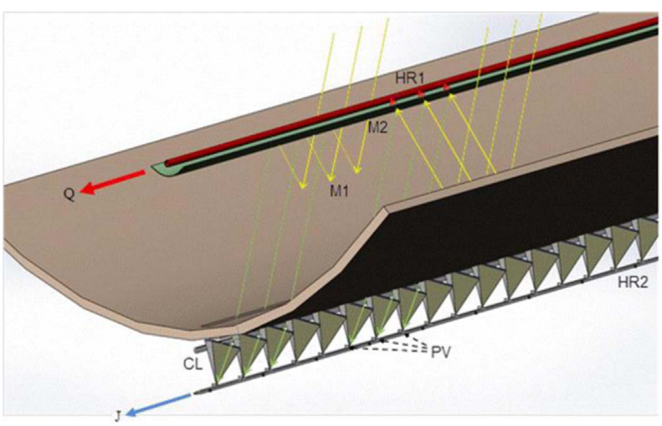


**Fig. 13.** The parabolic trough CPV-CSP hybrid system using a dielectric filter [58].

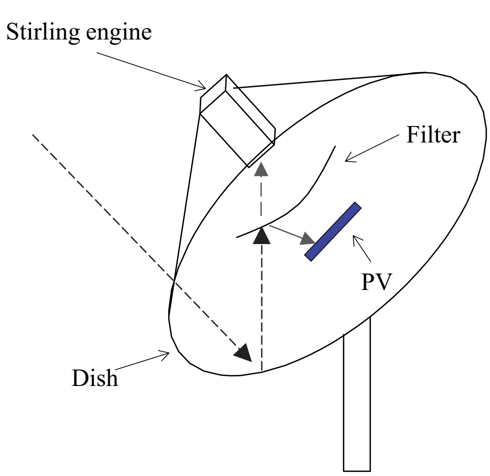


**Fig. 14.** The parabolic dish CPV-CSP hybrid system with a Stirling engine and a dielectric filter [60].

a conversion efficiency of 34%, and the rest part is converted by the thermal power process with a conversion efficiency of 25%. Considering the optical loss and other electrical losses, a total AC electrical efficiency of 20% could be achieved. Besides, the CPV-CSP hybrid system also aims at the waste heat recovery of both CPV and CSP systems, and the medium and the low temperature thermal energy could be produced from the gas turbine and the PV arrays, respectively. The total thermal and electrical cogeneration efficiency of the MTSA with the spectral beam filter is estimated to be 51%. For this system, the design and manufacture of broadband, low-loss, wide-incidence-angle filters are a big challenge, because the performance of common filters degrades when the incident angle deviates from the design angle. To solve the problem, Imenes et al. [63,65] investigated the radially variable beam filters. They designed wide-incidence-angle $TiO_2/SiO_2$ filters with the rugate coating and the discrete multilayer coating. Over the entire surface of a 562 $m^2$ heliostat field and a 10 m high tower of the MTSA, these filters showed acceptable efficiencies at incident angles ranging from 14° to 54°.

It is also a viable choice to directly combine flat PV panels with dichroic mirrors. In this way, the transmitted part of sunlight is converted by PV cells without concentrating and the reflected part is concentrated and absorbed by the thermal receiver. Ousterhout and Olson [66] discussed the potential of applying this method to improve the efficiency of conventional CSP power plants. As roughly estimated by the authors, for the 11 MWe PS10 tower CSP plant in Spain, if all the heliostats were substituted by the KIR film covered PV panels, the power output of the PV subsystem and the CSP subsystem could reach 10.5 MW and 4.4 MW, respectively, which would produce an extra 35% power output compared with the PS10 plant, or an extra 21% power output compared with an equal-sized PV system. Using the same method, the Nevada Solar One parabolic trough CSP plant would have a nominal capacity of 188 MWe (25.6 MWe from CSP and 163 MWe from PV), which is nearly 3 times of the CSP-alone system.

*2.2.2.2. The liquid absorption filter*. Some liquids or liquids with organic/inorganic dyes or nanoparticles are able to absorb solar radiation of a certain spectral range. Since the absorbed solar energy can be easily transported or stored by the liquids, the liquid absorption technology seems also attractive for the PV-CSP hybrid system.

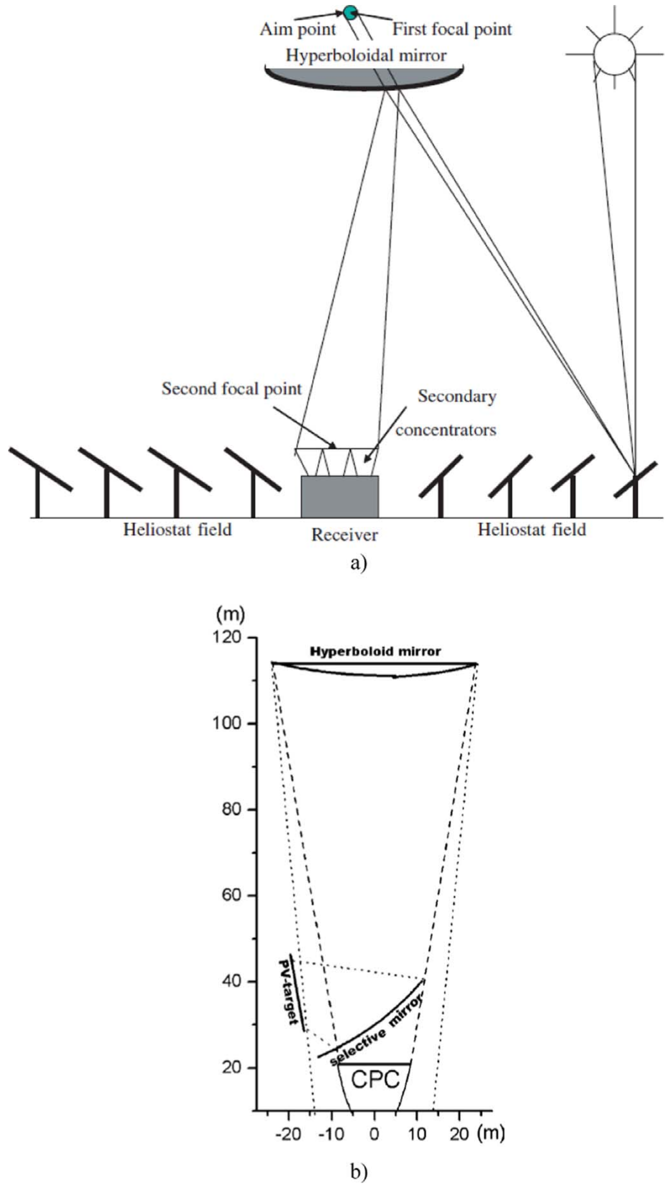


**Fig. 15.** Two tower SBS CPV-CSP systems: a) part of beams down; b) all of beams down [61].

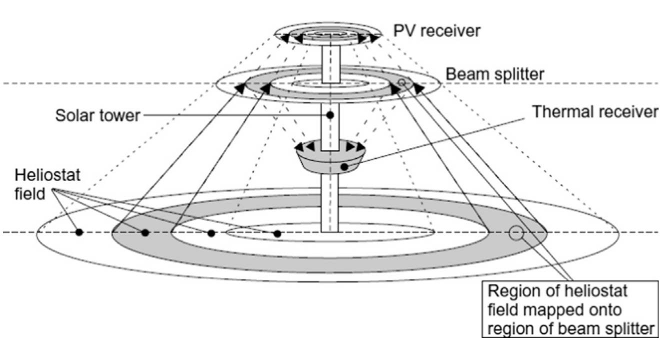


**Fig. 16.** The tower SBS CPV-CSP hybrid system with a flat spectral beam splitter [63].

However, the performance of liquid filter may degrade rapidly under high temperature and exposure to ultraviolet light. Besides, a secondary heat exchanger (for heat exchange between the absorptive liquid and the working fluid) which will induce additional losses is necessary for the power cycle. Other problems such as the absorption efficiency, the stability and lifetime are also needed to be solved before

