Concentrating Photovoltaic Thermal Technology

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Concentrating photovoltaic thermal (CPVT) technology has the potential to support the industrial sector with renewable electricity and heat simultaneously. The implementation of spectral splitting emerges as a possible approach to significantly increase the conversion efficiency, and furthermore, to hurdle the fundamental discrepancy of CPVT systems, that the electrical and the thermal receiver part have opposing temperature requirements.

beam splitting | hybrid solar collector | industrial heat | renewable heat and power

1. Introduction

The geopolitical upheavals of the year 2022 demonstrated quite dramatically the dependency of developed society on the availability of fossil energy. Especially in Europe, the market price for natural gas showed unknown and unpredictable fluctuations, with extensive impact on national economies. In order to partly compensate the lack of affordable gas, and to reduce the subjection from unreliable sources, an increased use of coal was one of the measures taken by several countries all over the world. This was one of the reasons why the global coal demand reached a new record of more than 8 billion tons in 2022 [1]. For the sake of security of supply, the increased use of coal might be necessary in the short-term. On the other hand, these turbulences in the global energy markets elucidate the undeniable need for renewable and locally available energy sources.

Solar energy technologies already play a substantial role by contributing to the required transformation of the global energy supply system. The worldwide photovoltaic (PV) market revealed a growth of 25% from 2020 to 2021, reaching an installed capacity of 942 GW_{el} by the end of 2021 [2], and the milestone of 1 TW_{el} installed PV-power in May 2022 [3]. The global market for solar thermal (ST) systems showed a growth rate of 3% from 2020 to 2021, prolonging the positive trend from the year before. The globally installed solar thermal capacity by the end of 2021 amounted to 522 GW_{th} [4]. The combination of PV and ST into a hybrid solar system (PVT) is currently a young variant of solar energy harvesting, although it exhibits promising market development. The totally installed capacity (combined electrical and thermal power) was around 1 GW_{el+th} in 2021, corresponding to a growth rate of 13% [4]. The PVT technology provides some benefits compared to separated solar systems if it is deployed for suitable applications. Mostly constructed for providing heat in the temperature range below 60 °C, PVT collectors show an increased annual yield of electrical energy up to 4% compared to PV-only installations, caused by the reduced cell temperatures due to permanent heat extraction [5]. Furthermore, combined thermal and electrical energy generation by one component significantly raises the surface-related efficiency from around 21% of PV-only systems up to 80% in PVT installations [5]. For achieving these benefits, PVT collectors are usually designed for maximizing the heat transfer between the electrical and the thermal part, thus enabling efficient heat extraction from PV cells. However, thermal coupling between the PV part and the heat transfer fluid limits the applicability of the PVT collectors regarding the possible outlet temperature, caused by the specified temperature limit of the PV laminate. This is the main reason why conventional PVT collectors are mostly utilized for low-temperature applications such as swimming pool heating, pre-heating of domestic hot water generation or space heating support [6].

Nevertheless, if the challenging task of transforming the world's energy supply system towards renewable sources shall be successful, emission-free heat is also needed in the higher temperature range. In 2015, 16% of the total final energy consumption in the EU28 was caused by industrial process heating, whereby 72% of these processes required temperatures above 100 °C [7]. The provision of solar heat greater than 100 °C is possible with conventional collector technologies such as flat plate collectors or evacuated tube collectors, but only with reduced efficiency [8][9]. By contrast, concentrating solar systems can supply heat at temperatures between 100 °C and 1000 °C, depending on the specific technology [10].

The combination of a concentrating thermal collector with PV results in a concentrating PVT (CPVT) collector, offering some benefits as already mentioned above. On the one hand, the surface-related efficiency can be distinctly increased and the costly mechanical construction for focusing is used twice, both for electrical and thermal energy generation. On the other hand, the required PV surface made of semiconductor material can be reduced by the concentration factor, which has a positive impact on the economic and ecologic effort for such solar systems. Finally, the generation of both forms of solar energy out of one system provides high flexibility to react to fluctuating demands within the operating industrial plant. Although there is the need for both mid-temperature solar heat and renewable electricity in the industrial sector, CPVT collectors are still a niche technology [4], because their construction shows a similar challenge to non-concentrating PVT collectors. The thermal part of the collector respectively the receiver shall provide temperatures as high as possible, while the PV part must not exceed the specified temperature limits of the cells, or should even be kept as cold as possible in order to work with the highest efficiency.

