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Technical-economic study of cooled crystalline solar modules

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ABSTRACT

Methods of cooling monocrystalline and polycrystalline solar modules with water vaporizing are analysed in the paper regarding the effects of temperature on performance and its economic relations. Since water usage may present a significant cost the aim of the research was to create a cooling system that operates without loss of flowing water. Results are evaluated from technical and economic points of view in relation to several countries based on systems with 5 kW capacity. Ideal setting of spray heads at 2 bar pressure was achieved with a distance of 0.26 m between the spray heads. In our experiment, a temperature following procedure was tested manually. Due to this procedure, the surface of the module can be cooled with an average temperature value that is calculated after cooling, depending on the temperature of the control solar module. Analysing the daily data of monthly production the number of "ideal days" in a given month were estimated. Comparing the temperature decrease as a result of vaporization measured in summer and in autumn showed no significant difference. The results achieved confirm the connection between temperature change and efficiency change of monocrystalline and polycrystalline solar modules (0.5%/1 °C), discussed in previous scientific literature. Effective application of solar module cooling systems is around 10–15% more expensive than the cost of systems without cooling. In general, under current economic conditions the operation of cooled solar modules is viable mainly in South European countries.

1. Introduction

Since the energy demand of mankind increases continuously, utilization of renewable energy resources is increasingly important besides reducing environmental effects. Solar energy is a clean and sustainable energy resource available in huge volume with greatest potential for all humans (Sahu, 2015; Hosenuzzaman et al., 2015). Around $8 \cdot 10^8$ TW h energy arrives to the surface of the Earth from the Sun each year equalling a potential around 8000 times greater than the energy demand of the world (Roth, 2005).

In recent years the distribution of solar modules developed rapidly mainly due to decreasing production costs, fast technological development and state support introduced in several countries. Nowadays the production costs of the photovoltaic (PV) systems and therefore their price is decreasing as well so the installation of the PV systems has shorter return time of investment. According to the data of Renewables, 2015 GSR the total installed performance of solar PV systems was 23 GW in 2009. This capacity increased to 117 GW by 2014 (REN21, 2015; IEA, 2014).

Spreading of solar PV systems has been intensified since the turn of the millennium due to the decreasing investment costs and the development of the technology. In recent decades certain examples show an increase of 40–90% of the total installed performance of installed systems with 40% decrease of investment costs in a year (REN21, 2015; Jäger-Waldau et al., 2011; Jäger-Waldau, 2013, 2011). Further reduction of investment costs can be achieved only by significant development of the production technology or by finding new processes or basic material.

Silicium based crystalline solar modules are the most widespread worldwide. These types react most sensitively to temperature rise influencing negatively electric energy production. As a result, one of the most effective methods of enhancing performance is to cool down the solar modules. In aim of this research was to study the effects of cooling with water as water is capable of releasing significant amount of heat. For this reason a vaporizing cooling system was created.

Several factors can influence the efficiency of utilizing solar energy arriving onto the Earth (Garcia and Balenzategui, 2004).

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One of the important factors in the case of solar modules is temperature undulation caused by the changing of daily temperature and global irradiation (Skoplaki and Palyvos, 2009; Alami, 2014). During hot days in Hungarian climatic conditions the temperature of solar modules may reach 60–70 °C. Due to its high temperature, the energy production of solar modules decreases, however, this could be solved by various cooling technologies (Chandrasekar et al., 2015). According to Bahaidarah et al. (2013, 2016), Zaoui et al. (2015), the performance of photovoltaic modules depends strongly on the temperature of operation.

Efficiencies in electricity production of 25.6% ± 0.5% and 20.8% ± 0.6% can be found in the case of monocrystalline and polycrystalline solar modules available in the market and their share of the market is around 85–90% due to their reliability (IEA, 2014; Green et al., 2015; Cosme et al., 2015; P.Corporation, 2014; Verlinden et al., 2014). The produced heat is not only lost but it also reduces the amount of producible electric energy. High module temperature limits the current energy production in the short-term and accelerates the ageing of solar modules in the long-term (Ndiaye et al., 2014; Kahoul et al., 2014). Reduction of efficiency may vary according to the type of the solar module. In the case of silicium based crystalline models, efficiency decreases by 0.5% with 1 °C of temperature increase (Skoplaki and Palyvos, 2009; Chandrasekar et al., 2015; Radziemska and Klugmann, 2002).