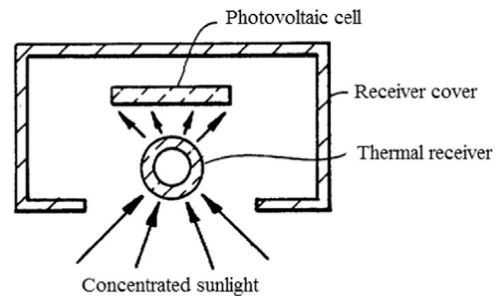


**Fig. 17.** The compact aerospace CPV-CSP hybrid system with a liquid absorptive filter [67].

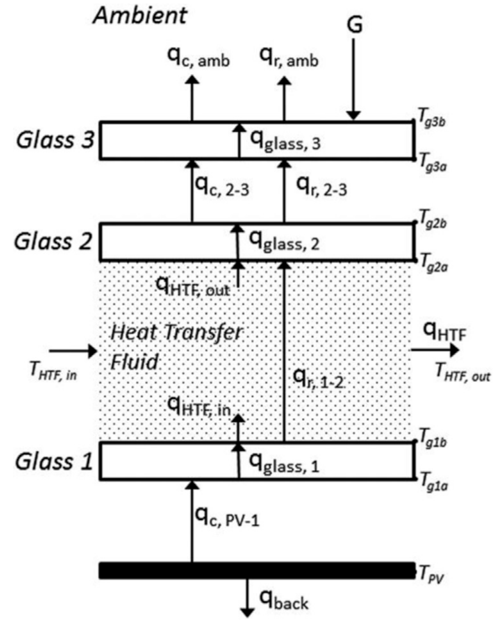


**Fig. 18.** The SBS CPV-CSP system with a liquid absorptive filter [69].

practical applications of liquid filters.

In the early stage of development, the SBS PV-CSP technology was mainly aimed to provide power for aerospace exploration. Some novel designs were proposed in the 1980 s, but these designs including the patents of Powell [67] and Meckler [68] are still far from practical applications. The patent from Powell [67] proposed a compact aerospace CPV-CSP hybrid system combining the liquid absorption technology. As shown in Fig. 17, a foldable parabolic reflector concentrates solar radiation onto a combined receiver. The HTF flows through a thermal tube and serves as the spectral absorptive filter, after which the absorbed thermal energy is used to drive a heat engine. Scattered agents such as small glass microspheres could be used in the HTF to achieve a more uniform radiation on PV-cells.

In recent years, several researches were carried out on the performance and costs of SBS PV-CSP systems using absorptive liquids as filters. Otanicar et al. [70] and Chowdhury et al. [71] theoretically discussed a CPV-CSP hybrid system with Therminol VP-1 as the absorptive liquid. As shown in Fig. 18, the back of PV cells is insulated, and the absorptive HTF flows over the front of PV cells. The maximum overall generating efficiency is 30.3%, and the PV cells contribute to over 80% of the power generation. Considering a perfect fluid filter, the overall generating efficiency could achieve 32%, which is 8% higher than that of the CPV-alone system [72]. Alternatively, when adopting an active cooling system on the back of PV cells, the overall generating efficiency achieves over 38%, of which 56% and 44% power generation is from the PV cells and the CSP, respectively. Therefore, using active cooling for PV cells is an effective way to improve the efficiency of the SBS CPV-CSP hybrid system. The authors also discussed the absorptive nanoparticle-based fluid filters [69]. The overall generating efficiency of the hybrid system with nanoparticle-based fluid filter is nearly the same as the conventional fluid filters. For the Ge, Si, InGaP, CdTe and InGaAs cells, the overall generating efficiencies are 20.58%, 23.51%, 27.32%, 29.03% and 28.74%, respectively. However, the filter thickness could be reduced after adding nanoparticles, so that a compact low-cost design is feasible.

Duquette and Otanicar [73] performed an economic analysis on different concentrating solar technologies, including CPV, CSP and CPV-CSP hybrid. For an installed total capacity of 100 MW, the CPV-CSP hybrid plant (using an absorptive fluid and active cooling) saves the direct cost nearly by 5% and reduces the land area occupation of the solar field by 40% compared with the conventional CSP plant. The hybrid system can provide power with a relatively high annual generating efficiency of 17.5%.

*2.2.2.3. The PV cell itself as a solid absorption filter.* Because the PV solar cell transmits photons with energy lower than the bandgap and absorbs photons with energy near or over the bandgap, the PV cell itself can be employed as a solid absorption filter. For this kind of PV-CSP hybrid system, the design of the front and back electrical grid and the fabrication of highly transmissive PV cells will be a big challenge.

This PV-CSP hybrid method was proposed by Vorobiev et al. [48,49]. As shown in Fig. 10a), PV cells mounted on the top of the concentrator absorb high energy photons and convert them to electricity, while the low energy photons transmitting the PV cells are concentrated to a second stage heat engine. Since the solar cells are operated under the non-concentrated condition, they can be kept at a low temperature, and thus achieve a stable PV efficiency without a cooling system. Similar to the previously mentioned PV-topping configuration, this PV-CSP hybrid system can also achieve over 40% generating efficiencies in terrestrial AM 1.5 sun spectrum.

Ji et al. [74] further developed and analysed this kind of hybrid system. As shown in Fig. 19a, the system consists of a dual-tracking concentrator, high efficiency infrared (IR) transparent CPV modules, and small scale thermal receivers with integrated TES. The infrared transparent CPV module with AlGaInP/InGaP/AlGaAs solar cells (Fig. 19b)) was modelled to analyse its optical, electrical and thermal properties. For the in-band light (mainly ultraviolet and visible light), the CPV module shows a conversion efficiency as high as 52.7% at the concentration ratio of 500 suns and the operating temperature of 80 °C. 80.1% of the out-of-band light (mainly near infrared light) is converted to thermal energy for power generation by CSP. The authors also pointed out that using PV cells themselves as filters showed possibility of cost reduction of solar cells by substrate reuse, but the fabrication of such PV cells was still not an easy task.

*2.2.2.4. The holographic filter.* The spectral beam splitting and concentration can be simultaneously accomplished by a phase hologram filter. The hologram filter has several benefits including thin thickness, light weight, low cost fabrication and high efficiency, which make it attractive for SBS devices. However, it should be noted that a precise tracking system is usually necessary for the hologram concentrator in PV-CSP systems, since the concentration ratio and the spectral performance of the hologram concentrator would suffer from misalignment. Another problem is that the bandpass of a single layer hologram filter is narrow, and the cost and the fabrication complexity of a large area multilayer hologram filter are still high, which restricts its application scope.

By using a hologram filter to concentrate and split solar radiation, Meckler [68] presented a PV-CSP hybrid device for the satellite power supply. As shown in Fig. 20, the infrared part of radiation is concentrated and received by the IR receiver of the Rankine generator, while the ultraviolet and visible parts could be received by the PV cells installed on the microwave antenna of the satellite. The microwaves can penetrate the hologram window and the PV cells, so that they can also be concentrated onto the satellite microwave receiver.

Kostuk et al. [76] proposed a patent on different kinds of PV/T and PV/B (photovoltaic/biofuel) systems using volume transmission holographic lenses as the concentrators and the spectral beam splitters. One of these proposed designs could also be regarded as a CPV-CSP hybrid system. As shown in Fig. 21, a narrow band of solar radiation is concentrated onto the PV cells by the holographic lens, while the rest part of solar radiation is transmitted through the holographic lens and reflected by a parabolic trough mirror. The reflected part is then concentrated to a thermal absorber for thermal power generation. According to their investigation [75], the overall generating efficiency of the hybrid system is 18.0%. The system can be improved by two possible configurations: one is "more light to PV" (the region above the aperture is cleared to allow all light to pass through without diffraction) and the other is "more light to thermal tube" (an additional concentrator such as a CPC could be added to direct incoming light toward the thermal tube). Using the improved configurations, the overall generating efficiencies increase to 21.4% and 18.7%, respectively, and the optical efficiency of the hologram filter increases from 81–93%.

