Renewable and Sustainable Energy Reviews 60 (2016) 1086–1099

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Technical and economic effects of cooling of monocrystalline photovoltaic modules under Hungarian conditions

Attila Bai [a], József Popp [a], Péter Balogh [a,*], Zoltán Gabnai [a], Béla Pályi [b], István Farkas [c], Gábor Pintér [b], Henrik Zsiborács [b]

[a] University of Debrecen, Faculty of Economics, Böszörményi Street 138, 4032 Debrecen, Hungary
[b] University of Pannonia, Georgikon Faculty, Deák Ferenc Street 16, 8360 Keszthely, Hungary
[c] Szent Istvan University, Pater Károly Street 1, 2103 Gödöllő, Hungary

ARTICLE INFO

Article history:
Received 22 May 2015
Received in revised form
15 January 2016
Accepted 7 February 2016

Keywords:
Cooling
Photovoltaic modules
Sprinkling
Cell temperature
Performance
Economic evaluation

ABSTRACT

This paper focuses on the impact of sprinkling and refrigerant based cooling methods of photovoltaic modules on actual performance, the duration of cooling and the quickness of the impact of cooling in comparison with monocrystalline photovoltaic modules without cooling. The obtained findings were analysed both from technical and economic aspects.

Based on the parameters of the regression model used in this study ($r=0.61$), it can be concluded that a 1 °C increase of air temperature in the examined range (18–29 °C) improves actual performance by 1.58 W and cooling is probably necessary at higher temperatures. On more cloudy days, the expected performance is 9.8 W lower on average ($P=0.001$).

In both experiments, there was an obvious negative correlation between module temperature and actual performance under constant radiation conditions. On more sunny days, one unit change in temperature resulted in a performance change of 1.2–1.3% ($R^2=0.87$–0.95), while more cloudy days resulted in less close correlation and a much lower change of temperature (0.8–0.9%) ($R^2=0.70$–0.81).

The following conclusions can be drawn in relation to the two examined cooling methods:

- The actual performance of the sprinkling method is higher than that of the other two alternatives (by 19% and 25% in the case of the control method and by 13% and 18% in the case of refrigerant based cooling, depending on the day of measurement).
- After deducting the electricity needed for sprinkling cooling, the electric performance was still 12% better on average, using 22.5 L water per day on average. In the case of the refrigerant based cooling method, the produced extra energy was less than the electricity need of the heat exchanger itself; therefore, this method obviously seems to be unviable both from energetic and economic aspects.

Contents

* Corresponding address: University of Debrecen, Faculty of Economics and Business Institute of Sectoral Economics and Methodology, Department of Research Methodology and Statistics, 4032 Debrecen, Böszörményi Street 138, Hungary. Tel.: +3652508009.

E-mail addresses: bai.attila@econ.unideb.hu (A. Bai), popp.jozsef@econ.unideb.hu (J. Popp), balogh.peter@econ.unideb.hu (P. Balogh), gabnai.zoltan@econ.unideb.hu (Z. Gabnai), palyi@georgikon.hu (B. Pályi), farkas.istvan@gek.szie.hu (I. Farkas), pg@georgikon.hu (G. Pintér), ifj.zsiboracs.henrik@gmail.com (H. Zsiborács).

http://dx.doi.org/10.1016/j.rser.2016.02.003
1364-0321/

1. Introduction

Of the different photovoltaic (PV) modules, the highest efficiency of transforming solar energy into electric energy is shown by monocrystalline photovoltaic modules. Transformation efficiency greatly depends on the proper temperature of photovoltaic modules; therefore, one of the simplest and most effective methods of increasing performance is to cool these modules during the warm summer period.

Based on the global radiation map of the world, it can be concluded that the yearly amount of energy from the sun ranges between 800–2800 kW h m^{-2} on the horizontal plane, due to the various geographical locations. In Europe, this amount of energy typically ranges between 800–2000 kW h/m^{-2}. In European terms, the natural endowments of Hungary are better than average, since the yearly amount of energy from the sun ranges between 1200–1360 kW h/m^{-2} on the horizontal plane. Based on the data of the Photovoltaic Geographical Information System, 1280 kW h electricity can be used in a year in the examined country with a 1 kWp photovoltaic system feeding back to the grid. These data are based on monthly measured climatic readings [1–4].