Simultaneous with the universal application of solar modules and the increasing number of installations research and development activities focusing on avoiding and solving the short-term and long-term efficiency decrease mentioned above become more of an issue. For this various active and passive cooling procedures can be applied with which the operation temperature of solar modules can be controlled (Elnozahy et al., 2015; Du et al., 2012). According to Chandrasekar et al. (2015), four groups of cooling techniques can be identified, namely air based, water based, heat exchanger/coolant based (Ji et al., 2008) and heat based categories.

This paper focuses on water based procedures (water vaporizing). In the case of vaporizing with water evaporation decreases the operation temperature of solar modules compared to modules operating in similar conditions without cooling (Abdolzadeh and Ameri, 2009). Change in temperature-efficiency thus temperature-performance is linear (Skoplaki and Palyvos, 2009). Performance of solar modules in shade free, ideal conditions is influenced dominantly by two factors, global irradiation and temperature (Skoplaki and Palyvos, 2009).

According to Skoplaki and Palyvos (2009), 1 °C increase of module temperature results in 0.3–0.5% of efficiency loss in general, however, according to Chandrasekar et al. (2015), this efficiency loss is 0.5% in the case of crystalline solar modules. On a typical summer day with 58 °C of module temperature (Odeh and Behnia, 2009) detected efficiency rise of 4–10% when the module surface temperature reached 26 °C. Similar water vaporizing experiments of Abdolzadeh and Ameri (2009) showed that 23 °C temperature decrease resulted in 17% efficiency increase.

The quantity of energy which can be produced by a solar PV module mainly depends on its type and composition, the joint effects of the location and the current environmental factors. Modules were tested and certified under laboratory conditions where their nominal performances were established (STC - Standard Test Conditions, AM = 1.5 air mass, 1000 W/m^2 solar radiation, and 25 °C module temperature). However, these conditions were not given during operation, so PV modules typically do not reach their nominal performance (T.S.A.Inc., 2015).

Fluctuating energy production is a severe disadvantage of photovoltaic modules as it shows a great difference depending on the period of use in terms of both the given part of the day and the actual season. Off grid systems can surmount this disadvantage only to a limited extent and they call for especially costly electric current storage equipment. In many countries it is possible for even residential customers with household-sized power plants to feed the energy produced by PV modules into the national grid.

In the analysed countries it is possible for residential customers to input energy produced by solar modules into the national electricity network in the framework of Household Size Small Power Plant System (HSSPPS). In the system delivery price of the produced energy is not guaranteed. Instead the electric energy produced by solar modules is bought by the service provider at actual price for electric energy (gross 0.112 EUR/kW h) if electric energy consumption of the consumer is less than the energy it produces and it does not exceed the nominal performance of 50 kW (Pintér et al., 2015; E_ON, 2015a). Above this value, between 50 kW and 20 MW and between 20 MW and 50 MW delivery prices are 0.10 EUR/W h and net 0.09 EUR/kW h respectively (E_ON, 2015b). Differences between prices indicate well that it does not worth for residential consumers to produce electric energy exceeding the consumption of the consumer.

In Croatia residential consumers receive step-like pricing for electric energy supplied into the electricity network according to the following:

- in the case of a system below 10 kW: 0.344 EUR/kW h,
- between 10 and 30 kW: 0.291 EUR/kW h,
- above 30 kW: 0.215 EUR/kW h.

A contract is made between the energetic market operator in Croatia (HROTE) and the producer for 14 years (Z.Energija, 2015; U.Nation, 2012).

Delivery of residential produced electric energy in Spain is composed of two gears giving pricing of 0.283 EUR/kW h and 0.15675 EUR/kW h until 20 kW of system capacity and above 20 kW respectively. Contracts cover 30 years (P.Magazine, 2015a).

In Australia residential consumers can also input energy produced using solar modules into the national electricity network. Most solar PV systems have a performance of 1.5–10 kW. Delivery price does not depend on capacity (Synergy, 2015; Martin, 2013).