*2.2.3. The combined SBS & PV-topping PV-CSP hybrid system*

The notion of combined SBS & PV-topping PV-CSP hybrid technology is proposed based on the fact that both the PV-topping and the SBS technologies have inevitable weaknesses:

1) In the PV-topping PV-CSP hybrid system, the solar cells can hardly

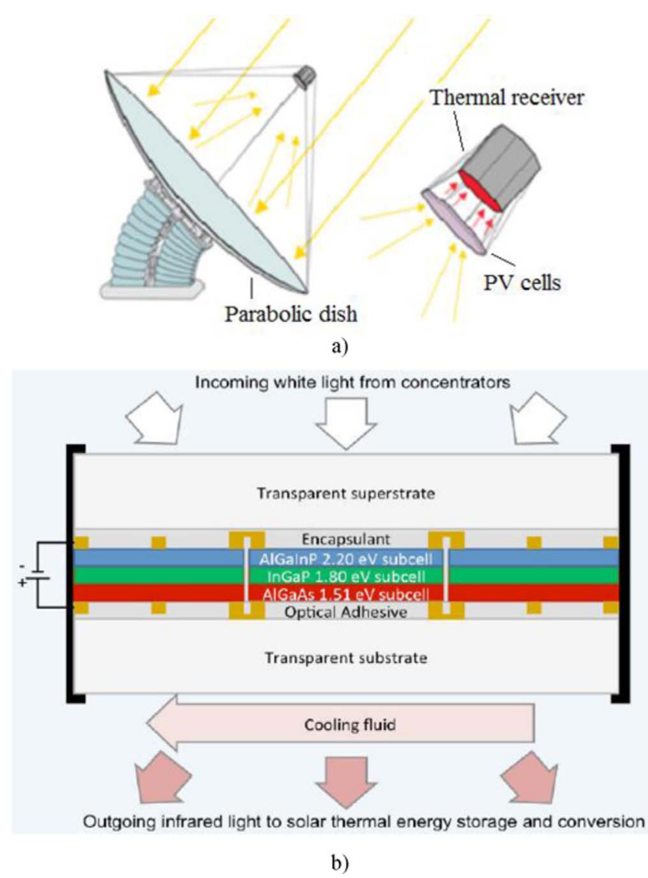


**Fig. 19.** The PV-CSP hybrid system using the PV cell as a filter, a) the hybrid system, b) the infrared transparent CPV module [74].

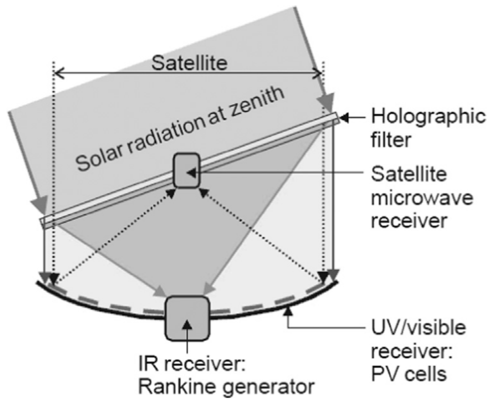


**Fig. 20.** The Aerospace PV-CSP hybrid system combining a holographic filter [68].

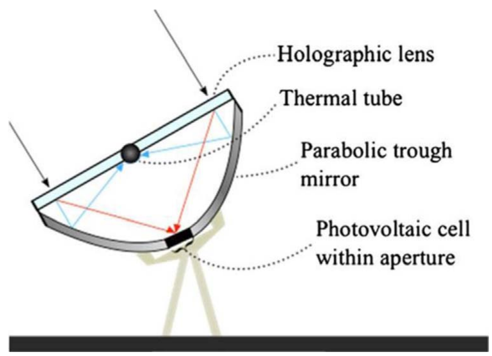


**Fig. 21.** The CPV-CSP hybrid system combining a holographic filter and a parabolic trough concentrator [75].

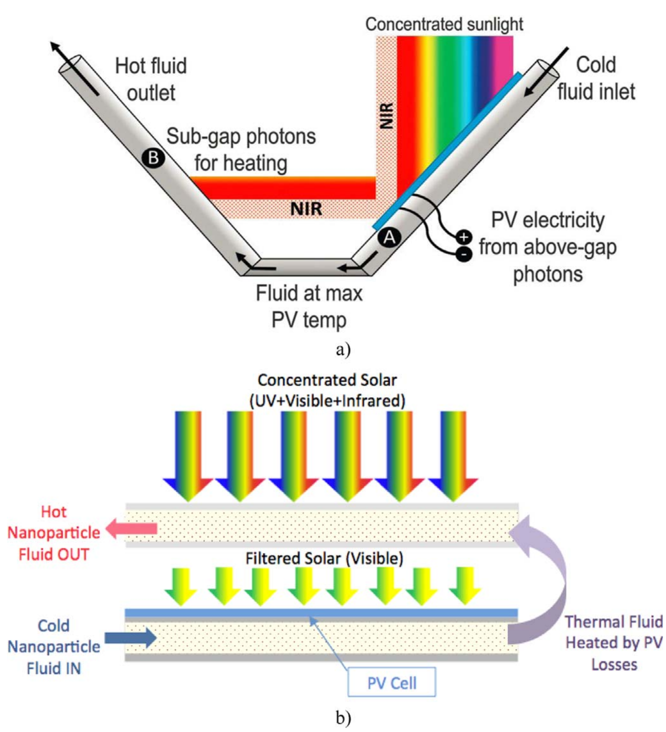


**Fig. 22.** The combined SBS & PV-topping PV-CSP hybrid system, a) combined with the interference filter [33], and b) combined with the liquid absorption filter [51].

be operated at high temperatures, and the conversion efficiency of solar cells will be reduced at high temperatures. That is also the reason why most of researches on PV-topping hybrid systems focused on the low temperature heat recovery.

2) Although the SBS technology can certainly reduce the solar cell temperature and increase the conversion efficiency, a large part of radiation received by PV cells is still dissipated as heat without further utilization. Especially when operating at high concentrations, the PV cell efficiency may also suffer from the heat generated.

Similar to some researches of the CPV/T system [77,78], the SBS and PV-topping technologies can be combined to achieve a lower PV temperature and a higher thermal fluid temperature. Implementations of the combined technology were mentioned by Branz et al. [33,51], and the schematic diagram is shown in Fig. 22. Fig. 22a shows the combined dichroic filter and PV-topping hybrid system. The concentrated sunlight is split by a PV module integrating a dichroic mirror. The working fluid is firstly preheated in the heat sink of the PV module, and then flows into the thermal receiver to be heated to a high temperature by the reflected near-infrared (NIR) illumination for power generation. Fig. 22b shows the combined liquid absorption filter and PV-topping hybrid system. Similar to the system mentioned above, the spectrum absorptive liquid absorbs the NIR illumination in a transparent chamber after being preheated by the PV modules. The conversion efficiency of the combined technology is expected to be improved, since a relatively high working fluid temperature can be achieved without sacrificing the PV efficiency or discarding the low temperature heat generated in the PV cells.

The hybrid system combining the liquid absorptive filter and PV-topping was theoretically investigated by Dejarnette et al. [79]. The system configuration was similar to that shown in Fig. 20b, and several kinds of plasmonic nanoparticle were directly suspended in the working fluid of the heat engine to absorb the solar radiation below the bandgap. The results showed that a particle combination of indium tin oxide (ITO), CuSe and Au nanorod has a good coincidence with the bandgap of GaAs cell. The overall system exergy efficiency is expected to be over 40%, in which 56% is converted to thermal energy for storage and overnight use.

