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Modeling and optimization of a solar system based on concentrating photovoltaic/thermal collector

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ABSTRACT

Concentrated photovoltaic thermal (CPV/T) solar collector systems are designed to provide simultaneously thermal and electrical energies. This paper analyzes a numerical model of a photovoltaic thermal collector in order to evaluate its performances from energy and economic viewpoints. Therefore, a two dimensional numerical model has been developed and applied in this study. This electrical/thermal model is based on the energy balance of the CPV/T receiver in order to calculate the net thermal and electrical output energy. A comparison between the numerical results and those obtained by experimental studies is presented in order to prove the viability of our developed model. The results show that the output power predicted by the numerical model has a good agreement with the experimental data with low mean percentage errors. Indeed, the effects of several parameters on the performance of the system were examined and discussed in details. The simulation process has allowed evaluating the power generation of the CPV/T system and performing a comprehensive economic analysis study under Chambery and Tunisia conditions. The CPV/T system has proven its viability and feasibility especially in regions with high solar radiation.

1. Introduction

It is well-known that the sun is the most significant renewable energy source due to its abundant irradiation to the earth surface. Solar energy conversion systems have been the main focus of several current research studies. In particular, the concentrating solar collector is the key component of using the solar energy for simultaneous thermal and electrical energy production. In fact, Concentrated Photovoltaic Thermal solar collectors (CPV/T) systems directly convert the solar energy into electrical and thermal energy. These cogeneration power systems can offer interesting solutions for several processes that require both PV and low/medium/high operating temperature. Moreover, conventional PV systems were suffering from low electrical conversion efficiencies with high outlet temperature since many decades. Hence, the use of such concentrating PV system will greatly enhance the effective solar density on PV cells. In the last years, a new important aspect of solar cell was discovered. A semi-conductor junction stack that absorbs solar energy on a wider light spectrum than conventional PV cells is used in concentrating solar systems. Thanks to their resistance to high temperature the stack of photoelectric material (Ga, As, In, B, P) is regarded as a high performance PV cell.

CPV/T systems are generally based on triple junction PV cells. In fact, cell efficiency can be increased logarithmically with the concentration ratio which makes them less influenced by the cell temperature increase (Buonomano et al., 2013; Davide et al., 2014; Bosco et al., 2012; Zondag, 2008; Skoplaki and Palyvos, 2009)

With this regard, many advanced researches have recently beaten very high efficiencies making triple junction PV cells more commercially accessible. Thus, several research studies were conducted to investigate such systems at laboratory scale and even for industrial cases as well.

Further, most of the researches are focused only on the thermal and the electrical behavior of the CPV/T system. A photovoltaic/thermal parabolic trough collector with a triangular linear receiver recovered by triple junction cells was studied by Calise et al. (2012). This type of PV cells improved the system performances and its efficiency was found to be expressively better than the use of silicon cells, especially when the operating temperature is high. Coventry Joe (2005) tested experimentally a parabolic trough photovoltaic thermal prototype. The combined efficiency reached 69% under a concentration ratio equal to 37 suns. Cappelletti et al. (2015) reported a monitoring system to check the CPV/T energy production by the providence of an alarm in the presence

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of any discrepancy. Their model is also validated by a prototype experimental data and it marked a good enhancement by the decrease of the solar collector shadowing.

Gibart (2018) made a study on a cylindrical reflective surface, thanks to the simplicity of the technology. The results showed that the electrical and thermal efficiencies are higher than those of a conventional solar system. Furthermore, based on an economic study, it is expected that the system will have a return time of 10.5 to 12.8 years.

Quaia et al. (2012) and Ming et al. (2011) completed the first commercial scale demonstration for the CPV/T technology by the end of 2004 at the Center for Sustainable Energy Systems (CSES) at the Australian National University (ANU). They developed a combined solar collector (CHAPS) which provided electricity and hot water for the heating of a residential school with a combined efficiency of 69%. The ANU produced mono-crystalline silicon PV cells. Under a concentration ratio of 30, PV cells were characterized by a low resistance in series around $0.043\,\Omega\,cm^{-2}$ and efficiency equal to 20% at 25 °C. Xu et al. (2012) worked on two CPV/T systems in the research institute of the National University of Australia. A detailed study on a CPV/T and much work had already been done on the design of the collector as well as the development of new solar cells. They compared the system for two different types of PV cells. The researchers have admitted that GaAs cells have higher electrical efficiency, thanks to their low resistance in series that results an excellent system performance. However, for the crystalline cells, the generated system powers are decreased due to the high series resistance leading to high power losses. Nevertheless, crystalline cells are characterized by the better thermal efficiency.

Three absorber shapes of linear CPV/T systems (tubular, vertical plate and horizontal plate) were reported in Sharan et al. (1987). A Comparative performance between these forms was discussed. Results showed that the solar concentrator system with a tubular absorber provides the maximum electrical power, the optimum electrical efficiency and the lowest cell temperature. Thus, its efficiency reached the highest value compared to the other configurations.