There are constant endeavours to exploit renewable energy sources and the amount of energy produced from these sources increases on a yearly basis, in parallel with the energy demand of the population. Of these sources, solar energy is available to the greatest extent and it is clean, inexhaustible and sustainable [5,6]. The yearly amount of solar energy reaching the surface of the Earth is 120,000 TW, which is more than the yearly energy need of the global population (around 15 TW) [7]. There has been a rapid increase recently in energy production with photovoltaic modules, mainly due to quick technological development, decreasing costs and government support being introduced in numerous countries. This phenomenon is represented by the following data: according to the Renewables 2015 Global Status Report, the total installed capacity of photovoltaic systems was 23 GW in 2009. This capacity increased to 177 GW by 2014, which represents more than a sevenfold increase [8–10]. As a result of further installation, 53–57 GW extra capacity is expected in 2015. Currently, it is one of the greatest challenges find a way to exploit this rather promising energy source to the greatest possible extent and to develop a solution to effectively store this energy [11].

In general, it can be stated that the currently available crystalline photovoltaic modules are capable of transforming 20% of solar radiation into electricity. As a result, the significant amount of solar radiation is transformed into heat without utilisation, which deteriorates the efficiency of photovoltaic modules and this can be reduced with cooling [12]

Experiments of continuous flow cooling systems resulted in a relatively slight increase in efficiency, while evaporation loss was also observed, along with the need to mobilise a significant amount of water due to recirculation. For this reason, this research focused on cooling methods which either make use of the cooling energy of evaporation or those which perform cooling in a closed loop system without any water loss. In both cases, the obtained findings were evaluated against non-cooled monocrystalline photovoltaic modules, both from technical and economic aspects. During economic calculations, public and small scale plant photovoltaic module systems were evaluated on the basis of Hungarian consumer prices. Further measurements and calculations were also performed in relation to how air temperature and the impact of the sun affect the operation of non-cooled systems, in order to determine the specific air temperature at which photovoltaic modules are best for cooling.

2. Technical literature overview

In order to justify the relevance of these examinations, this section provides a brief overview of the characteristics of photovoltaic modules, the findings achieved so far in relation to the cooling of photovoltaic modules, as well as the Hungarian system of purchasing electric energy, which serves as the basis of economic calculations.

2.1. Characteristics and market of photovoltaic modules

In addition to several other advantages, electricity produced from solar energy could greatly contribute to sustainable energy management. Based on the life cycle of photovoltaic modules and taking the energy and material need of their manufacturing into consideration, they produce green energy for free without any CO_2 and other emission or waste production for many years [6,13]. It is a significant advantage of solar energy that it makes decentralised energy production possible in any part of the world or even in space.

A photovoltaic module is equipment utilising solar energy which produces electric energy from solar energy in accordance with the laws of physics, as a result of the photo-electric effect. The solar energy utilisation efficiency of photovoltaic modules, as well as the amount of energy to be produced, primarily depend on the type and constitution of the given module. These aspects are also subject to installation-related and current natural circumstances and factors. Although the most frequently used silicon-based photovoltaic modules have a theoretical efficiency of 25%, their efficiency in practice is around $18 \pm 2\%$ [14]. The newly produced four-junction solar cell is a current example of technological advancement, as this cell has an outstanding theoretical efficiency of 44.7% [15]. This result is due to the fact that this solar cell consists of more (four) cell units as opposed to conventional solar cells; therefore, it is capable of utilising a much wider frequency of the solar radiation spectrum [15].

Under ideal and shade-free circumstances, the performance of solar cells is basically determined by two factors, global radiation and temperature [16]. The significance of the shade effect is high in the case of serially connected solar cells. Serial connection is necessitated by the higher resulting voltage. Even if only one solar cell is partially shaded, the affected cell determines the resulting current and, therefore, the output performance of the whole module. As a result, partial shading has to be avoided by all means, whenever possible [17]. In addition to the above specified