## 3. Key technologies for the PV-CSP hybrid systems

The PV-CSP hybrid systems mentioned above are at different stages of development. The non-compact PV-CSP hybrid system is now entering the stage of commercialization because of the maturity of both the PV and CSP technologies. But the development of the compact PV-CSP hybrid system is fairly restricted by several critical issues. So far, the reported studies or designs on the compact PV-CSP hybrid system are merely novel design ideas, theoretical performance predictions, or experiments of some components, and experimental studies on prototype of a whole system have not been reported yet. The key technologies for further development of the PV-CSP hybrid systems especially the compact ones involve various research fields, such as the hybrid convertor, the management strategy, and the optical design. In this section, the key technologies which are significant for compact hybrid systems are summarized and discussed, including the high temperature solar cells, the spectral beam filters, and the compact high heat flux heat exchanger.

### 3.1. High temperature solar cells

For the PV-topping hybrid system, it is very important to develop efficient solar cells that can operate at high temperatures (350–450 °C) for a long term (20–30 years) [33]. This appears to be an extremely significant technical challenge. Some basic studies on high temperature solar cells have been done, and the initial application of high temperature solar cells in PV-CSP hybrid systems is hopeful to be realized in the near future.

For the moment, the high temperature solar cells are mainly developed for aerospace exploration. In NASA's MESSENGER project, solar panels were improved to conform to the demands of Mercury exploration [80]. The solar cells were tested under −130–270 °C in vacuum, and the life cycle test from −130 to 150 °C was successfully finished. Since the efficiency degradation at high temperatures is mainly affected by the open-circuit voltage, it was suggested [81] that high-bandgap solar cells which have higher voltage and lower temperature coefficient would perform better at high temperature conditions. For example, the efficiency temperature coefficient of the silicon cell (1.1 eV) is −0.45%/°C, while that of the GaAs cell (1.4 eV ) is −0.21%/°C. Landis et al. [82]'s measurements on GaInP cells between 350 and 400 °C also verified this viewpoint. Their investigations [83] also showed that the optimal bandgap of a solar cell shifts from 1.4 eV for operation at 25 °C, to 2.3 eV for operation at 900 °C. High-bandgap solar cells, such as AlGaP/GaP [84], GaInP/GaAs [85], GaInP [81,82], GaP [86], GaN [87] and SiC [88,89], have showed potential to operate at high temperatures. Besides, improving the contact material and metallization method, optimizing the grid and busbar contact design, and developing high temperature diodes (such as SiC diodes) would also help the solar cells to operate stably at 300–400 °C [90,91].

The temperature of solar cells usually climbs to over 75 °C at most of the regions with abundant solar resources. This fact will lead to an over 25% power output and efficiency losses for the low-bandgap cells. Thus, terrestrial PV system would also benefit from the high-bandgap solar cells, such as the III-V cells, the improved CIGS thin-film cells with bandgaps over 1.2 eV [92], and the properly doped silicon cells [86]. The development of low temperature PV-CSP systems, including the CPV-ORC system, would also benefit from these high temperature PV cells. The researches on extremely high temperature PV cells, which is suitable for the high temperature PV-topping hybrid system, were also supported by ARPA-E. Wilcox [93] and Gray [94], theoretically explored semiconductive materials with suitable bandgap for the concentration ratio range of 500-2000x and the temperature range of 25–800 °C. The bandgap of the optimized material increases with the temperature, but decreases with the concentration ratio. Therefore, cell materials should be selected according to the temperature and the concentration ratio of a specific system to achieve the maximum efficiency. Meanwhile, a high temperature dual-junction GaInP/GaAs solar cell is under development in MicroLink Devices Inc. and Yale University [95,96], which aim to design and fabricate solar cells for long-term operation at 400 °C and 500 suns. Recently, III–V solar cells with five or more junctions were developed for the space or terrestrial applications [97], and AlGaInP subcells with bandgaps between 1.9 and 2.2 eV [98] also showed potential for improving the solar cell efficiency at high temperatures.

### 3.2. SBS technologies

Using the SBS technologies, PV and CSP systems can be thermally decoupled. The system efficiency will benefit from the high temperature of CSP subsystem and the low temperature of PV subsystem. Among the SBS techniques which have been theoretically or experimentally studied for the PV-CSP hybridization, the system using interference coating or absorptive liquid seems more promising.

The interference coating can be fabricated of dielectric multilayers with high/low refractive index such as $SiN/SiO_2$ [99–101], $ZrO_2/MgO$, $ZrO_2/SiO_2$, $TiO_2/Ta_2O_5$, $Nb_2O_x/SiO_2$ [102–105], $TiO_x/SiO_2$ [106–109], or metal-dielectric multilayers such as the dielectric-Au-dielectric and the Tin doped $In_2O_3$ filter [110]. The dielectric multilayer has a lower absorptivity and higher optical efficiency than the metal-dielectric multilayer, which performs better at high concentrations. Thus, the dielectric multilayer filter is more commonly used for SBS devices. However, for its application on PV-CSP hybrid systems, there are still some aspects to be improved:

a) Although there are hundreds of dielectric materials, including the halides (eg. $MgF_2$), oxides (eg. $TiO_2$), sulphides (eg. ZnS), and semiconductors (eg. Ge), the filter materials still need to be carefully selected, and the fabrication processes need to be further improved to achieve better chemical stability and mechanical durability.
b) It's difficult to fabricate a dielectric filter without substantial side-band loss for a certain wavelength range. Although rugate filters can provide a better solution on this issue (such as the $TiO_2/SiO_2$ rugate filter [65,111]), the fabrication of rugate filters is still complex and high-cost.
c) The performance of interference filters degrades rapidly when the incident angle increases and deviates from the optimal design. It's a significant challenge to fabricate wide acceptance angle beam splitters for large scale PV-CSP hybrid systems such as tower-heliostat systems [33,62].

On the other hand, various absorptive liquids were tested in the 1980s in Arizona, the USA, including the solutions of inorganic cobalt, copper, and nickel salts ($CoCl_2$, $Co(NO_3)_2$, $CoSO_4$, $Co(C_2H_2O_2)_2$, $Cu(NO_3)_2$, $CuSO_4$ and $NiSO_4$) [106], the organic heat-transfer oils, lubricating oils, edible oils, and silicone brake fluids [112,113]. But most of these fluids are not suitable for working at high temperatures, and the durability of long-term operation of these fluids was also untested.

In recent years, detailed experimental investigations on the spectral absorption characteristics of HTFs (including propylene glycol, mineral oil, and silicone oil) were carried out systematically [114]. The results showed that the absorbance of the mineral oil and the silicone oil did not deviate much with temperature. The accelerated lifetime test [77] showed that Duratherm 600 (315 °C), Duratherm G (260 °C), and Royco 782 (205 °C) were promising to be used as absorptive filters in hybrid systems.

Alternatively, nanofluids based optical filters may also provide a low-cost, high-efficiency and compact hybridization method for the PV-CSP hybrid system. The stable metallic shell/dielectric (silica) core particles, including $Au/SiO_2$, $Ag/SiO_2$, $Al/SiO_2$ particles and pure Ag particles [115,116], could be suspended in Therminol VP-1 (400 °C) base fluids. The results showed that the nanofluid-based filters performed better than the conventional fluid filters. Moreover, the costs of nanofluids would not be high, because the majority of particles was silica and little expensive metal material was required.

### 3.3. Heat management of PV cells under high heat flux

For the compact PV-CSP hybrid system, it's usually important to employ optical system with high concentration ratios to reduce the costs and to improve the conversion efficiency [33]. However, when the concentration ratio is ranging from 200 to 2000 suns, the dissipated heat of solar cells will reach an extremely high magnitude of $10^5$ to $10^6$ W/m$^2$. Furthermore, for a large scale PV-CSP hybrid system with DA-CPV modules, the non-uniform radiation on PV modules will be a serious problem, since it results in mismatch losses and even partial damages [117]. Thus, the heat management of PV cells is a critical issue for the compact PV-CSP hybrid system.

