Available online at www.sciencedirect.com

SCIENCE DIRECT

Solar Energy Materials & Solar Cells 82 (2004) 131–137

Solar Energy Materials & Solar Cells

www.elsevier.com/locate/solmat

Increased electrical yield via water flow over the front of photovoltaic panels

Stefan Krauter*

Department of Physics, Federal State University of Ceará (UECE), Av Paranjana 1700, Fortaleza 60740-000 CE, Brazil

Abstract

Reflection of the sun's irradiance typically reduces the electrical yield of PV modules by 8–15%. Facade applications located in the tropics may even experience a 42% drop in yield, due to flat incidence angles. Additionally, when a module's cell temperature is elevated there is 0.4%/K decrease in voltage and power for single- and multi-crystalline silicon solar cells: in reference to STC, that number may reach 20%.

Numerous ideas to reduce reflection have been proposed, but most have drawbacks: anti-reflective-coatings are not durable and structured surfaces are expensive, accumulate dust and are difficult to clean. Yet water, with a refractive index of 1.3, is a viable intermediary between glass ($n_{\text{glass}} = 1.5$) and air ($n_{\text{air}} = 1.0$). In addition to help keeping the surface clean, water reduces reflection by 2–3.6%, decreases cell temperatures up to 22°C and the electrical yield can return a surplus of 10.3%; a net-gain of 8–9% can be achieved even when accounting for power needed to run the pump.

Keywords: Cooling; Liquid layer; Optical matching; Anti-reflective-coating; Cleaning

1. Introduction

1.1. Optical loss

As is often mentioned in literature, solar radiation hitting a glass encapsulated or laminated PV-module at a perpendicular incidence angle yields a reflection loss in the range of 4–5%. Yet for most applications the incidence angles do differ from zero

---

*Tel./fax: +55-85-2992804.

E-mail address: info@rio4.com, krauter@uece.br (S. Krauter).

0927-0248/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.solmat.2004.01.011

and thus result in an increased reflection loss as according to Fresnel's laws (e.g. Ref. [1]).

The accumulated reflection loss over one day for a fixed tilt-angle of the module depends on the latitude, clearness index (diffuse-direct ratio), surface treatment and the match of refractive indices within the layers of module encapsulation.

Using a sophisticated three-layer optical model[1] [2,3], the optical performance of a three-layer-encapsulation module was calculated (including multiple reflections inside and between the layers). During the day, when utilizing only the original material properties of the module at operating conditions [4], the accumulated reflection loss can be as great as 8–15% for conventional PV-Systems and as great as 42% for PV-façade applications located in the tropics.

1.2. Improved matching of the refractive indices of the module encapsulation layers

By utilizing the optical model presented above for a simulation of the optical system consisting of front glass, EVA, anti-reflective coating and silicon solar cells, a variation of parameters led to the following result: an improved optical match between the two upper layers (glass and EVA) and an increased optical transmittance of 3.2% for materials with ideal properties of $n_1 = 1.33$ and $n_2 = 1.73$ (see Ref. [5]). Unfortunately, these ideal properties for the top layer cannot be achieved with solid materials. Yet water, with a refractive index of 1.3, returned an increased yield in the vicinity of 3% for both optical transmittance and electrical generation.

Other methods for reducing reflection also work, but have disadvantages. Anti-reflective coating of glass is often not durable and structured surfaces are costly, have a tendency to accumulate dust and are thus difficult to clean.

1.3. Thermal loss

A crystalline silicon solar cell's electrical power generation depends on its operating temperature. While the short circuit current (I_{sc}) increases slightly with increasing temperature, the open circuit voltage (V_{oc}) decreases significantly (about $-2.3\,\mathrm{mV}/^\circ\mathrm{C}$) with increasing temperature. This results in a reduction of electrical power output (and electrical yield) of $-0.4\%/^\circ\mathrm{C}$ to $-0.5\%/^\circ\mathrm{C}$ for mono- and multi-crystalline silicon solar cells (which are used in most power applications).

1.4. Preliminary studies for temperature reduction

Because efficiency and electrical yield decrease with increased operating temperatures it is preferable to maintain low system temperatures. By mounting

---

[1] The optical model is mathematically exact for slabs thicker than the wavelength of the irradiance—all possible internal and external reflections are considered. An irradiance model, which accounted for the spatial distribution of direct and diffuse irradiance during clear sky conditions was implemented in order to calculate the solar reflection performance of an optical system during the daytime.

the PV module on a water-filled tank and due to the high thermal capacity of water in the tank, the operating temperatures were kept at low levels during most parts of the day. This design provided for an effective reduction in the cell temperatures without expending energy for refrigeration; the water virtually soaked up the heat flow generated by the module during daytime.

The design was improved as different prototypes were built over previous years [6–8], and has resulted in an increased electrical energy yield of 12%. The drawback is the unit's huge weight of 200 kg/module which makes conventional roof mounting difficult.

