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Energy performance of the cooled amorphous silicon photovoltaic (PV) technology

Henrik Zsiborács[1*], **Béla Pályi**[1], **Hegedűsné Nóra Baranyai**[1], **Mihály Veszelka**[1], **István Farkas**[2], and **Gábor Pintér**[1]

[1] *University of Pannonia, Georgikon Faculty, Deák Ferenc Street 16, 8360 Keszthely, Hungary*

[2] *Szent Istvan University, Páter Károly Street 1, 2103 Gödöllő, Hungary*

**Corresponding author E-mail: ifj.zsiboracs.henrik@gmail.com*

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Abstract—In this paper, the effect of two types of water based cooling methods of amorphous silicon (a-Si) modules and a panel was studied in the summer period. One new (unused) and some 11-year-old a-Si modules and a panel with two different cooling techniques (sprinkling and flowing water cooling) were examined. Our reference for the evaluation was an unused a-Si module without any cooling. The results were analyzed from both statistical and technical aspects.

Key-words: solar energy, temperature dependence, water cooling, Z-test

1. Introduction

Renewable energies have an increasing role in the process of energy production (*Szabó et al.*, 2015, *Horváth et al.*, 2015). Besides numerous other benefits, energy production based on solar performances can significantly contribute to sustainable energy management. By a one-time investment in solar PV technology it is possible to produce CO_2-free, green energy for free without producing any waste for several decades (*Hosenuzzaman et al.*, 2015, *Aman et al.*, 2015).

The quantity of energy which can be produced by a solar PV module depends primarily on its type and composition and the joint effects of the location and the current natural factors. Modules are tested and certified under laboratory conditions under which their nominal performances are established (STC-Standard Test Conditions, AM = 1.5 air pollution, 1000 W/m^2 solar radiation, and 25 °C module temperature). However, these conditions are not given during operation, so PV modules hardly ever produce their nominal performance (TÜV SÜD America Inc, 2015).

Due to their reliability, the market share of crystalline silicon PV modules is 85–90%, and their efficiency can reach 25.6% ± 0.5% in the case of monocrystalline modules and 20.8% ± 0.6% in the case of polycrystalline ones (*Green et al*., 2015; IEA, 2014; *Cosme et al*., 2015; Panasonic Corporation, 2014; *Verlinden et al*., 2014).

The amorphous silicon solar module is a type of thin film PV solar module with an efficiency of up to 10.2% ± 0.3%. The market share of all thin film PV modules is 10–15%, but that of amorphous silicon solar modules within that is difficult to determine (*Green et al*., 2015; IEA, 2014; *Matsui et al*., 2013).

The temperature coefficient of thin film solar modules is better than that of crystalline ones. Thus, their use is favorable primarily in very hot, desert environments and in power stations (*Fábián,* 2015).

Several factors may influence the efficiency of the utilization of solar energy coming to the Earth. In the case of solar PV technologies, the fluctuation of module temperatures due to the change of air temperature and global radiation is one of the important factors (*Skoplaki* and *Palyvos,* 2009; *Hai Alami,* 2014). Under Hungarian climatic conditions, the temperature of solar PV modules can reach 60–70 °C on warm days, which results in a decrease of power generation in the module. For this problem, various cooling technologies may offer solutions.

According to *Bahaidarah et al.,* (2013), the performance of PV modules strongly depends on the actual module temperature. Generally it can be said that most of the incoming energy turns into thermal energy in the PV modules and is not utilized (*Chandrasekar et at.,* 2013). The arising quantity of heat gets lost, on the one hand, and causes additional losses in the short and long term, on the other hand, since the increase in the temperature of the modules reduces the efficiency of the system, and, thus, it reduces the quantity of electric energy produced, while, in the long run, they also accelerate the ageing of the PV modules (*Ndiaye et al.,* 2014; *Kahoul et al*., 2014). The decrease in efficiency may vary depending on the type of the PV module. In the case of crystalline silicon PV modules, the efficiency characteristically decreases by 0.5%, while in the case of a-Si modules by 0.3% as a result of a 1 °C temperature rise (*Radziemska* and *Klugmann*, 2002).