In the USA the price of energy supplied into the national network from solar modules is also independent of PV system size. In the case of San Diego (California) the time frame of the contract is 10, 15 or 20 years while in the case of Miami (Florida) it is 20 years (O.U.C. (OUC), 2015; P.Magazine, 2015b; C.P.U. Commission, 2015).

2. Methods and details of the technical and economic assessment

The aim of the current research was to create a vaporizing cooling system that on the one hand would operate without loss of flowing water and on the other hand focuses only on the cooling effect resulting from the heat of the evaporation of water and on the achieved efficiency increase and performance maximum. Technical and economic evaluation of the results was compared to solar modules without cooling. Justified application of vaporizing cooling systems is determined in the case of Hungary and of other countries with more favourable climatic conditions and a reliable regulation of green energy delivery. Another important factor for the application of the vaporizing technology was the access to water nearby for water supply.

Countries and locations analysed were the following:

- Hungary (Keszthely and Siófok)
- Croatia (Šibenik)
- Spain (Murcia)

- Australia (Broome)
- USA (San Diego)
- USA (Miami)

Results were evaluated regarding technical and economic points of view in comparison with monocrystalline and polycrystalline solar modules operated without cooling. Following are the details and conditions regarding the assessed active cooling method.

2.1. Technological background

Comparative experiments were carried out in the summer and autumn of 2015 outdoors, in real climatic conditions using monocrystalline and polycrystalline solar modules with the same type and performance, with 50 W nominal performance, installed on ground fixed platforms at the same location. One set of the modules had no cooling while the other set had cooling using spray heads (Table 1, Fig. 1).

During the experiments measurement of the solar modules was continuous using one 12 channel and one 16 channel PicoLog data logger. These instruments allowed second-based, continuous data recording by a PC. Regarding the control solar module surface temperature was measured at one point (in the middle of the top third of the module) and voltage and current intensity were also measured. Surface temperature on the solar module with the spray head was measured at two points. Sensor 1 was located in the middle of the top third of the module (facing the solar module) and sensor 2 was located at the left edge of the bottom third of the module. Apart from surface temperature, the temperature of the vaporized water, voltage and current intensity were measured. Cooling of the solar module was controlled by a thermostat measuring the surface temperature of the module. In order to minimize the amount of vaporized water spray heads were operated periodically so that only the amount of water necessary for vaporization was sprayed. Water entered the circulation via an ion exchanging resinous water softener and flowed into the hydraulic spray head with a rotating shaft.

For measuring temperature Pt 100 sensors were applied. Calibration of the complete measurement circle was performed using a digital LM 35 based precision temperature measuring sensor the voltage change of which is linear (10.0 mV/°C). Considering its accuracy, difference can be ±1/4 °C and ±3/4 °C between −55 °C and +150 °C respectively.

Additionally, the following technical-environmental parameters were determined:

- Voltages and current intensity (Voltcraft VC607 professional multimeter was used that was controlled prior to the measurements using an LT1021 voltage reference (10.000 V ± 5 mV).
- Relative moisture content of air (HYTE-ANA-1735).
- Global irradiation (Eppley Black and White Modell 4–48 pyranometer, certified by the National Meteorological Survey).
- Wind speed (JL-FS2, 4–20 mA, aluminium device with 3 spoons).

Analogous electric signals available during the measurement reached the input of PicoLog after appropriate fitting.

In the case of solar modules, Maximum Power point Tracking (MPPT) can be performed in several ways with the help of which higher efficiency and energy yield can be achieved. In the course of the measurements True Maximum Point Seeking (TMPS) artificial load was applied that was operated on oscillation basis. With keeping voltage multiplied by current intensity at the maximum value the solar module was operated at the maximum energy point Water supply required by the cooling of solar modules was carried using a pump at the measurement point, from a dug well with filtered and softened groundwater (Fig. 2).

Performance of the household water plant pump motor used for the experiment is 750 W, its consumption is 750 W h and the pump transports 30 L/min (1800 L/h) water. Operation of the pump is not continuous as a pressure tank is connected to it. In the case of spray heads used in the research, ideal setting is achieved using two pieces of solar modules with almost homogeneous sprayed surface at pressure of 2 bars. Distance between spray heads is 0.26 m and their range varied between 1.0 m and 1.2 m depending on weather conditions.

