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Comprehensive analysis and general economic-environmental evaluation of cooling techniques for photovoltaic panels, Part I: Passive cooling techniques

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ABSTRACT

This paper deals with the analysis of passive based cooling techniques for photovoltaic panels (PVs). A comprehensive review and evaluation of the research activities and in general studies related to the development of passive cooling techniques for PVs was obtained. A major contribution to the herein reported research study is the provision of a general economic analysis for the passive cooling options as there is a gap in present research studies related to the economic aspect of the proposed cooling techniques (the same issue was also noticed for environmental aspects). Based on the comprehensive literature review, it was found that most of the examined passive cooling options are ones with an assumed application of PCM, then air based, liquid based (water, nanofluids, etc.) and finally radiative based. A 30 kW PV plant case study was considered in order to estimate the LCOE for each considered passive cooling technique, i.e. to examine the economic aspect (where general performance data were used with respect to the obtained analysis of the passive cooling techniques). Furthermore, LCA was also carried out in order to check the environmental aspects of the considered passive cooling techniques for PVs. Finally, according to the gained results and existing technical solutions, the currently most viable passive cooling option, both from a technical and economic point of view, is the air based cooling option with Al-fins mounted on the backside surface of the PV panel. The PCM based passive cooling technique for PVs could only be an option in future terms if a significant PCM material price drop were to occur. Therefore, the future development of passive cooling techniques could be focused on the research of hybrid cooling options. The hybrid passive cooling option assumes a mix of passive cooling techniques. Finally, the advantage of each cooling technique could be efficiently utilized in that manner.

1. Introduction

Nowadays, photovoltaic technology is widely used in different applications, [1] for renewable electricity production. Without the more intense application of photovoltaic technologies and other renewables as well as the development of novel and alternative renewable based energy concepts, [2,3] we would not be able to reach the general targeted goals related to the restriction of energy consumption and reduction of harmful impacts to the environment. However, and despite a significant reduction in capital investment required, the overall initial investment cost for PV systems is an issue, especially for smaller systems when considering their rather modest energy conversion efficiency. The average initial investment of a PV system for residential applications usually ranges from about 2.6 USD/W to 3.4 USD/W, while for large systems the overall investment can range from 2.0 USD/W to 2.3 USD/W on average, [4]. Furthermore, if we analyze the cost structure of the overall investment related to the PV system, the highest share falls on the PV panel itself (about 0.64 USD/W, [4]). In this line of approach, improvements in PV technology is a crucial factor in order to boost their market propagation, in accordance with the main targets of the Paris climate agreement and the EU goals for 2030, [5,6]. Currently, the older Silicon (Si) based photovoltaic technology (usually in Si-poly or Si-mono variant) accounts for the largest market share, with an average efficiency usually ranging from 10% to 15%. Although, the Si-mono variant has higher efficiency than the Si-poly one, the Si-poly PV technology has become more popular in recent years due to a lower overall investment cost, by about 20–30% on average, as well as due to reasonable

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Nomenclature

AC	Total life cycle cost, €	n	Amortization period, years
CRF	Capital recovery factor	OM	Operation and maintenance cost, €/year
EO	Average annual overall energy output from the hybrid energy system, kW h/year	p	Interest rate, % P.a.
IC	Installation cost (overall investment), €		

efficiency when compared to other PV technologies. It is also important to stress that the Si-poly technology is more sensitive to the PV panel's operating temperature, when compared to Si-mono, and which affects the overall PV panel efficiency. Other market available PV technologies, like ones from amorphous silicon, thin film (CdTe) or CIS/CIGS are less represented on the market due to a significantly lower energy conversion efficiency (about 6–12%, depending from the technology) and due to other general issues. Significant research efforts are being implemented in order to find novel PV technologies with a higher efficiency and to achieve economically more viable PV technologies. However, we are dealing with technologies that are not ready for a wide market implementation and that are currently under intense research activity, so it is more likely that Si-poly or Si-mono PV technologies will further have the highest market share in the near future. Focusing on research efforts that try to improve existing market available Si-based technologies in order for them to become more attractive and more economically reasonable are therefore more worthwhile.