Various active and passive cooling procedures are used in solar PV technology for controlling the operating temperatures of the modules (*Chandrasekar et al*., 2015; *Elnozahy et al*., 2015; *Du et al.,* 2012). Four groups of the cooling techniques can be distinguished (*Chandrasekar et al.,* 2015; *Ji et al*., 2008):

- air-based,
- water-based,
- refrigerant-based,
- heat pipe-based.

In the present study, the water-based (water spraying and water flow over the front) procedures are discussed. In the course of spraying with water, the temperature of cooled PV modules decreases significantly compared to modules without cooling (under identical circumstances) due to the phenomenon of evaporation (*Abdolzadeh* and *Ameri,* 2009).

2. Measurement site

In the present experiment, cooled and uncooled Kaneka amorphous silicon PV modules were examined under real meteorological circumstances. The measurements took place in the same location on 8 different days in August 2015 with 4 different settings:

- A: ground-mounted, unused PV module without cooling as control,
- B: ground-mounted, unused PV module with cooling (sprayed),
- C: ground-mounted, 11-year-old PV modules with cooling by flowing water over the module front,
- D: roof-mounted, 11-year-old PV panel (with 6 modules) with cooling by flowing water over the module front connected to the grid with an inverter (*Fig. 1*).

Long-term global radiation data were not available for our research. Thus, the economic data related to cooling the PV modules were calculated on the basis of the above-mentioned days.

The unused amorphous silicon PV modules were facing south with a tilt angle of 35°. For the measurements, two PicoLog data acquisition systems were used, one with 12 and one with 16 input channels. These instruments allowed second-based, continuous data recording by a personal computer. The advantage of the data acquisition devices used for this research is that several units can be connected to one computer and its software is flexible. Consequently, the incoming signs are simultaneously visible (*Zsiborács et al*., 2015).

In the case of the control module – besides the voltage and the current –, the surface temperature was measured at one point (in the middle of the top third of the module).

Table 1. The parameters of the solar modules examined

Specifications	**Amorphous silicon PVmodule (unused)**	**Amorphous silicon PVmodule (11-year-old)**
Country of origin	Japan	Japan
Manufacturer/Distributor	Kaneka	Kaneka
Model	G-EA050	K54
Nominal output (Pm) (W)	50	54
Power output tolerance (%)	±10%	±10%
Maximum power voltage (Vmp) (V)	67	62
Maximum power current (Imp) (A)	0.75	0.87
Open circuit voltage (Voc) (V)	91.8	85
Short circuit current (Isc) (A)	1.19	1.14
Module dimensions (mm)	960×990×40	920×920×40

Fig. 1. The measurement site in Keszthely (*Zsiborács et al*., 2015).

In the case of the sprayed amorphous PV module, the temperature was measured at two places. One sensor was placed in the middle of the top third of the a-Si module, and the other one was on the left side of the bottom third of the a-Si module. This article uses the data from the first sensor. The temperature of the sprayed water, the voltage, and the current were measured. The automation of the cooling system was controlled by a thermostat, which was connected to the surface of the middle of the top third of the PV module.

In order to save water, the spray heads sprinkled the unused amorphous silicon modules intermittently, using exactly the amount of water needed to replace the water evaporated (*Zsiborács et al*., 2015). However, the location of the 11-year-old a-Si modules did not allow the application of the spraying method. That is why the technique of flowing water over the module front was used, creating a homogeneous water film.

The water got to the spray head through an ion-exchange resin water-softening appliance The water needed for the cooling of the a-Si modules was supplied by a domestic waterworks from a garden well with filtered groundwater (*Fig. 2*) (*Zsiborács et al*., 2015).