2.2. Meteorological background

Intensity of solar radiation and the price for delivery electricity significantly vary country-by-country resulting in significant differences in assessing cost efficiency of the realization of the systems.

Table 2 presents global irradiation conditions of various countries together with electric energy that could be produced by a 1 kW solar PV system. Data of Photovoltaic Geographical Information System and PV Watts were used. Data of the former included 10 years long real climate data series while the latter were real climatic data series of several decades (P.G.I.S.-I. Maps, 2015; NREL, 2016; SolarGIS, 2015).

In the course of the experiment carried out in Hungary the performance increase as a result of cooling was around the same both in summer and autumn in the measurement time period therefore these values are suitable for analysing the estimated operational period of the cooling system. This is in close connection with the linear connection between efficiency and temperature and thus the change of temperature and performance (Chandrasekar et al., 2015; Radziemska and Klugmann, 2002). Measurements indicated that around 450 W/m^2 is required for applying the cooling system in the case of a minimum air temperature of 20 °C while in the case of 30 °C air temperature 390 W/m^2 is required. In order to determine ideal energy production time periods solar PV systems with internet based remote control and/or production data measured daily (thus production data are available by hours) were used.

For determining the applicability of the cooling system the following online software were applied:

- Photovoltaic Geographical Information System,
- PVWatts Calculator,
- WeatherSpark weather modelling system.

Data of WeatherSpark originate from the National Climatic Data Centre, the Norwegian Meteorological Institute, the World Weather Online and from more than 4000 weather stations and from airports having METAR meteorological stations (giving

Table 1
Parameters of the studied solar modules.

Parameters	Monocrystalline solar module	Polycrystalline solar module
Country of origin	Germany	Italy
Producer/distributer	Prevent GmbH	Energiesolaire100
Model	SM636-50	SL50TU-18P
Nominal performance (Pm) (W)	50	50
Performance tolerance (%)	±3%	±3%
Nominal voltage (Vmp) (V)	18.18	19.12
Nominal current (Imp) (A)	2.8	2.62
Idle running voltage (Voc) (V)	23.17	22.68
Idle running current (Isc) (A)	3.08	2.80
Size of module (mm): (width × height × depth)	510 × 680 × 35	545 × 668 × 28

Fig. 1. Measurement location for the studied crystalline solar modules in Keszthely, Hungary (Zsiborács et al., 2015).