One possible approach to solving this discrepancy is known as spectral splitting and has already been investigated for several years [11]. The main intention of this method is to divide the incident solar spectrum into several wavelength ranges by different means of optical filtering. The PV part of such a CPVT receiver with integrated spectral splitting is only impinged with the spectrum range where the applied PV cells provide maximum spectral response, whereas all other domains of the solar spectrum are directly converted into heat within the thermal part of the receiver. Therefore, the spectral splitting configuration is chosen in a way that only concentrated solar light in the wavelength range between 700 nm and 1100 nm reaches the PV cells, where the conversion efficiency reaches a maximum (blue area). The shorter wavelengths below 700 nm are less suitable for electricity generation, because the high energetic photons cause thermalization losses within the semiconductor and lead to additional heat dissipation. Furthermore, wavelengths above 1100 nm do not contribute to electricity generation, because the corresponding photons do not carry enough energy to lift electrons beyond the bandgap. Therefore, these spectral ranges between 280 nm and 700 nm as well as the remaining spectrum beyond 1100 nm (red areas) are not guided to the PV cells, but are directly transformed into accessible heat. Depending on the constructive implementation of the spectral splitting approach, the threshold wavelengths of the blue area can be varied, and therefore the configuration can be adapted to the specific PV technology in use.

The main benefits of spectral splitting integrated in a CPVT receiver can be summarized in the following way:

- The electrical conversion efficiency is increased compared to full spectrum operation, because less suitable wavelengths are not directed to the PV cells.
- The PV cell temperature can be kept low, even if operated under concentrated light, on the one hand, because the cells do not receive the full irradiance, and on the other hand, because waste heat dissipation within the cells is reduced by the optimized spectrum.
- A large part of the solar spectrum, which would be radiated as waste heat in a concentrated PV system, becomes accessible as solar heat in a temperature range above 100 °C.

The implementation of spectral splitting in a CPVT receiver can be done in different ways based on various physical and optical effects. As thoroughly described in review articles over the past few years, splitting up the solar spectrum as explained above is possible by selective reflection, selective absorption, interference filters, glass prisms and other mechanisms [11][12][13][14]. According to the opinion of the authors, the constructive design of a spectral splitting CPVT receiver should not be too complex, because if this technology shall overcome its niche status on the long-term perspective, it must also be economically viable in the future. Therefore, the research work of the authors focusses on spectral splitting by selective absorption, because this approach appears to be promising for developing compact CPVT receivers with a high probability of being experimentally feasible [15][16][17][18][19][20][21].

2. Spectral Splitting by Selective Absorption Using Liquid Filters

Within this sub-category of spectral splitting by selective absorption, the required filtering of wavelengths takes place by the heat transfer fluid (HTF), which has the main purpose of transporting the heat generated in the receiver to the connected heat sink to thermal storage. If the HTF also works as an optical filter, no additional component is needed to realize spectral splitting, which supports the aim of keeping the CPVT receiver designs as simple as possible.

One of the latest examples for such a CPVT receiver design using a liquid filter was presented by Huang et al. [22]. The centerpiece of this design is the flowing optical filter fluid, which acts as HTF for the high-temperature circuit and as a spectrum-splitting optical filter. This fluid channel is surrounded by vacuum gaps for minimizing the heat loss to ambient air and undesired heat transfer to the adjacent PV module. In this configuration, the concentrated solar light enters the CPVT receiver from the bottom side, passes the first vacuum gap and penetrates the liquid filter HTF, which absorbs domains of long and short wavelengths that are unsuitable for conversion into electricity. The remaining spectral band passes the second vacuum gap and impinges the PV module, where it is converted into electricity with maximum efficiency. This receiver design offers another cooling channel at the backside of the PV module for extracting remaining waste heat that occurs within the semiconductor. In this way, high-temperature heat is provided by the optical filter fluid due to the absorption of selected wavelengths, while low-temperature heat is extracted from the PV modules by the backside cooling channel. The length of the proposed receiver is defined by 1 m, while the thickness of fluid channels and vacuum gaps is assumed to be 10 mm.