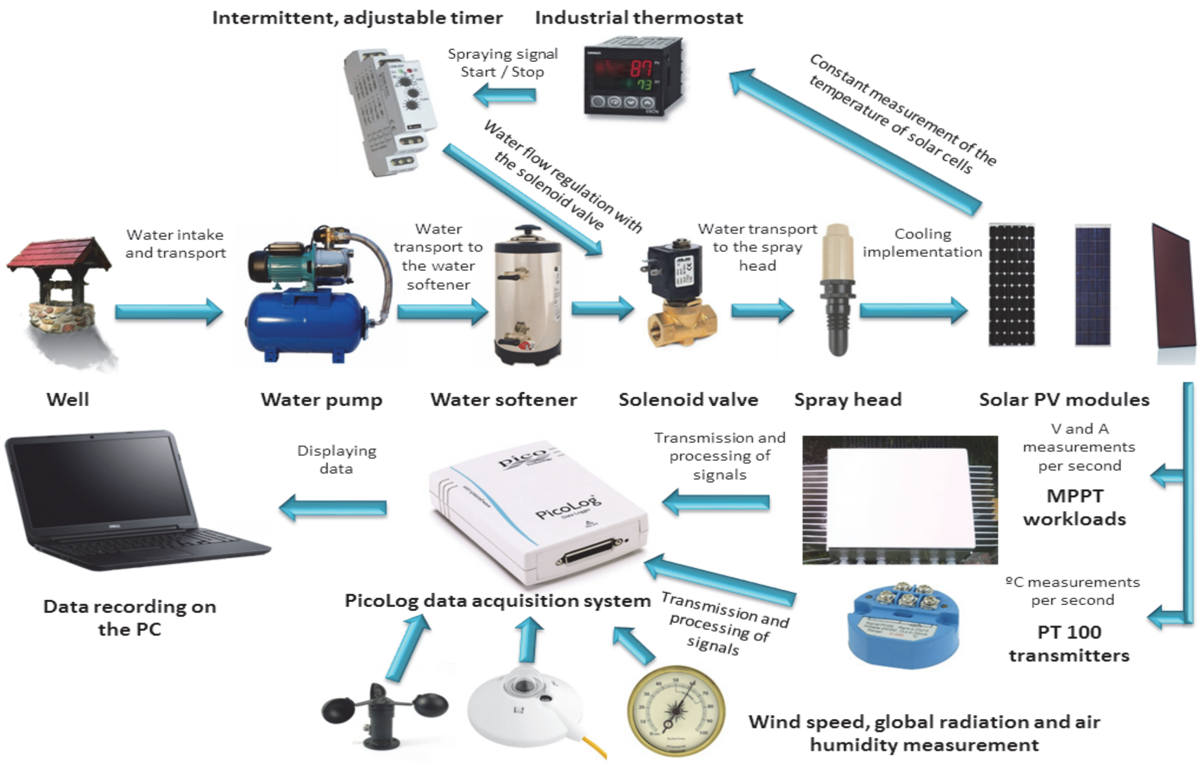

Fig. 2. Schematic diagram of PV modules measuring point (*Zsiborács et al*., 2015).

For measuring the temperatures, Pt 100 sensors were used with the help of the PicoLog devices (*Zsiborács et al*., 2015). The calibration of the whole temperature measurement system was done using an LM 35 digital thermometer with a linear voltage change (+ 10.0 mV/°C, 0.1 V = 1 °C, 1 V = 100 °C) and an accuracy of ± 1/4 °C at room temperature and that of ± 3/4 °C between –55 and + 150 °C.

A Voltcraft VC607 professional multimeter, which was checked by an LT1021 device (10,000 V +–5 mV), was used for the calibration of the voltage and the current.

The humidity of the air was measured by a HYTE-ANA-1735 device. The global radiation was measured by a pyranometer (an Eppley Black and White Model 4 – 48, certified by the Hungarian Meteorological Service). The wind speed was measured by a JL-FS2, 4–20 mA, 3-spoon aluminium device. The electric signs from the measurements were transmitted to the PicoLog device (*Zsiborács et al*., 2015). The pyranometer was placed next to the PV modules at a 35° angle (same as the PV modules). The air humidity and wind speed measurements took place at the side of the PV modules at a height of 80 cm (*Fig. 3*).