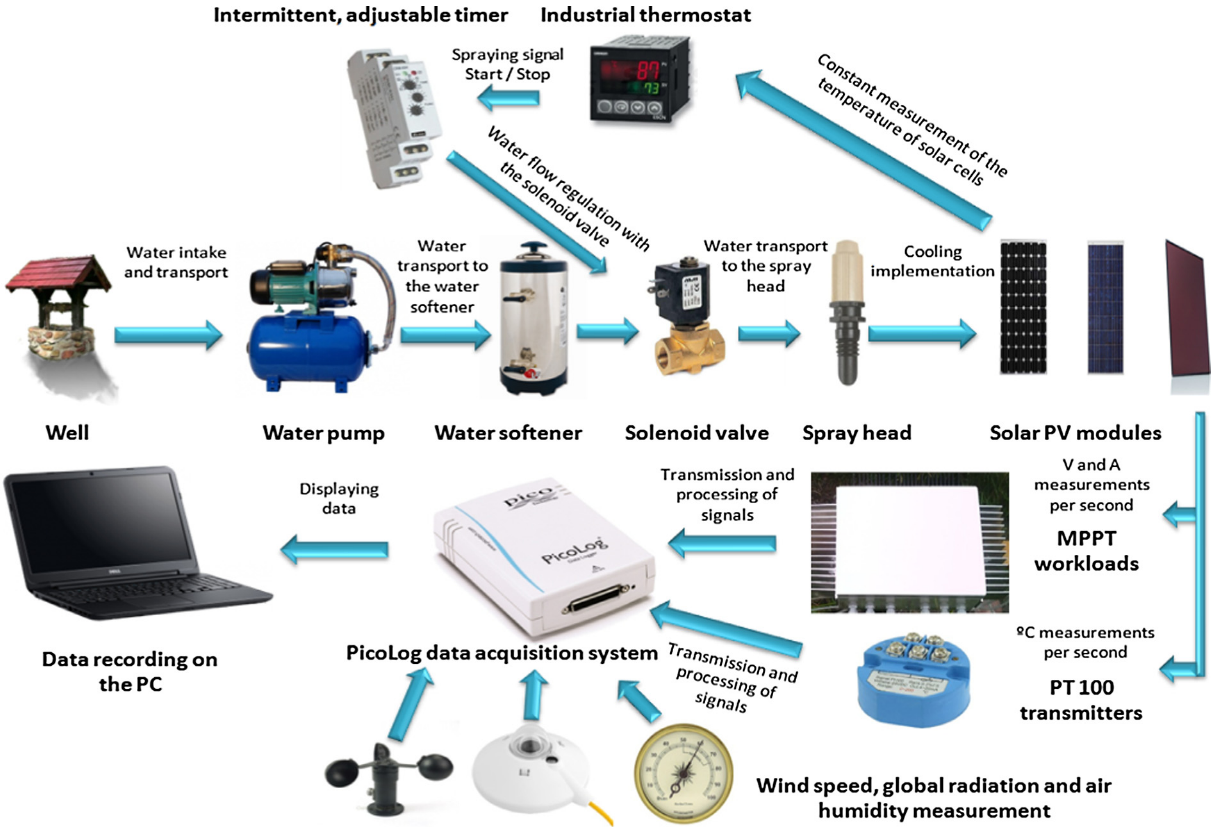

Fig. 2. The scheme of the measurement procedure (Zsiborács et al., 2015).

Table 2
Data of global irradiation and electric energy production in the studied countries. *Source*: P.G.I.S.-I.Maps (2015), NREL (2016), SolarGIS (2015).

Subject	World	Hungary (Keszthely)	Croatia (Šibenik)	Spain (Murcia)	Australia (Broome)	USA (San Diego)	USA (Miami)
Average global irradiation of country (kW h/m^2/year)	800–2800	1200–1360	1200–1600	1200–1950	1100–2300	1200–2200	
Average electric energy production of the studied town in the case of 1 kW solar PV system (kW h/year)	–	1280	1580	1720	1863	1763	1568

regular actual weather conditions related to flying). Using this software detailed and reliable data were acquired regarding the meteorological conditions of the given settlement (P.G.I.S.-I. Maps, 2015; NREL, 2016; WeatherSpark, 2015a–f).

Using the cooling system is practical when the daytime average temperature of the air is at least 20 °C. Daily electric energy production curves of given solar power plants have similar shape to daily global irradiation since primarily this determines energy production.

Analysing the daily data of monthly production the number of "ideal days" in a given month were estimated. This means days when the value of global irradiation was undisturbed. Annual production data were analysed so that the average number of ideal days of the given months were calculated for each studied country. Based on the calculated number of ideal days, the average yield of cooling in the next 15 years was also calculated. Characteristics of the production and cooling periods of the studied countries are presented in Table 3.

Decrease of annual performance in the case of crystalline solar modules was determined to be around 0.5% that is a generally accepted value (Jordan and Kurtz, 2012; Belluardo et al., 2015). An interval of 15 years was studied as operation time because solar PV systems supplying energy into the national network typically demands supervising in every 15 years. Maintenance work needs to be carried out in this time period as well and the inverter should be replaced in every 15 years as well. In the case of systems without cooling at 100% own resources and within 15 years of operation no maintenance costs are calculated while in the case of cooled systems the costs of replacing water filters are incorporated into the calculations. Due to low operation times repair or replacement of pumps (resisting salt water as well) should not be necessary. Economic calculations were performed based on 5 kW solar modules due to the regulation of electric energy supply. Electric energy prices were based on the above data (Table 4) in the first year of the current calculation (Allenbach and Imobersteg, 2014). Our calculations involved 6% of loss in the system and 35° of dip angle (Pintér et al., 2015).

2.3. Surplus performance of crystalline solar modules

In the course of studying solar PV modules experiments were carried out in every hour in accordance with weather conditions and data were recorded between 9 am and 6 pm. Monocrystalline and polycrystalline solar modules were handled separately.