The cooling methods for PV cells under high heat flux include microchannel, jet flow, heat pipe, phase change [118], immersion cooling [119] and so on. Comparatively speaking, the microchannel cooling method has the advantages of sufficient heat exchange capacity, compact structure, low cost, long-term stability and nontoxic working fluid, and thus matchs the cooling demand of PV cells better. Moreover, if the microchannel cooling method combines with other cooling technologies, an extremely high heat transfer coefficient and an excellent temperature uniformity will be achievable for PV cells. Good examples are the microchannel/impinging-jet hybrid cooling device proposed by Barrau et al. [120–122] and the manifold microchannel/impinging-jet hybrid cooling device proposed by Escher et al. [123,124].

For the compact PV-CSP hybrid system, it's important to decrease

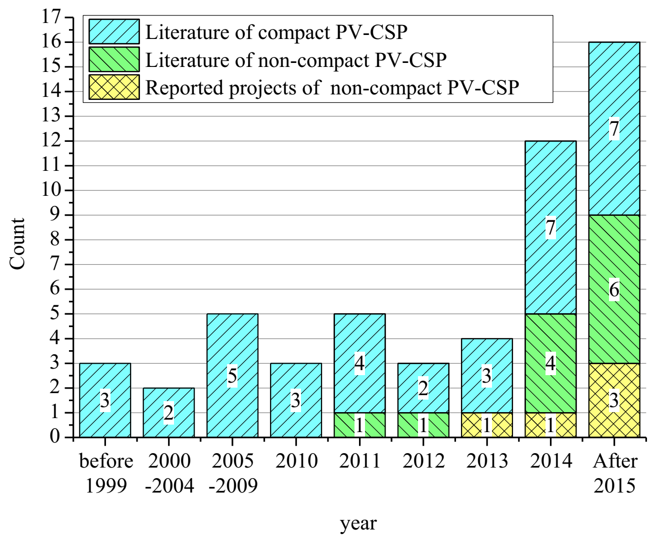


**Fig. 23.** Projects and studies of the PV-CSP hybrid system in the literature according to year.

the temperature difference between solar cells and the coolant, or rather to increase the coolant temperature as high as possible. Except for improving the cooling device structures, the packaging of the PV module and cooling device is another important issue which affects the coolant temperature. The thermal resistance due to packaging between the solar cell and the heat sink may take up a large proportion of the total thermal resistance [125]. Using a packaging material with a high thermal conductivity such as liquid metal would help to decrease the contact thermal resistance between the heat sink and the solar cell. And it's noteworthy that it may be an effective way to combine the cooling structure with the solar cell substrate [126], avoiding the contact thermal resistance between the heat sink and the solar cell. It was demonstrated that the substrate integrated cooler (SIC) can decrease the total heat resistance remarkably (less than half of the traditional thermal interface material), which is also superior to the used liquid metal.

## 4. Summary and discussion of the development status

From the above exhaustive literature review, it can be seen that the researches on the PV-CSP hybrid system gradually increase in recent years. As shown in Fig. 23 and Table 1, there are only a few researches on the PV-CSP hybrid system before 2010, and all the researches were concerned with the compact PV-CSP hybrid system. After 2010, the researches on both the non-compact and compact PV-CSP hybrid systems increase dramatically, and several projects of non-compact PV-CSP have been started since 2013 (as listed in Table 2), indicating that the PV-CSP hybrid system becomes more attractive as the maturity of PV and CSP technologies. As summarized in Table 3, most of the researches on the non-compact hybrid systems are focused on the economic analysis and the development of operating strategies. While as summarized in Table 4, the researches on the compact ones are much more concerned with the new designs, performance modeling, and components development. So far, many approaches have been proposed and discussed for the PV-CSP hybridization, including different kinds of optical concentrators, spectral beam filters, thermal receivers, thermodynamic cycles and solar cells. Since there is no dominant technical approach, the hybrid systems will still exhibit diversiform approaches of hybridization during development in the future.

The non-compact PV-CSP systems share the same operating condition and efficiency as the PV-alone and CSP-alone systems, and thus can obtain efficiencies ranging from 10% to 30% as aforementioned. However, the efficiencies of compact PV-CSP systems can be improved through different approaches. Figs. 24 and 25 show the relationship between the generating efficiency, the concentration ratio and the temperature of hot end of compact PV-CSP hybrid systems. The silicon solar cell (a-Si, c-Si and multi-junction Si) PV-topping hybrid systems operate at low concentration ratios (≤100 suns) and low hot end temperatures (≤130 °C), leading to the efficiencies of lower than 25%. While the III-V solar cell (single-junction and multi-junction) PV-topping hybrid systems can operate at concentration ratios ranging from 500 to 2000 suns and hot end temperatures ≤450 °C, leading to high efficiencies ranging from 35–45%. If adopting the beam splitting technology, the hot end temperature will be no longer limited (ranging from 250 to 670 °C). As a result, both the silicon solar cells and III-V solar cells can achieve a medium-high efficiency, and no significant difference between them can be observed. Compared with the III-V solar cell PV-topping system, the dissipated heat of solar cells is not recovered in the SBS PV-CSP hybrid system, and additional losses of filters are introduced, resulting that the theoretical efficiency of the SBS hybrid system is usually lower than that of the PV-topping hybrid system. Combining the SBS and PV-topping technologies would be a better choice from the technical point of view, and the only accessible data showed that the combined technology can achieve a similar efficiency as the PV-topping technology. However, the specified system configuration of the compact PV-CSP hybrid system should take more evaluation factors, constraints, and criteria into consideration, and the configuration of hybrid system can also be improved by introducing some decision-making methodologies [127,128].

Fig. 26 shows the overall generating efficiency, as well as the proportion of PV and CSP output, for various compact hybrid systems. In most cases, the power fraction of the CSP subsystem is relatively high, which means the dispatchable electricity of CSP would be near or over the non-dispatchable electricity of PV. If combined with suitable TES, the CF of the hybrid system would be high and the quality of electricity would be sufficient for the demands of base or mid-merit load as the non-compact hybrid system.

**Table 1**
Projects and studies of the PV-CSP hybrid system according to year and hybridization method.

| Type | | Before 1999 | 2000–2004 | 2005–2009 | 2010 | 2011 | 2012 | 2013 | 2014 | After 2015 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Non-compact | Project | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 3 | 5 |
| | Flat PV-CSP | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 3 | 3 | 7 |
| | CPV-CSP | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 3 | 5 |
| Compact | Project | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | PV-topping | 0 | 0 | 2 | 1 | 2 | 2 | 0 | 3 | 5 | 15 |
| | SBS | 3 | 2 | 5 | 2 | 2 | 0 | 2 | 5 | 3 | 24 |
| | Combined | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 3 |
| Total[a] | | 3 | 2 | 5 | 3 | 5 | 3 | 4 | 12 | 14 | 53 |

[a] Repeated documents deducted.