A True Maximum Point Seeking (TMPS) device, which maintained the maximum power point (MPP) was used for the measurements. The schematic diagram of the measurement point is shown in *Figs. 2, 3,* and *4*.

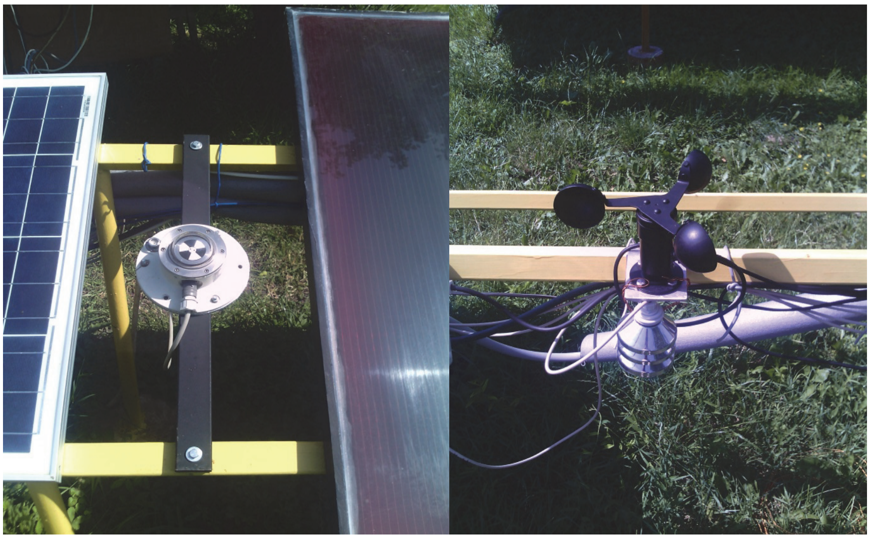

Fig. 3. The pyranometer, the wind speed sensor anemometer, and the humidity module.

Fig. 4. The unused amorphous silicon solar module measurement site in Keszthely.

A solar field consisting of 84 thin-film modules were used for the measurements of the 11-year-old a-Si modules, which had a nominal power of 4.5 kW. This system was set up at the same angle and location as the system above (*Fig. 5*). A Fronius Ig Tl inverter was used for the solar PV system.

Protection against TCO (transparent conductive oxide) corrosion, which can be caused by the chemical reaction of the water and the a-Si module if water gets under the glass, is important. If this problem is not prevented, the PV modules might go wrong in a couple of years (SMA Solar Technology AG, 2010). Grounding was impossible through the Tl inverter. However, the problem was solved by using a three-position switch. Silicone sealant was also applied to protect the PV modules between the glass and the frame.

The data from the 11-year-old modules were transmitted either to the PicoLog device or to the Fronius inverter. The control PV module was again an unused a-Si module.

The water needed for the PV module came from a domestic waterworks from a garden well with filtered underground water, after water softening.

For measuring the temperature of the 11-year-old amorphous silicon solar modules, a Lux Tools laser thermometer, which had been calibrated by a Pt100 sensor, was used. It was necessary to use the thermometer, since Pt100 sensors could not be used at the a-Si modules due to the limited number of channels of the measurement data collecting device.

The oscillation True Maximum Point Seeking device was suitable for receiving the data, because the voltage and current values were not far from each other. The a-Si modules examined are shown in *Fig. 5*, the first two columns on the left.

Fig. 5. The 11-year-old amorphous silicon solar panels

First the reaction of the six ground-mounted modules to cooling with flowing water over the module front was investigated one by one compared to that of the unused ones between 11.00 am – 12.15 pm on August 16, 2015. Each solar PV module examined was separated from the PV system and the parameters of the cooling were recorded one by one.

In the second phase the PV panel (with six a-Si modules) was studied (*Fig. 6*) in a way that only the panel was connected to the inverter. The other modules were disconnected at this time. That way the power surplus resulting from the cooling process could be measured. Here the TMPS solution, which was used in the first phase, could not be used. Thus, the data were supplied by the inverter.

Fig. 6. Amorphous silicon solar panel on the roof.