2. Cooling by flowing water over the module front

Cooling by utilizing a flowing film of water on the module front should theoretically allow operation at even lower temperatures than the device described above: Due to the quick flow of the water there should be only a minimal increase in water temperature. Additionally, the evaporating water should further decrease temperatures thus result in increased electrical yields.

2.1. Measurements

2.1.1. Conditions

The M 55 modules were selected due to their equal open-circuit voltage, short circuit current, and power output. The measurements were recorded during a clear day at the PV-Labs in Rio de Janeiro on the 21st of March 1999. Irradiance was measured by a BM 5 Kipp and Zonen pyranometer at the same incidence plane of the modules: north at an elevation angle of 23°. Ambient temperature was measured in the shade. Temperature sensors (Pt 100) were installed on the back of the two modules where the actual cell temperatures are about 1.5°C above the temperatures on the front of the module. Wind speed was measured about 30 cm above the modules. Tracking of the "maximum power point" was done manually by utilizing the variation of an ohmic load and measuring electrical power output. Data was recorded every 15 min (details see Ref. [9]).

2.1.2. Water film

Approximately, 2 litres (l) of water/min were pumped from a large tank located underneath the module into a small (53 l) tank above the module. Twelve nozzles located along the top of the module generated a flow of water that spread over the cell's surface at a thickness of about 1 mm (see Fig. 1). Considering the module area, the specific water consumption was 4.4 $\mathrm{l\,min^{-1}\,m^{-2}}$.

2.1.3. Results

Due to the water flow and additional cooling by evaporation (specific evaporation was 0.016 $\mathrm{l\,min^{-1}\,m^{-2}}$ or about 1 $\mathrm{l\,h^{-1}\,m^{-2}}$ in average, equivalent to a total of 680 Wh evaporation cooling/h including cooling of the surrounding air), the cells

Fig. 1. Creation of the water film on the PV module by a line of nozzles.

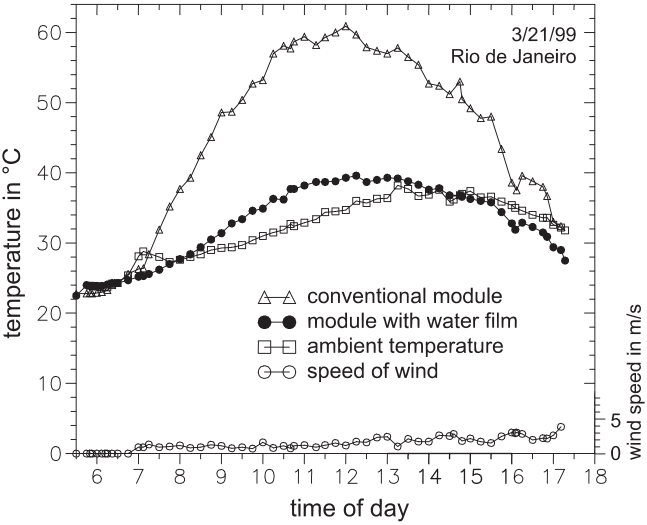

Fig. 2. Comparison of cell temperatures of a conventional PV module vs. a PV module with water flow.

operating temperatures were reduced significantly in comparison to a conventional reference module which was measured simultaneously (up to 22°C reduction, as could be seen in Fig. 2), leading to an improved conversion efficiency (see Fig. 3). The measured increase of electrical energy yield over the whole day was 10.3% (see Fig. 4).

Measurements of the short circuit current of the module, which is nearly temperature-independent, indicated that the water flow improved the optical performance by 1.5%. This was less than the 3% gain that was theoretically expected. An explanation for that discrepancy could be given by the

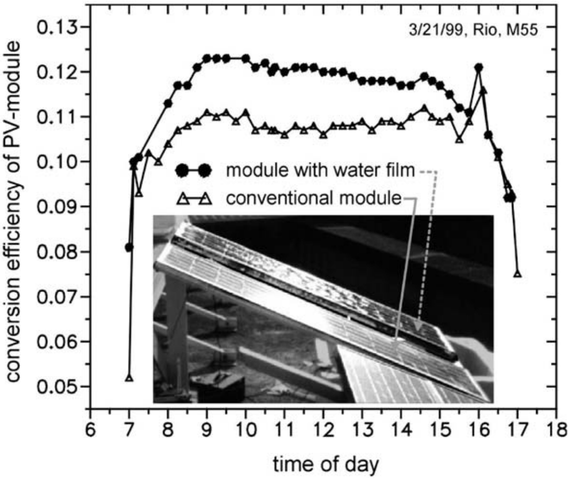

Fig. 3. Comparison of photovoltaic conversion efficiencies of the PV-modules.

