Energy Conversion and Management 155 (2018) 301–323

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

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

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ARTICLE INFO

Keywords:
Photovoltaics
Active cooling techniques
Review
Solar energy
LCA
LCOE

ABSTRACT

This paper deals with active cooling techniques for photovoltaic panels (PVs) where a detailed review was obtained as well as analysis by examining the findings of existing literature. Based on the obtained review, an elaboration of the main performance parameters was obtained for each specific considered coolant (air, water or nanofluids). It was found that the less investigated cooling techniques are the ones related to CPV (Concentrated Photovoltaic) systems and only a few studies exist with nanofluids as the considered coolant. The majority of tested active cooling options are based on water as the coolant and for PV/T (Photovoltaic/Thermal) configurations. The economic and environmental aspects of the active cooling techniques were not analysed in the majority of research studies thus there is an obvious gap in the existing literature. Therefore, the main outcomes of the herein obtained research are reflected through summarized analysis of all important aspects related to active cooling options for PV applications (performance, economic and environmental). According to the obtained results, the highest increase in PV panel performance is achieved by water base cooling techniques and they range from about 10% to 20% on average. To analyse economic and environmental aspects, a 30 kW PV system was studied as a case study. Regarding the economic aspect, the LCOE (Levelized Cost of Electricity) for the considered case study of a 30 kW PV system ranged from 0.096 €/kW h to 0.159 €/kW h. For the given circumstances, it was found that the considered active based cooling options were not economically viable (it is crucial to ensure optimization for the specific liquid (water) based active cooling technique followed by "smart regulation" in order to provide a more reasonable LCOE). However, with the proper optimization of active cooling techniques, it is more than reasonable to expect an additional LCOE reduction as it could significantly reduce the operating cost. The environmental analysis (LCA) showed that out of all the herein evaluated cooling techniques, the air based cooling techniques are the most harmful to the environment which is primarily due to more intense global warming and environmental acidification effect. Other environmental impacts are approximately of the same magnitude for the specific analysed active cooling options.

1. Introduction

The siliceous based photovoltaic (PV) technology is currently the most dominant PV technology on the market, although it is the oldest photovoltaic technology [1]. Other PV technologies such as amorphous, CdTe, CIS/CIGS, did not find a significant market share which is mostly due to their lower average energy conversion efficiencies, usually from 6% to max. 12% (when compared to Si-mono or Si-poly PV technologies), as well as other issues related to their implementation in practical terms. However, there are certain applications where other markets available technologies (as Thin Film) are more suitable than convectional Si-based. In recent years, novel market PV technologies have appeared on the market (i.e. bifacial PV panels [2] and HIT PV panels [3]). The main issues related to the relatively novel PV technologies are either their limitation (applicability) for specific applications or their general high investment. Currently, the highest recorded energy conversion efficiency for market available PV technologies is in the case of HIT PV panels which equals to about 25.6% [3] (when CPV systems are excluded as they reach the highest efficiency levels, i.e. more than 40%, Fig. 1). On the other side, convectional and most used Si-based PV technologies have an average energy conversion efficiency that usually ranges in practical terms from about 10% to 15%, (depending from the specific geographical location). However, an analysis obtained by Fraunhofer ISE [4], emphasizes that there is a certain progress related

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http://dx.doi.org/10.1016/j.enconman.2017.10.071
Received 19 July 2017; Received in revised form 16 October 2017; Accepted 25 October 2017
0196-8904/

Nomenclature

AC	total life cycle cost, €
CRF	capital recovery factor,
EO	average annual overall energy output from the hybrid energy system, kW h/year
IC	installation cost (overall investment), €
n	amortization period, years
OM	operation and maintenance cost, €/year
p	interest rate,% p.a.

A review of cooling techniques for a variety of solar collectors and PV cells was obtained in [9] and related to the application of nano-fluids. A general overview of the cooling techniques was elaborated from a performance aspect as well as from an environmental aspect (where solar collectors as well as PV and PV/T configurations were analysed). A detailed heat transfer analysis related to nanofluids was also obtained for a variety of experimental configurations (flat plate solar collectors, direct absorption solar collectors, evacuated tube solar collectors, parabolic through, concentrated-parabolic and finally PV/T collectors). An exergy and energy analysis was also performed and annual thermal energy and exergy gains were calculated for different technologies. Finally, the authors concluded that the application of nanofulids could be reasonable in the future, especially for PV/T systems (however, only if a substantial improvement in efficiency and a reduction in costs could be ensured).