It is possible that the power changes in the control a-Si module due to natural effects during the period of the cooling process of the test modules. These changes have to be deducted from the power of the cooled amorphous silicon solar module.

The data were sampled hourly while spraying during sunny periods. The duration of cooling varied between 10 and 20 minutes depending on the measurement settings.

The surplus power was measured in the periods examined:

- before switching on spraying,
- at the end of the cooling period in a given hour.

Ten-minute cooling periods were sufficient for investigating the method of flowing water over the module.

The surplus power was measured in the periods examined:

- before switching on spraying,
- at the end of the cooling period in a given hour.

During the research, two-sample Z-tests were used to establish if there were any significant percentage differences in the performances of the cooled and the control PV modules.

3. Measured data and statistical analysis

In this chapter, the following issues are dealt with:

- regulation of the spraying water,
- the extra power produced by the unused and the 11-year-old amorphous silicon solar modules and panel,
- the actual daily energy production,
- hard water treatment.

3.1. The regulation of the spraying water at the unused a-Si module

The daily water consumption under operating conditions was examined on August 8, 2015.

In order to reduce water consumption, the spray heads were operated intermittently, thereby the system used minimal energy and only the amount of water necessary for evaporation. This way the efficiency of the spraying method could be determined for the amorphous silicon solar module.

By using the digital thermostat, a temperature regulating method that – depending on the temperature of the control module – can reduce the temperature of the surface of the cooled module by the average value of temperature reduction achievable in the given hour of the day was tested manually. Thus, the daily cooling period was maximally exploited.

In the case of the 50-W unused amorphous silicon solar module, 3 nozzles placed at a distance of 32 centimeters from each other were used. Depending on the weather, this system created a nearly homogenous sprayed surface (100 cm wide, 100 to 120 cm long) at 2 psi. From 9:00 am to 05:00 pm the water consumption was 4.2 l.

3.2. Detecting extra performance produced by the sprayed unused amorphous silicon PV module

The unused, test, and control PV modules were the same type and capacity according to the manufacturer's specifications. The relative changes in their performances were compared on August 7, 2015 (01:00 pm – 05:00 pm). The data were recorded every second. The two-sample Z-test established that the relative changes in the performances of the two unused modules were the same (P= 0.634).

Depending on the weather conditions (sunny weather), the measurements took place every hour between 09:00 am and 05:00 pm. This experiment involved 21 measurements. The average measurement data are shown in *Table 2*. By this test, the extra performance and temperature decrease of the PV module achievable by the sprinkling method were determined. It can be seen that the daily average extra performance increase of the unused amorphous silicon solar module was + 3.6% compared to the control a-Si module. Our tests support the results of *Skoplaki* and *Palyvos* of 2009, since in the case of the cooled a-Si module, an average performance increase of 0.3% for every 1-°C decrease in module temperature was observed.

Table 2. Data of the unused PV modules during spray cooling in August

Time (h)	**Average global radiation (W/m^2)**	**Average wind speed (m/s)**	**Average air temperature (°C)**	**Average air humidity (%)**	**Sprayed a-Si module average temperatures decrease (°C)**	**Observed average extra power during spray cooling (%)**
9–10	455.45	0.2	28.0	38.0	7.3	2.6
10–11	679.3	0.2	27.2	37.0	12.7	4.0
11–12	771.5	0.1	30.5	37.0	13.5	3.4
12–13	904.8	0.3	29.0	37.0	14.4	4.1
13–14	925.7	0.4	32.9	35.8	17.4	4.8
14–15	928.5	0.2	32.6	36.4	15.1	3.3
15–16	816.3	0.0	29.4	37.8	15.1	3.6
16–17	641.8	0.5	28.3	37.5	12.4	3.0
Average						**3.6**
CV (%)						17.9

3.3. *Detecting extra performance produced by the 11-year-old, ground-mounted a-Si modules cooled by water flow over the front*

The testing of the 11-year-old a-Si modules took place on August 26, 2015 from 11:00 am to 12:15 pm.