**Table 2**
Details of the non-compact PV-CSP hybrid projects.

| Project | Year | Affiliation | Country | Type | Cell type | CSP type | PV capacity | CSP capacity | Energy storage | Status |
|---|---|---|---|---|---|---|---|---|---|---|
| Atacama I [15] | 2013 | Abengoa | Chile | Flat PV-CSP | | Tower heliostat | 100 MW | 110 MW | 17.5 h molten salt | Under construction |
| Redstone & Lesedi & Jasper [20] | 2014 | SolarReserve | South Africa | Flat PV-CSP | | Tower heliostat | 75+96 MW | 100 MW | 12 h molten salt | Under construction |
| Atacama II [16] | 2015 | Abengoa | Chile | Flat PV-CSP | c-Si | Tower heliostat | 100 MW | 110 MW | 15 h molten salt | Under development |
| Copiapó [18] | 2015 | SolarReserve | Chile | Flat PV-CSP | | Tower heliostat | 150 MW | 130*2 MW | 14 h molten salt | Under development |
| Ottana Solar Facility [27] | 2015 | Sardegna Ricerche and University of Cagliari | Italy | CPV-CSP | 3 J III-V | Linear Fresnel reflector | 0.4 MW | 0.6 MW | 15 MWht thermal oil and 430 kWhe Sodium-Nickel batteries | Under construction |

## 5. Conclusion

The PV-CSP hybrid system has several advantages over the PV-alone or CSP-alone system, and the benefits can be summarized as follows:

1) Better power quality. The PV system can be used to satisfy the load demand of the power grid during the day time, while the CSP system stores thermal energy to produce electricity during the cloudy day or night time. PV and CSP complement each other well to supply dispatchable power, so that the hybrid system can satisfy base or mid-merit load demand.
2) Higher generating efficiency. With PV-topping and SBS technologies, proper energy allocation and energy cascade utilization can be achieved, leading to improved generating efficiencies. Based on the current technologies, it is possible to realize a hybrid solar power system with an overall generating efficiency of over 40%.
3) Lower cost. Although the economy of the PV-CSP hybrid system is still under debate, the hybrid system still shows some possibilities or potential on cost-cutting of the solar power generation. The costs of PV-CSP hybrid systems would be low because of its high CF. Under proper operating management and climate conditions, the CF would be close to that of conventional coal-fired plants and much higher than that of other intermittent renewable power generation methods. The costs may also be reduced in compact PV-CSP hybrid systems because of its high generating efficiency. To store energy in form of heat is also much cheaper than the electrochemical energy storage.
4) Convenient final product and broad market. The only final product of the PV-CSP hybrid system is electricity, which can be transported and used conveniently. Compared with the PV/T hybrid system, it is not necessary to consider the limitation of transmission distance or to match the combined thermal and electrical energy demands of consumers.
5) Suitable to develop large-scale solar power plants. Conventional PV/T technology is engaged in small-scale energy systems providing both thermal and electrical energy for buildings, greenhouses, domestic hot water, etc. But the PV-CSP hybrid technologies are more suitable to be used in large-scale power plants which can provide dispatchable power to the grid. Furthermore, the costs would be reduced because of the scale effect. Micro-scale solar power generation system may also be developed for remote districts by the compact PV-CSP hybrid technology.

Currently, the non-compact PV-CSP hybrid technology has stepped into initial commercialization stage. Large-scale PV-CSP hybrid plants had been started to build in the Chile desert, which is expected to operate in the near future. However, the compact PV-SCP hybrid technology is still not mature enough, facing some significant technical challenges. Existing researches have shown that both the PV-topping technology and the SBS technology have great potential to improve the overall generating efficiency, and the notion of combined SBS and PV-topping also provides a possible solution to avoid the technical difficulty of developing high temperature solar cells. Of course, for the PV-topping hybrid system, like all combined cycle power generation, a high temperature difference in the topping cycle means a low hot side temperature in the bottoming cycle. Only when the efficiency of the topping cycle is significantly higher than that of the bottoming cycle, or the hot end temperature of the bottoming cycle is limited by some reasons such as materials, costs or power demands, this kind of hybrid method has advantages over single cycle systems. For the PV system, although the multi-junction solar cells can utilize nearly full spectrum (typically from 200 nm to 1800 nm) of solar radiation, the maximum efficiency of 4-junction solar cell is still less than 50% and most of radiation is dissipated as heat. The technologies of further utilizing the dissipated heat, including PV/T and PV-CSP, will attract more atten-

**Table 3**
Summary of researches on the non-compact PV-CSP hybrid system in the literature[*].

| Year | Reference | Method[a] | Classification | Concentrator (CSP) | Capacity (PV) | Capacity (CSP) | CF | LCOE | HTF | TES (2-tank) | PV Cell | $T_{PV}$ | $T_h$ | $\eta_g$ | $\eta_{PV}$ | $\eta_{CSP}$[b] | Remark |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | MW | MW | % | $/kWh | | | | °C | °C | % | % | % | |
| 2012 | Bootello et al. [17] | PA | Flat PV-CSP | Tower-heliostat | – | – | – | – | All | 4 h molten salt/ steam | Film/Si/III-V | – | – | – | – | – | – |
| 2015 | Green et al. [13] | TH | Flat PV-CSP | Tower-heliostat | 100 | 60 | 80–90 | – | molten salt | 14 h molten salt | –/fixed tilt | – | – | – | – | – | High capcacity factor |
| 2014 | Hlusiak et al. [21] | TH | Flat PV-CSP | Parabolic trough | 48–71 | 30 | – | 0.145–0.203[c] | – | molten salt | – | – | 380 | – | – | 35(P) | Economic analysis |
| 2014 | Ramon [22] | TH | Flat PV-CSP | Tower-heliostat | 50 | 50–150 | 44 | 0.088–0.140 | molten salt | 4–6 h molten salt | c-Si/fixed tilt | 45 | 568 | 21.5 | – | – | Economic analysis |
| 2014 | Dominio [23] | TH | Flat PV-CSP | Tower-heliostat | 20 | 120 | 42 | 0.186 (PPA) | molten salt | 5 h molten salt | – | – | – | – | – | 38(P) | Economic optimization |
| 2015 | Larchet [14] | TH | Flat PV-CSP | Tower-heliostat | 81 | 200 | 99 | 0.122 | molten salt | 22 h molten salt | –/2-axis | – | – | – | – | – | Economic optimization |
| 2016 | Parrado et al. [24] | TH | Flat PV-CSP | Parabolic trough | 20 | 30 | – | 0.147 0.139 | – | 15 h molten salt | c-Si | – | – | – | – | – | Economic analysis |
| 2011 | Vetter [25] | RE | CPV-CSP | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| 2014 | Platzer [26] | TH | CPV-CSP | Parabolic trough | 50 | 50 | 50 | 0.138[c] | Thermal oil | 12 h molten salt | – | – | 393 | – | 30 | 38(P) | Economic analysis |
| 2015 | Camerada et al. [27] | TH | CPV-CSP(ORC) | linear Fresnel reflector | 0.4 | 0.6 | – | – | Thermal oil | 15MWht Thermal oil | 3 J/2-axis/500 suns | – | 260 | – | 22 | 18(P) | 430 kWh battery |
| 2015 | Cau et al. [28] | TH | CPV-CSP(ORC) | linear Fresnel reflector | 0.4 | 0.6 | – | – | Thermal oil | 15MWht Thermal oil | 3 J/2-axis/500 suns | – | 260 | – | 24 | 18.8(P) | 430 kWh battery |
| 2016 | Cocco et al. [29] | TH | CPV-CSP(ORC) | linear Fresnel reflector | 0.4 | 0.6 | – | – | Thermal oil | 15MWht Thermal oil | 3 J/2-axis/500 suns | – | 260 | – | 19.9 | 18.5(P) | 430 kWh battery |

[*] $T_{PV}$: PV cell temperature; $T_h$: hot end temperature of CSP; $\eta_g$: overall generating efficiency of hybrid system; $\eta_{CSP}$: conversion efficiency of PV subsystem; $\eta_{PV}$: conversion efficiency of CSP subsystem.
[a] TH: theoretical research; PA: patent; RE: brief report.
[b] P means the efficiency of the power block of CSP, the efficiency of solar field is usually around 60%.
[c] 1 €=1.11 $.