It is well known that the operating temperature of PV panels strongly affects the already modest PV technology efficiency, where about 0.25%/°C up to 0.5%/°C is the rate of expected PV panel efficiency degradation caused by the rise of PV panel operating temperatures, [7]. Thus, proper cooling techniques for PV panels could ensure additional and desirable increases in PV panel energy conversion efficiency. Another favorable aspect associated with the implementation of cooling techniques for PVs is the prolonged premature degradation of PV panel efficiency (increased lifetime). According to some authors, the lifetime of PVs can be prolonged from about usually 25–30 years up to 48 years [8], by applying the specific cooling techniques for PVs. Furthermore, PV cleaning issues can also be resolved by applying certain cooling techniques and hence achieving an additional increase in annual average delivered electricity yield.

For these aforementioned reasons, significant research efforts were focused on during the last two decades by investigating different cooling techniques which can be in general divided into passive and active. The major concern related to the existing research findings is related to the economic and environmental aspects of the proposed cooling techniques for PVs. Several review research studies were also reported, however, they focused on specific PV applications (solar concentrator photovoltaics – CPV, solar thermal–PV/T, photovoltaics for building applications, i.e. building integrated photovoltaics–BIPV, etc.). For example in paper [9], a critical review of cooling techniques for photovoltaics was obtained for solar concentrator systems (CPV). Namely, different CPV systems have been analyzed from a base application aspect and finally grouped according to their geometry. Furthermore, both cooling and passive cooling techniques are summarized and each cooling technique was evaluated on a few criteria such as; heated area, pump power, pressure drop, mass flow rate and thermal resistance. It is important to emphasize that comparisons were reported both for theoretical and experimental studies. The study results [9] imply that micro channels or impinging jets are the best solution for the cooling of solar CPV systems with concentration levels higher than 150 suns. Paper [10] provided a review of thermal management techniques for PV systems. Namely, different cooling techniques for photovoltaics (natural, forced, hydraulic cooling of PV/T systems, water impingement cooling, Heat pipe cooling and PCM) have been addressed. The main outcome of the study [10] provided a summary of general data related to PV system type, and finally data related to PV panel operating temperature. Authors found that naturally ventilated PV systems will work in a range of operating temperatures between 50 °C and 70 °C and a forced one between 20 °C and 30 °C. It also emphasized that the De-ionized liquid immersion method can reduce operating temperatures by 30 °C to even 45 °C in the case of CPV systems. Finally, PCM systems turned out to be viable cooling options according to the authors. However, authors did not analyze the economic aspects of the proposed cooling techniques.

Different cooling techniques for PVs were addressed in [11], i.e. for hybrid photovoltaic systems, water and liquid based PVT systems, refrigerant based PVT systems, heat pipe PVT systems, PCM based PVT collectors and finally thermoelectric cooling (almost all of the cooling techniques for PVs were considered). The review paper ended by summarizing the advantages and disadvantages of each cooling technique mentioned above. Important parameters for each analyzed cooling technique, like for example the PV technology type, improvement of electrical efficiency, thermal efficiency, overall exergy efficiency and reported PV operating temperature were specified. Finally, authors addressed that water based cooling systems within PVT configuration are the most promising ones and have the most specific advantages. A numerical and experimental study related to the novel PV/T system was elaborated in [12]. The authors reported an average increase in thermal efficiency by about 41.9% and about 9.4% in electrical. The system was investigated for typical Chinese climate conditions and it is suitable for operation in cold regions without freezing issues. The optimization and design for the PV/T heat-pipe system with a PCM was addressed in [13] through a developed numerical model and for Beirut climate conditions. An optimal system was found with improved general efficiency. The theoretical aspect of the considered PV/T system with an integrated compound parabolic concentrator was elaborated in [14] (where the developed model allowed a detailed performance analysis). Different aspects were addressed in [15] and related to the PV/T configuration (a specific simulation model was developed to obtain analysis).

Various cooling techniques were addressed in [16] as for example the use of PCM, water passive and active, evaporation, heat-pipe and finally air forced techniques. The analysis was finalized with the comparison of different cooling techniques based on the achieved effective increase in PV panel peak output. The comparison was therefore only obtained for those studies which reported a net increase in PV panel output, after which power losses are taken into account and related to the considered cooling technique. According to the authors, the best results were achieved for water forced cooling techniques for photovoltaics and the most promising systems are the PV/T systems where an efficient usage of rejected heat can significantly contribute to the economic viability of the mentioned systems.