In the first phase of the test, the relative change in the performance of the ground-mounted PV modules was examined over time without cooling compared to the unused module. Before the cooling experiment, all six a-Si modules were examined for 30 seconds each, one by one. The two-sample Z-test established that the relative change in the performance of the modules was the same (P= 0.759).

The cooling was done by water flow over the front. The averaged measurement data are shown in *Table 3*. In this test, the achievable extra performance and temperature decrease of the PV modules were determined. It can be seen that compared to the control a-Si module, the average performance increase of the 6 modules was 3.8% during the measurements. For the unused a-Si module this value was + 3.6%, meaning that the reaction to cooling was almost the same after 11 years of use.

Table 3. Data of the 11-year-old a-Si modules cooled by water flow over the front on August 26, 2015 (11:00-12:15)

Module	**Average global radiation (W/m^2)**	**Average wind speed (m/s)**	**Average air temperature (°C)**	**Average air humidity (%)**	**Sprayed a-Si module average temperatures decrease (°C)**	**Observed average extra power during cooling (%)**
1.	748.2	0.6	24.7	35.8	11.1	4.3
2.	767.7	0.5	25.5	36.0	14.1	3.4
3.	787.7	0.5	25.8	35.4	15.0	3.4
4.	816.3	0.3	26.6	35.0	12.5	4.0
5.	830.5	0.5	26.5	34.7	16.8	3.5
6.	844.1	0.5	26.2	35.5	14.3	4.3
Average						**3.8**
CV (%)						10.1

3.4. *Detecting extra performance produced by the 11-year-old a-Si panel connected to a grid-connected inverter*

The testing of the amorphous silicon panel took place on August 26, 2015 from 11:00 am to 2:00 pm. During the experiment only 6 a-Si modules were connected to the inverter. Thus, the extra power resulting from the water cooling effect could be detected more easily. During the experiment three tests were carried out, but the last measurement was not reliable due to changes in global radiation.

The Fronius inverter constantly checks the MPP and shows the changes in performance every 2 seconds. To establish the amount of extra performance during the first measurement, the average performance of the 1 minute before the start of cooling and the average performance in the last 1 minute of the cooling were used. The first test lasted for 8 minutes, during which the temperature of the a-Si module decreased by 18.3°C and the performance increased by 5.2% (*Table 4*).

During the second measurement, the average performance of the last 30 seconds before the start of cooling and the average performance in the last 1 minute of the testing process were used to establish the quantity of extra performance. The duration of the second measurement was 6 minutes, since the global radiation changed after that. During the test, the temperature of the amorphous silicon solar PV module decreased by 15.3 °C and the performance increased 3.8% (*Table 4*).

The grid-connected PV system tests showed that increases in power were detectable not only in PV modules but also in the inverter-connected 11-year-old amorphous silicon panel.

Table 4. Data of the 11-year-old a-Si panel cooled by water flow over the front on August 26, 2015 (13:00 – 14:00)

a-Si panel number of measurements	**Average global radiation (W/m^2)**	**Average wind speed (m/s)**	**Average air temperature (°C)**	**Average air humidity (%)**	**Sprayed a-Si module average temperatures decrease (°C)**	**Observed average extra power during cooling (%)**
1	887.5	0.2	27.5	36.3	18.3	5.2
2	880.4	0.2	26.9	36.9	15.3	3.8

3.5. The actually achievable daily energy production

The average extra performance data detected during the investigation of the unused a-Si module were projected onto an a-Si system (4.6 kW) located in Balatonudvari, since the measurement site in Keszthely undergoes two shady periods in the early morning and in the late afternoon, which could have distorted the results. On the two ideal summer days the examined PV system in Balatonudvari reached a peak performance of 3.4 kW and 3.3 kW between 1 pm. and 2 pm. That means that the actual performance was between 71.7% and 73.9% of the maximum performance theoretically achievable. Consequently, the inverter capacity was not completely utilized, which could provide an opportunity for increasing the performance by cooling (SZALONTAI Rendszerintegrátor Kft., 2015).