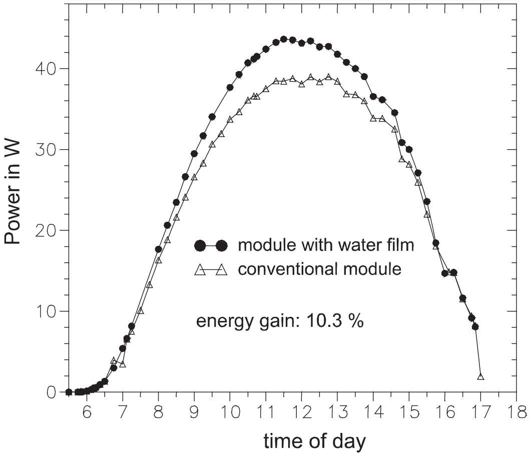

Fig. 4. Comparison of output power of the PV-modules (m 55, $P_{STC} = 53$ Wp) during 21st of March 99.

non-homogeneous thickness of the water flow and/or the light-absorbing properties of the water.

2.2. Esthetics

An unexpected, yet beneficial side effect was the visual appearance of the film of water. The water flowing over the surface of the module creates a pleasing design and architectural nuance providing people with the opportunity to view an active process at the PV-generator rather than the static appearance of the conventional unit (see Fig. 5).

Fig. 5. Close-up of the flowing film of water at the PV module surface.

2.3. Benefit-balance of electrical energy

The measurements described above have been carried out using a small, low-cost pump with a poor pump efficiency in the vicinity of 14% (including motor losses). Using such a pump did not justify the use of the flowing water film in terms of energy gains within an energy balance. After a survey [10] on available pumps we found a very high efficiency, but nevertheless simple pump designed by the Institute of Machine Design's division of Hydraulic Turbo-machinery and Fluid Dynamics at the Technical University Berlin in Germany.

This pumping system consisted of a high efficient 305 W brushless DC motor coupled to an optimized centrifugal pump (SP 175) offering a pumping head of 4 m at a flow rate of 17 m^3/h. Assuming a PV water pumping application, a PV generator consisting of six M 55 modules (width 0.66 m, length 3.9 m) and the pump described above. The cooling water flowed from 24 nozzles lined up over the width of two modules (0.66 m) and along the lengths of three modules (3.9 m). This configuration utilized 1.4% of the pumped water for cooling and the rest could be used directly, e.g., for irrigation.

Utilizing the system configuration described above a study by Wachsmann [10] revealed an 8% net gain in electricity generation.

An increase of the size of the generator by two M 55 modules would lead to a 9% increase in electricity yield, compared to an equivalent PV generator of the same size, but without cooling.

Acknowledgements

Thanks to all who participated in the development of the device: Uwe Schmid, Ulrike Wachsmann Heiko Roitsch and Marco Schmidt. Special thanks to Keith Parsons for text revisions.

References

[1] M. Born, E. Wolf, Principles of Optics, 5th Edition, Pergamon, Oxford, 1975.

[2] S. Krauter, R. Hanitsch, The influence of the capsulation on the efficiency of PV-modules, in: Proceedings of the 1st Word Renewable Energy Congress, Reading, UK, September 23–28, 1990, Vol. 1, pp. 141–144.

[3] S. Krauter, R. Hanitsch, Ph. Strauss, Simulation-program for selecting efficiency improving strategies of PV-module encapsulations under operating conditions, in: Proceedings of Renewable Energy Sources'91", International Conference, Vol. 3, Prague, CFSR, July 1–4, 1990, pp. 48–53.

[4] S. Krauter, R. Hanitsch, P. Campbell, S.R. Wenham, Optical modelling, simulation and improvement of PV module encapsulation, in: Proceedings of the 12th European Photovoltaic Solar Energy Conference and Exhibition, Vol. 2, Amsterdam, April 11–15, 1994, pp. 1198–1201.

[5] S. Krauter, Betriebsmodell der optischen, thermischen und elektrischen Parameter von PV-Modulen, Köster Press, Berlin, 1993.

[6] S. Krauter, Thermal and optical enhanced PV-modules, in: proceedings of the 13th European Photovoltaic Solar Energy Conference, Nice, France, October 23–27, 1995, pp. 2306–2309.

[7] S. Krauter, R. Hanitsch, Sol. Energy Mater. Sol. Cells 41/42 (1996) 557–574.

[8] S. Krauter, R. Hanitsch, L. Moreira, New optical and thermal enhanced PV modules performing 12% better under true module rating conditions, in: Proceedings of the 25th IEEE-PV-Specialists Conference, Washington DC, USA, May 13–19, 1996, pp. 1323–1326.

[9] U. Schmid, Thermische und optische Optimierung von PV-Modulen mittels aktiver Wasserkühlung zur Verbesserung des Wirkungsgrades, Master Thesis, Institute of Electrical Energy Technology, Technical University Berlin, Germany, 1999.

[10] U. Wachsmann, Technische und ökonomische Bewertung einer Ertragssteigerung durch Modulvorderseitenkühlung an Photovoltaischen Pumpsystemen, Master Thesis, Institute of Electrical Energy Technology, Technical University Berlin, Germany, 2000.