Proved surplus performance was determined in the given period as follows:

- prior to switching on vaporization,
- final state achieved as the effect of vaporization in the given hour period.

Type and performance of the solar modules are the same based on the data given by the producer. Relative change in the performance of cooled and not cooled modules was studied without cooling in the time period between 1 pm and 5:20 pm on 11th June 2015. Data were recorded by seconds. A two-sample z-test proved that the relative change in the performance of the cooled and not cooled modules of the polycrystalline solar modules is the same (monocrystalline solar module: $p = 0.767$ and polycrystalline solar module: $p = 0.772$).

This made possible that the changes of environmental factors emerged during the cooling process (the changes in the control solar module's performance) could be corrected on the cooled solar module.

The authors had the assumption that protection is required against scaling and/or salty water. Such protection can be achieved using a water cleaner based on reversed osmosis. Required pressure at the spray heads is provided by a dilatational tank (containing the filtered water) after the water cleaner and by an industrial magnetic valve.

In the given hour the higher performance occurred as a result of cooling and the associated relative standard deviation (CV%) were determined. In this study acceptance of the average was allowed at moderate differentiation (CV% = 10–20) due to the variability of weather conditions.

2.4. Economic background in the analysed countries

For the solar PV system with 5 kW nominal performance selected for economic evaluation 20 pieces of 250 W polycrystalline solar modules were used. Length and width of the modules were 1.64 m and 0.992 m respectively. With the use of vaporization it is rationale to place solar modules next to each other lengthwise because in this way six spray heads can supply the appropriate sprayed surface for one module. Appropriate distance is also necessary for the assembly of frames due to potential shades of the installed spray heads.

During the experiments water consumption was measured in day-long operational conditions on 16/06/2015, 07/07/2015, 22/07/2015 and on 08/08/2015.

With the help of the digital thermostat a temperature following process was tested manually that is capable of reducing the temperature of the surface of the module to be cooled by an average value (for the given hour) calculated after cooling depending on the temperature of the control solar module. This solution was simulated best on 7th July 2015 over the time period of cooling between 9 am and 5:50 pm. This method results in maximum efficiency in the cooling period.

In order to determine the volume of vaporized water 4–4 repetitions were carried out measured using a KERN PLS 510-3A type digital scale. One spraying onto the surface of the modules lasted for 0.5 s. Averaging the measurements, 0.01354 kg and 0.0153 kg water was vaporized in one spraying in the cases of monocrystalline solar modules and polycrystalline solar modules respec-

Table 3
Characteristics of production and cooling periods in the studied countries. *Source*: On the basis of data of WeatherSpark (2015a–f), Sunnyportal (2015a–f).

Subject	Hungary (Keszthely, Siófok)	Croatia (Šibenik)	Spain (Murcia)	Australia (Broome)	USA (San Diego)	USA (Miami)
Available annual production period (year)	1.5	3	4	5	3	5
Number of periods and days suitable for 9 h cooling time	June – August, 70	June – August, 85	May – September, 128	September – June, 270	July – September, 83	May – September, 114
Number of periods and days suitable for 8 h cooling time	May, 18	End of April, May, September, 53	From the first third of March, April, 33	July, Augustus, 31	From mid April – June, October, 78	March, April and October, 75
Number of periods and days suitable for 7 h cooling time	–	October, 19	October, November, 32	–	November, 17	November – February, 92
Number of periods and days suitable for 6 h cooling time	September, 13	–	–	–	–	–

Table 4
Bond yield interest rates and delivery price of electric energy in the case of a 5 kW system. *Source*: Investing.Com (2016a–e), T.W.Bank (2015), T.Economics (2015–e), E. S.explained (2016), EIA (2016a,b).

Subject	Hungary	Croatia	Spain	Australia	USA (SD)	USA (M)
Rate of average inflation (2012–2015) (%)	1.79	2.4	0.8	2.22	1.33	
Bond yield interest rate, 15/01/2016[a] (%)	3.88	3.99	2.29	2.89	2.04	
Delivery price for electric energy in the case of a 5 kW system (EUR/kW h, 2015)	0.112	0.344	0.283	0.045	0.082	0.046
Share of green electricity (%, 2014)	7.3	45.3	37.8	13.1	13	

SD: San Diego, M: Miami.