**Table 4**
Summary of researches on the compact PV-CSP hybrid system in the literature.

| year | Reference. | Method[a] | Classification | Concentrator | PV Cell[b] | $CR_{PV}$ | $CR_{CSP}$ | Tracking | Working fluid/ HTF | $T_{PV}$ | $T_h$ | $\eta_g$ | $\eta_{PV}$ | $\eta_{CSP}$ | Remark |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | suns | suns | | | °C | °C | % | % | % | |
| 2011 | Ji et al. [34] | PA | Low temperature PV-topping | CPC | a-Si | – | – | Static | HCFC114/– | – | 78 | 13. 37 | 6. 79 | 6.58 | Compact CPV-ORC |
| 2010 | Li et al. [35] | TH | Low temperature PV-topping | CPC | a-Si | 4.9 | 4.9 | Static | HCFC123 | 120 | 118 | 13.1 | 6.2 | 6.9 | Compact CPV-ORC |
| 2012 | Zhang et al. [36] | TH | Low temperature PV-topping | – | GaAs MJ | 695 | 695 | – | R134a, , | 95 | 85 | 39.8 | – | – | Compact CPV-ORC |
| | | | | | | | | | R245fa | 130 | 120 | 43.7 | 30.5 | 13.2 | Ditto |
| | | | | | | | | | R365mfc | 150 | 140 | 44.5 | – | – | Ditto |
| 2014 | Zhao et al. [37,38] | TH | Low temperature PV-topping | – | – | – | – | – | R245fa /– | – | 120 | – | – | – | Compact CPV-ORC |
| 2015 | Han et al. [39] | TH | Low temperature PV-topping | Tower-heliostat | GaAs MJ | 500 | < 500 | 2-axis | R134a | 100 | 124 | 44 | ~24 | ~20 | External thermal receiver |
| | | | | | | 2000 | < 2000 | 2-axis | R134a | 100 | 77 | 36.8 | – | – | Ditto |
| 2015 | Ju et al. [40] | PA | PV-topping | Dish/tower-heliostat | – | – | – | 2-axis | – | | – | – | – | – | External thermal receiver |
| 2011 | Kosmadakis et al. [41] | TH | Low temperature PV-topping | parabolic trough | Si | 40 | 40 | 1-axis | R245fa | 140 | 130 | 11.83 | – | – | Compact CPV-ORC LCOE=0.125 $/kWh |
| | | | | | Si | 2 | 2 | 1-axis | R245fa | 100 | 90 | 6.4 | – | – | Ditto |
| | | | | | Si | 100 | 100 | 1-axis | R245fa | 100 | 90 | 10.71 | – | – | Ditto |
| 2012 | Orosz [42] | TH | Low temperature PV-topping | parabolic trough | c-Si/a-Si | 25.5 | 25.5 | 1-axis | R245fa/ Monoethylene glycol | – | 126 | – | ~8.5 | ~9.5 | Compact CPV-ORC |
| 2015 | Calise et al. [43] | TH | Low temperature PV-topping | parabolic dish | Si MJ | 33 | 33 | 2-axis | R245fa/ Diathermic oil | – | 90–130 | 22 | | 10(ORC) | Compact CPV-ORC Economic analysis |
| 2015 | Focused Sun [44,45] | RE | PV-topping | Linear Fresnel reflector | – | – | – | 1-axis | –/mineral oil | – | < 300 | – | 18 | – | – |
| 2006 | Vorobiev et al. [48,49] | TH | High temperature PV-topping | – | GaAs MJ | 50 | 50 | 2-axis | – | 327 | 327 | 43 | 14 | 27 | – |
| | | | | | GaAs | 50 | 50 | 2-axis | – | 327 | 327 | 42 | 17.5 | 16.5 | – |
| | | | Photovoltaic filter SBS | – | – | 1 | 50 | 2-axis | – | 27 | 327 | 40 | 11 | 28 | – |
| 2015 | Branz et al. [33] | TH | High temperature PV-topping | – | GaAs MJ | 100 | 100 | – | – | 450 | 450 | 43 | 19 | 24 | General theoretical investigation |
| | | RE | Combined PV-topping & Interference filter SBS | – | – | – | – | – | – | – | – | – | – | – | Ditto |
| 1999 | Izumi et al. [53] | PA | Interference filter SBS | Parabolic trough / Linear Fresnel lens | – | – | NA | 1-axis | – | – | – | – | – | – | High/low temperature thermal energy |
| 2014 | Liu et al. [57] | TH | Interference filter SBS | Linear Fresnel reflector & secondary reflector for thermal receiver | c-Si | 23.9 | – | 2-axis | – | 25–50 | 300 | 25.6–26.5 | 9.1 | 16.4–17.3 | – |
| 2015 | Pan [58] | RE | Interference filter SBS | Parabolic trough & secondary concentrator for PV | GaAs MJ | – | – | – | – | – | – | – | – | – | – |
| 2011 | Shou et al. [60] | TH | Interference filter SBS | Parabolic dish | c-Si (II –3B) | 87 | 600 | 2-axis | – | ~47 | > 477 | 28 | 17 | 11 | – |

(continued on next page)

**Table 4** *(continued)*

| year | Reference. | Method[a] | Classification | Concentrator | PV Cell[b] | $CR_{PV}$ | $CR_{CSP}$ | Tracking | Working fluid/ HTF | $T_{PV}$ | $T_h$ | $\eta_g$ | $\eta_{PV}$ | $\eta_{CSP}$ | Remark |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2004 | Segal et al. [61] | TH | Interference filter SBS | Tower-heliostat & CPC secondary concentrator for thermal receiver | c-Si | 500 | ~2500 | 2-axis | – | – | – | 32 | 11.7 | 20 | Rankine-Brayton cycles |
| 1996 | Yogev et al. [62] | PA | Interference filter SBS | Tower-heliostat & CPC secondary concentrator for thermal receiver | – | – | – | 2-axis | – | – | – | – | – | – | – |
| 2003 | Imenes and Mills [64] | TH | Interference filter SBS | Tower-heliostat | Si | ~550 | – | 2-axis | – | – | – | ~20 | ~9.8 | ~10.8 | – |
| 2006 | Imenes et al. [63,65] | TH | Interference filter SBS | Tower-heliostat | Si | ~550 | – | 2-axis | – | – | – | – | – | – | Rugate filter & discrete multilayer filter design |
| 2013 | Ousterhout and Olson [66] | TH | Interference filter SBS | Tower-heliostat (PS10) | – | 1 | – | 2-axis | – | – | – | 19.3 | 13.6 | 5.7 | Replace mirrors by PV modules coated with the spectral reflective film. |
| | | | | Parabolic trough (Nevada Solar One) | – | 1 | – | 1-axis | – | – | – | 15.7 | 13.6 | 2.1 | Ditto |
| 1988 | Powell [67] | PA | Liquid absorptive filter SBS | Parabolic trough | – | – | – | 1-axis | –/Water or High temperature oil | – | – | – | – | – | Areospace power, using liquid filter with scattering agents suspended |
| 2013 | Otanicar et al. [69] | TH | Liquid absorptive filter SBS | – | Ge | 200 | 200 | – | –/water or Therminol VP−1 | < 100 | 600–700 | 20.58 | – | – | Using liquid filter with nanoparticles |
| | | | | | CdTe | 200 | 200 | – | –/water or Therminol VP−1 | < 100 | 600–700 | 29.03 | – | – | Ditto |
| | | | | | Si | 200 | 200 | – | –/water or Therminol VP−1 | < 100 | 600–700 | 23.51 | – | – | Ditto |
| | | | | | InGaP | 200 | 200 | – | –/water or Therminol VP−1 | < 100 | 600–700 | 27.32 | – | – | Ditto |
| | | | | | InGaAs | 200 | 200 | – | –/water or Therminol VP−1 | < 100 | 600–700 | 28.74 | – | – | Ditto |
| 2010 | Otanicar et al. [70] | TH | Liquid absorptive filter SBS | – | Bandgap 1.5–2.0 eV | 10–50 | 10–50 | – | Therminol VP−1 | < 100 | 250 | 30.3 | 24 | 5.7 | General theoretical investigation |
| 2010 | Chowdhury et al. [71] | TH | Liquid absorptive filter SBS | – | Bandgap 1.5–2.0 eV | 10–50 | 10–50 | – | Therminol VP−1 | < 100 | 250 | 30.3 | 24 | 5.7 | General theoretical investigation |
| 2011 | Otanicar et al. [72] | TH | Liquid absorptive filter SBS | – | Bandgap 1.8 eV | 200 | 200 | – | Therminol VP−1 | < 100 | 250 | 38 | 21.2 | 16.7 | General theoretical investigation |
| 2014 | Duquette and Otanicar [73] | TH | Liquid absorptive filter SBS | Parabolic trough | – | – | – | 1-axis | – | – | 670 | 17.5 | 10.59 | 6.89 | Economic analysis (Active cooling) |
| | | | | | | | | | | | 579 | 14.8 | 7.02 | 7.75 | (Active cooling) |
| | | | | | | | | | | | 387 | 13.9 | 11.51 | 2.43 | (Passive cooling) |
| | | | | | | | | | | | 409 | 15.3 | 12.37 | 2.93 | (Nanofluid, insulated cell) |
| 2015 | Ji et al. [74] | TH | Photovoltaic filter SBS | Parabolic dish | GaAs MJ | 500 | – | 2-axis | – | 80 | – | – | – | – | PV filter modeling |
| 1985 | Meckler [68] | PA | Planar holographic filter | Holographic transimissive | – | 1 | – | – | – | – | – | – | – | – | Areospace power |