Nowadays, it is still a challenge to achieve high outlet temperature from (CPV/T) systems. Multilayer thin film filters ($SiNx/SiO_2$) were studied and fabricated to act as beam splitting. Felipe et al. (2014) investigated a CPV/T collector using $SiNx/SiO_2$ thin film filters and demonstrated the feasibility of this technology. They also indicate that this type of system might exploit 85.6% of the incoming solar spectrum. Proell et al. (2016) focused on the influence of the CPC reflectors on the PV efficiency. Authors studied experimentally the flux distribution and, especially, they measured the angle modifier of the PV efficiency. Results showed the negative effect of a non-uniform irradiation on the PVT absorber which decreased their efficiency. Moh'd et al. (2017) examined the behavior of a (CPV/T) system that utilizes an Organic Rankine Cycle (ORC) integrated with a geothermal condenser and an energy storage unit. It was found that without cooling, the PV cell's efficiency reached 3.88% in comparison to 18.92%, while using the cooling system and 21.96% by using the ORC as a waste recovery system.

Currently, the adoption of nanofluids in concentrated solar systems present an interesting option, which attracted a significant attention. Based on a numerical model, Xu and Clement (2014) investigated the use of an (Al/water) nanofluid for cooling a linear parabolic CPV/T system. According to their results, the efficiency of the PV cell increase with an increase in nanoparticle volume fraction. Farideh and Mehran (2017) investigated using nanofluids as the working fluid on the CPV/T system. The results indicated that using nanofluids in the laminar flow is more effective compared to the case of the turbulent regime. In diverse types of solar collectors' technologies; Verma and Tiwari (2017) reviewed the nanofluid application. However, relatively fewer informations are available for using nanofluids in PV/T systems, especially in CPV/T systems.

Based on previous works, several researchers have studied distinctive applications of CPV/T systems. In fact, Xu et al. (2012) proposed a novel low-concentrating solar photovoltaic/thermal system to heat water from 30 °C to 70 °C for domestic supply, space heating or associating a solar cooling system under an output electrical efficiency around 17.5%. While, CPV/T systems face different challenges, as a new application for this technology, a concentrated photovoltaic thermal system that drive an air conditioner was investigated (AL-ALili et al., 2012). The results showed that the performance of the proposed system is higher than the vapor compression cycle powered by photovoltaic panels and a solar absorption cycle. This new system is also able to meet the humidity and temperature requirements of buildings regardless of the climate. One of the proposed promising application for the exploitation of the CPV/T system is the coupling of a linear Fresnel concentrator with a channel photovoltaic/thermal collector that reached a total efficiency over 60% (Rosell et al., 2005).

Another advantage of the exploitation of the CPV/T system outputs is the increase of the potential cogeneration heat. However, this issue decreases the electric efficiency (Conventry, 2005; Calise et al. (2012); Xu et al., 2012). In fact, for high-temperature the most appropriate PV cells for these technologies is the triple-junction type, witch's nominal efficiency reached 20% at 513 K. Therefore, the use of such semi-conductor materials can lead to a higher outlet temperature at judicious conversion efficiency. Different applications make the perspective of using CPV/T systems with outlet high-temperature very interesting. With this regard, Mittelman et al. (2007a,b) were interested in a CPV/T system equipped with triple junction cells with a nominal conversion efficiency of 37%. The prototype operates at temperatures above 100 °C and its output thermal energy can be useful for different processes such as steam production, refrigeration and water desalination. Moreover, some authors studied a combination of a parabolic dish and high efficiency solar photovoltaic cells at high temperature. They explored a concentrating PV/T system operating at 453 K with an acceptable thermal and electrical efficiency driving a two-effect absorption chiller (Buonomano et al., 2013)

Lately, simplified models are used also to investigate CPV/T plants at high temperatures. The outcomes revealed that exploiting the wasted system heat for cooling might lead to greater overall efficiency (Kribus et al., 2006).

For higher temperature necessities, concentrating solar collectors are the only solution; several examples consist in the use of this high-temperature provided by the CPVT to drive a thermal motor (Vorobiev et al., 2006), an Organic Rankine Cycle (Kosmadakis et al., 2011) or a Solar Heating and Cooling system (Calise and Vanoli, 2012). A CPV/T installation based on a dish concentrator was considered for both water desalination and solar cooling applications (Mittelman et al., 2007a,b).

Ben Youssef et al. (2017) proposed a numerical model of a CPV/T system operating under 200 °C. The modeling gives a detailed analysis of the thermal and electrical performances of water heating for an application of the textile industry. Results of an innovative CPV/T system that incorporates spectral beam splitter and vacuum tube sensors showed that the thermal load of the cell can be reduced and the outlet temperature can be up to 250 or 300 °C (Otanicar et al., 2015).

Accordingly, the all above mentioned results showed that the CPV/T technology has been greatly developed and it has been increasingly embraced. Consequently, it definitely holds a very high potential for market penetration in the energy sector.

In previous published studies, the main objectives were focused to improve the heat transfer in the CPV/T system with low outlet temperature and there were few papers in which they investigated medium or high temperature. In the present study, differently from traditional photovoltaic systems, the CPV/T systems with triple junction PV cells, guarantees recovering the thermal energy with high electrical efficiency. Detailed analysis is performed using the 2-D developed numerical model in order to identify the significant parameters affecting the overall performance of the CPV/T system. Thus, the proposed model is applied to improve the cogeneration system capacity and to retain competitive prices. It is used to optimize the CPV/T system

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