Huang et al. [22] performed comprehensive optical, electrical and thermal modelling of their receiver design, investigated different upper and lower thresholds for the optical filter fluid, and considered two different kinds of PV technologies (Si and CdTe). Their simulations resulted in a possible output of high-temperature heat with 400 °C at a thermal efficiency of 19.5%, low-temperature heat at 70 °C with 49.5% efficiency and electrical output with an efficiency of 17.5%. The temperature of the PV module remained below 100 °C. These investigations were performed under the assumption that an optical filter fluid is available with ideal optical, hydraulic and thermal properties. This premise could be appraised as quite optimistic for the perspective of real feasibility, as experimental research has already shown [21][23]. Furthermore, the implementation of vacuum gaps formed by glass channels with rectangular cross-section could be challenging in terms of mechanical stability. The output temperature of 400 °C could only be reached within the simulations by setting the mass flow to a very low value of 7 kg/h. For possible future implementation in a real application, such a low mass flow rate is disadvantageous for the further transfer of the gained heat, as heat transfer coefficients in heat exchangers will be very low.

Adjustability of spectral splitting behavior is crucial for the development of such CPVT receivers, because this offers a possible adaption to different kinds of PV technologies and various demands from the application side. Han et al. [24] concentrated their research work on the optical filter itself by investigating a hybrid base fluid consisting of $CoSO_4$ and propylene glycol (PG). Silver (Ag) nanoparticles in different concentrations between 5.3 ppm and 84.7 ppm were added to the base fluid, which affected the transmissivity of the liquid filter. The concentrated incident solar light penetrates the liquid filter, where a certain part of the spectrum is absorbed and converted into heat. The remaining wavelengths are transmitted to the PV cells where they generate electricity. In this case, the PV technologies Si and GaAs were considered.

The investigation of five different Ag concentrations in the nanofluid was done with comprehensive experiments on stagnant fluid within a glass container. This fluid filter with a thickness of 10 mm was arranged above the PV cells and exposed to an irradiance of 1000 W/m^2 within a sun simulator. The results yielded clear coherence between the Ag particle concentration and the electrical and thermal performance of the CPVT configuration. With increasing Ag concentration, the electrical efficiency was reduced, while the thermal efficiency was rising. The maximum electrical output could be achieved with the hybrid base fluid only, without Ag nanoparticles, where the efficiency resulted in 9.74% for GaAs cells. On the other hand, the maximum thermal efficiency of 79.4% was measured with the highest concentration of Ag particles of 84.7 ppm. Although the maximum measured temperature of 61.7 °C was not yet in the range of industrial process heat, these experiments demonstrated the possibility of adapting the performance of a liquid filter according to the needs of the specific application. Furthermore, it would be recommendable to analyze the thermal and optical stability of the considered nanofluid by performing a long-term stress test at temperatures above 100 °C in order to evaluate its suitability for the industrial temperature range.

A similar approach was chosen by Huaxu et al. [25], who investigated a liquid filter consisting of a nanofluid on a glycol basis combined with ZnO nanoparticles. The chosen PV cell technology was monocrystalline silicon with a bandgap at around 1100 nm. Therefore, the liquid filter should basically absorb the wavelengths above 1100 nm and transmit the lower domain of the spectrum (300 nm to 1100 nm) to the PV cells.

Experimental analysis of different fluid configurations was performed by varying the concentration of ZnO nanoparticles between 11.2 ppm and 89.2 ppm. The nanofluid was tested on a 2-axis tracking solar collector with a Fresnel lens concentrator. The resulting tendencies of the performance measurements correlated to the ones from Han et al. [24], as rising ZnO concentration led to reduced electrical output but increased thermal output of the CPVT system. While the electrical efficiency decreased from 14.49% to 13.1%, the thermal efficiency could be raised from 7.4% to 10.97% with adding more ZnO to the nanofluid. However, the absolute numbers of thermal efficiency would require further investigation. Besides technical performance evaluation, Huaxu et al. [25] also compared the ZnO nanofluid with other fluids in terms of costs. At the time of publication at the beginning of 2020, the price for ZnO nanoparticles was 0.285 USD/g, whereas Ag nanoparticles utilized by Han et al. [24] as mentioned above had a price of 37.5 USD/g. This difference in costs corresponds to a factor of 132, which illustrates clearly that ZnO nanoparticles can contribute to lowering the overall costs for CPVT receivers using liquid optical filters.

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