*(continued on next page)*

**Table 4** *(continued)*

| year | Reference. | Method[a] | Classification | Concentrator | PV Cell[b] | $CR_{PV}$ | $CR_{CSP}$ | Tracking | Working fluid/ HTF | $T_{PV}$ | $T_h$ | $\eta_g$ | $\eta_{PV}$ | $\eta_{CSP}$ | Remark |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | SBS | concentrator for thermal receiver | | | | | | | | | | | |
| 2013 | Kostuk et al. [76] | PA | Planar holographic filter SBS | Holographic transimissive concentrator for PV & parabolic trough for thermal receiver | – | – | – | 1-axis | – | – | – | – | – | – | – |
| 2015 | Vorndran et al. [75] | TH | Planar holographic filter SBS | Holographic transimissive concentrator for PV & parabolic trough for thermal receiver | GaAs | ~4 | ~25 | 1-axis | – | – | – | 18 | 11.0 | 7.0 | – |
| | | | | | | | | | | | | 18.7 | 8.4 | 10.3 | More light for thermal |
| | | | | | | | | | | | | 21.4 | 14.4 | 7.0 | More light for PV |
| 2014 | Branz [51] | RE | Combined PV-topping & liquid absorptive filter SBS | – | – | – | – | – | – | – | – | – | – | – | – |
| 2014 | DeJarnette et al. [79] | TH | Combined PV-topping & liquid absorptive filter SBS | Parabolic trough | GaAs | – | – | – | –/Duratherm S or PM–125 | – | 300 | 40 (exergy efficiency) | 17.6 (exergyefficiency) | 22.4 (exergyefficiency) | Using liquid filter with nanoparticles |

*$CR_{PV}$: concentration ratio of PV; $CR_{CSP}$: concentration ratio of CSP; $T_{PV}$: PV cell temperature; $T_h$: hot end temperature of CSP; $\eta_g$: overall generating efficiency of hybrid system; $\eta_{CSP}$: conversion efficiency of PV subsystem; $\eta_{PV}$: conversion efficiency of CSP subsystem.

[a] TH: theoretical research; PA: patent; RE: brief report.

[b] MJ: multi-junction solar cell.

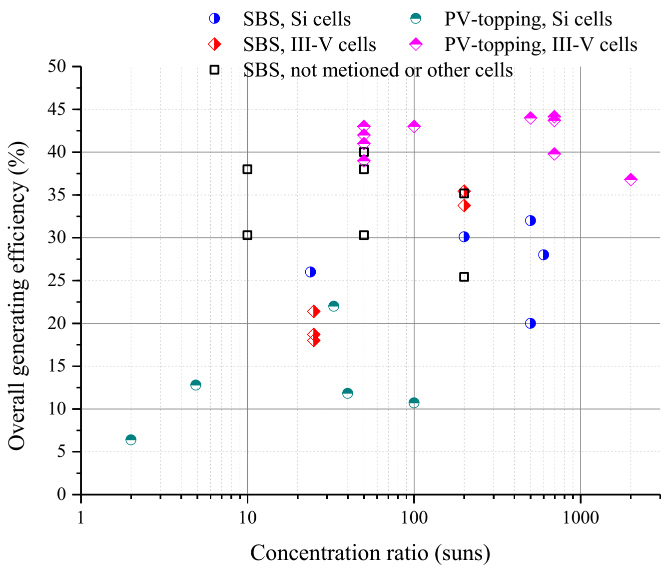


**Fig. 24.** Variation in the overall generating efficiencies of compact PV-CSP hybrid systems with the concentration ratio (If the concentration ratios of the PV and CSP are different, primarily using the CSP's concentration ratio).

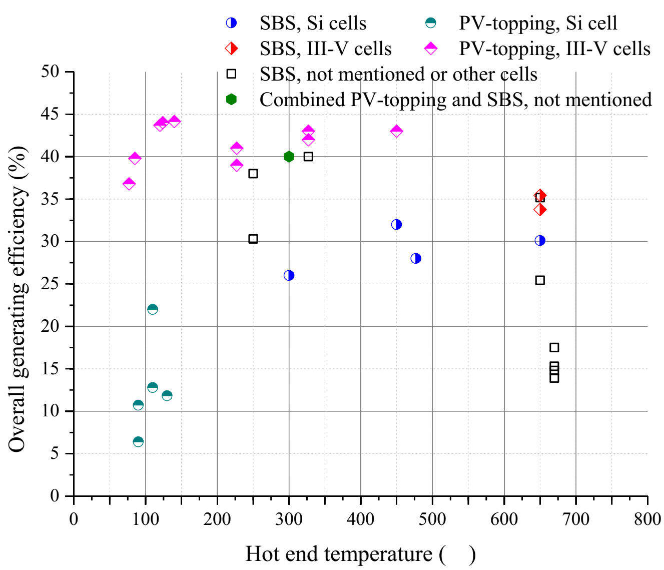


**Fig. 25.** Variation in the overall generating efficiencies of compact PV-CSP hybrid systems with the hot end temperature.

tions in the future. For the CSP system, owning to the high system cost and low conversion efficiency, it's a reasonable choice to combine CSP with PV. Considering the fundamental characteristics of PV and CSP systems in stability, power quality, energy storage, costs, efficiency and so on, the PV-CSP hybrid system seems a promising candidate for providing dispatchable power with renewable energy, and the PV-CSP hybrid technology will be a long-term issue for researchers and developers.

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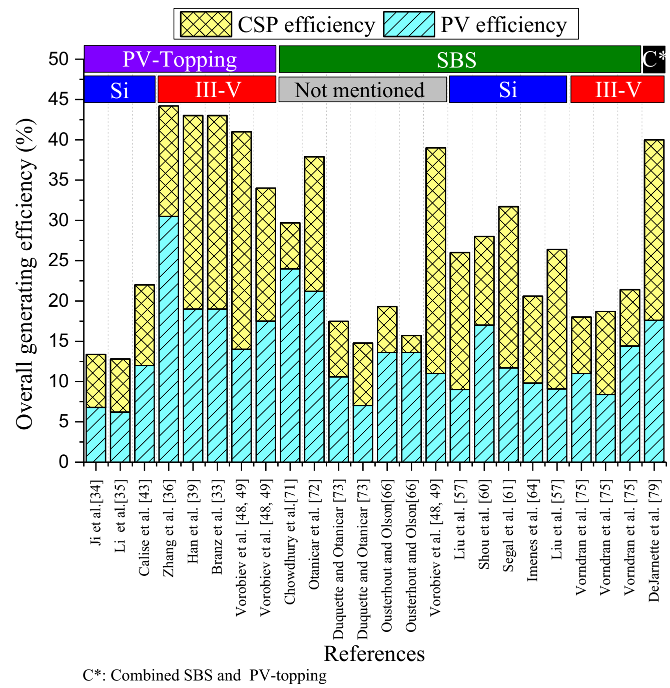


**Fig. 26.** The proportion of the PV and the CSP output for various compact PV-CSP hybrid systems in the literature.

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