As seen above, the average performance increase of the unused cooled a-Si module was + 3.6% between 9 am and 5 pm. compared to the control amorphous silicon PV module, which means 3.6% more energy output during that period.

In the experiment, a domestic waterworks consuming 750 Wh energy (1800 l/hour, 30 l/min) was used. The pump did not have to operate all the time, since as a pressure tank, it also belonged to the system. For one a-Si module, 4.2 l of water and 1.75 Wh pump energy were used (from 9:00 am – 5:00 pm) during the cooling period.

For determining the daily energy actually produced the above-mentioned 4.6-kW a-Si PV system in Balatonudvari was used. The plant, situated at a distance of 44.6 km from Keszthely, is equipped with an online monitoring station with production data. In order to calculate the average daily production three ideal days were selected in August (August 01, 10, 28, 2015).

In *Table 5*, the energy production of the PV system determined for the given days on the basis of the available hourly actual energy production data series is shown. It was established that 6.5% of the average daily energy produced could not be used for cooling due to the characteristics of the cooling method, since no reaction to cooling was detectable before 09:00 am and after 05:00 pm. According to our measurements, a minimum global radiation of 450 W/m^2 at an air temperature of 20 °C and 390 W/m^2 at an air temperature of 30 °C is necessary to operate the cooling system. For this reason, the actual significance of water cooling for energy generation decreased from 3.6% to 3.4% on a daily basis. If the 1.75 Wh energy necessary for the pump is deducted from the energy produced daily, the actual energy gain decreases to 2.7%.

Table 5. Daily production data of the 4.6-kW PV field in Balatonudvari

Time (day)	**Actual daily energy production (7-20) (kWh)**	**Energy produced during the cooling period (9-17) (kWh)**	**Released 3,6% extra energy during cooling period (9-17) (kWh)**	**Total energy production with cooling (kWh)**	**Actual extra energy during cooling period (kWh)**	**Daily amount of energy that cannot be used for cooling (%)**	**Actual daily extra energy (%)**	**Average daily extra energy (%)**
Aug 1, 2015	25.0	23.3	24.2	25.9	0.8	7.3	3.4	
Aug 10, 2015	23.1	21.5	22.3	23.9	0.8	7.3	3.4	3.4
Aug 28, 2015	23.5	22.4	23.2	24.3	0.8	4.9	3.4	

3.6. Hard water treatment

The protection against limescale is necessary for the applied cooling method, since limescale is deposited on the glass surface of the PV modules. Ion-exchange polymers do not solve the problem completely. Therefore, it is advisable to apply a reverse osmosis water purifier.

4. Summary

Two different techniques (sprinkling and flowing water cooling) for cooling a-Si modules and a panel were examined in the summer period to establish their average extra performance increase thanks to the cooling process. The performance increase in the case of the cooled unused amorphous silicon solar module was +3.6% compared to the control a-Si module. Our experiments confirmed the results of *Skoplaki* and *Palyvos* of 2009, since in the case of the cooled a-Si module, an average performance increase of 0.3% for every 1-°C decrease in module temperature was observed.

It was found that compared to the control a-Si module, the average performance of the six cooled, 11-year-old, ground-mounted a-Si modules was 3.8% higher during the measurements. For the unused a-Si module this value was + 3.6%, meaning that the reaction to cooling was almost the same after 11 years of use.

The grid-connected PV system tests showed that increases in power were detectable not only in PV modules but also in the inverter-connected 11-year-old amorphous silicon panel.

Based on data from the PV system in Balatonudvari it was established, that 6.5% of the average daily energy produced could not be used for cooling due to the characteristics of the cooling method, since no reaction to cooling was detectable before 09:00 am and after 05:00 pm. According to our measurements, a minimum global radiation of 450 W/m^2 at an air temperature of 20 °C and 390 W/m^2 at an air temperature of 30 °C is necessary to operate the cooling system. For this reason, the actual significance of water cooling for energy generation decreased from 3.6% to 3.4% on a daily basis. If the 1.75 Wh energy necessary for the pump is deducted from the energy produced daily, the actual energy gain decreases to 2.7%.

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