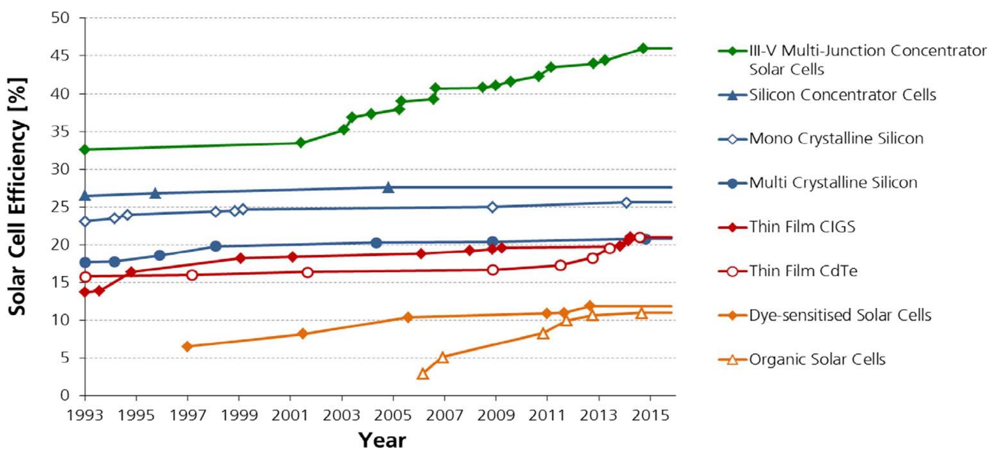

Fig. 1. Laboratory efficiency of different PV technologies [4].

to the increase in average efficiency regarding silicon PV technology, achieved by the further development and optimization of its technology (increase to about 17% and about 21% for super mono). With the development of technology, there is a significant reduction of material usage (more than 2.5 times [4]).

The main disadvantage of the most used silicone based PV technology is its sensitivity to the operating temperature magnitude. Namely, the energy conversion efficiency is reduced with the increase of the PV panel operating temperature which usually ranges from 0.4%/°C to 0.5%/°C (less for amorphous siliceous technology, about 0.25%/°C). Therefore, by limiting the PV panel operating temperature, a higher energy efficiency rate could be ensured. The previous reason resulted in significant research efforts in past years and focused on the development of efficient cooling techniques for PV panels. In general, cooling techniques for PVs can be divided into active and passive ones. The herein provided study is focused on active cooling techniques and different active cooling options were generally investigated regarding existing research studies which are related to different applications (PV, PV/T, BIPV, CPV, etc.). Thus, besides the development of novel photovoltaic technologies, an investigation of thermal phenomena as well as novel potential PV applications is also crucial issues that are under research activity [5–8].

A review of the advances in liquid based photovoltaic PV/T collectors was obtained in [8]. The authors analysed water based and refrigerant based PV/T systems, where the mentioned fluids are generally used to remove sufficient heat from PV/T panels. The main influential parameters were summarized and presented, which were related to general PV/T system performance. It was found that PV/T systems still need significant development in order to obtain reasonable efficiency, and that different cooling strategies need to be proposed and analysed with respect to the specific climate conditions. According to authors, the main direction for the development of PV/T systems should be the integration of a combined PV/T water cooled system for space heating and cooling applications (in order to develop a multi-functional energy system, where COP (Coefficient of Performance) could be significantly improved when compared to conventional heat pump systems).

An energy and thermo-fluid dynamics evaluation of the photovoltaic systems cooled by water and air was elaborated in [10]. The analysis was obtained for different cooling techniques using TRNSYS software where the final goal was to check the annual performance of the considered cooling techniques. The cooling performance of air and water based cooling systems was analysed in detail, as well as the energy analysis with respect to different construction solutions. Regarding the water based cooling systems for PVs; it was found that the application of plastic materials was most favourable for a variety of reasons when compared to metal sheets. Further, water based cooling systems are generally more complex in terms of overall installation and other issues. Finally, the authors concluded that the yearly improvement of convectional PV systems with air or water based cooling is expected to be about 5%.

A detailed review of cooling techniques related to solar concentrating photovoltaics (CPV) as well as its recent development was obtained in [11]. Various CPV cooling techniques were addressed in detail as for example: heat pipe cooling, water cooling, jet impingement cooling, CPV/T hydraulic system, liquid immersion cooling, micro-channel heat sink cooling, PCM (Phase Change Material) based cooling, thermos-photovoltaic cooling and ground coupled cooling systems. The authors summarized the considered CPV techniques with detailed specifications for each technology (type of cooling system, CPV cell material, CPV cell temperature, cooling effect, and concentration ratio, type of concentrator, flow conditions, heat transfer, location and surrounding conditions). The advantages and disadvantages for each considered cooling technique, and their general challenges in construction and application were addressed. The authors concluded that additional experimental work is still needed in order to determine the best method for CPV system cooling. Namely, the choice of cooling method is extremely sensitive regarding the specific location (climate conditions) and assumed application as concluded in [11].