[a] HU, SP, AU 15 years long, while HR and USA 10 years long bond yield interest rate.

tively. This equalled the application of 0.00176 kg of excess water in the latter case. As a result the cooling system of the polycrystalline solar module switched on less frequently in a day due to better effects of cooling (Table 7) and to longer cooling-warming periods. All these finally lead to saving water. Thus in the case of the monocrystalline solar modules 2 spray heads equal the vaporization of water and the well 50 W polycrystalline solar modules sprayed 3.2 L while in the case of polycrystalline solar modules at 50 W detected also the solar pane vaporization of 3 L of water was achieved.

In the analysis, five countries' investment conditions were compared. In case of Hungary, the cooled polycrystalline modules' actual water usage and average decrease in temperature in the given location and time interval were considered. In the other countries analysed average daily surplus energy yield was calculated for 3 days of every ideal month based on the solar irradiation data of the given town. Due to different geographical locations the ideal operational time period of the cooling system was corrected based on the data of the Photovoltaic Geographical Information System, the WeatherSpark weather modelling system and the daily performance curve of the solar PV system in the given town (P.G.I. S.-I. Maps, 2015; WeatherSpark, 2015a–f; Sunnyportal, 2015a–f).

Table 4 shows the bond yield interest rates and the delivery price of electric energy in the studied countries. There is a close connection between the national green electricity prices and the shares of renewable electricity. In case of the US and Hungary the share of solar energy from green electricity is under 1%, but the relatively cheap normal electricity prices could explain the low green electricity feed-in tariffs.

Table 5 presents the equipment required for establishing a 5 kW solar PV system – additional equipment of the cooling system for a cooled system – and their investment costs in the studied countries. Investment costs for non-cooled solar modules are extremely high in the US while differences in other countries involved in the analysis are below 20%. Costs of installing a cooling system are much more even among countries analysed. Investment costs of both cooled and not cooled solar PV systems are lowest in Hungary.

Analysing operational costs it was assumed that water-charges were not applied (rainwater, existing driver bell) therefore only the cleaning, transport and spraying of water involves operational and investment costs. Price change for electric energy were forecasted using the average inflation value of the years 2012–2015 while expected yield was calculated according to the 10 or 15 years long bond yield valid at 15th January 2016 in the given country. Inflation could be important because of changing fixed delivery prices while state bond yield is required to calculate expected future yield.

Based on dynamic return indicators the net present value (NPV), profit index (PI) and discounted payback period (DPP) of 5 kWp nominal performance cooled and non-cooled solar PV systems were determined according to internationally applied methods for economic calculations (Brealey and Myers, 2003). With the help of calculated indexes – bearing in mind the specific characteristics of the particular region – important conclusion could be drawn regarding the systems analysed.

3. Experimental results and their economic evaluations

In the recent section experience related to the cooling system, characteristics of the crystalline solar PV modules during cooling in the summer period and the economic characteristics of the cooling of 5 kW solar PV systems are presented.

3.1. Effect of cooling on the operation of the analysed crystalline solar modules

Average data measured when the vaporizing system was used are presented in Tables 6 and 7 showing well performance excess and temperature decrease achieved in the given hour with the help of periodical spraying in summer.

Temperature decrease due to vaporizing at 5% significance level showed no significant difference ($p > 0.05$) between measurements at summer and autumn and this was justified using a two-sample *t*-test ($p = 0.059$ in the case of monocrystalline solar module and $p = 0.169$ in the case of polycrystalline solar module). Analysing performance excess resulted by cooling, similar values were detected in the two periods ($p = 0.397$ and $p = 0.722$ in the cases of monocrystalline and polycrystalline solar modules respectively). Thus summer measurements in Hungary showing higher number

Table 5
Investment conditions for establishment and required material and equipment for cooled and non-cooled 5 kW solar PV systems. *Source*: Based on quotations from Hungary (2015), S.Energija (2015), F.E.Solar (2015), A.S.World (2015), FreeCleanSolar.com (2015).

Subject	Hungary	Croatia	Spain	Australia	USA
Size of solar PV system	1.5 kW				
Required equipment and material for non cooled systems	Solar module, inverter, frame on roof, cable with outlets, additional electric outfit, costs of installation and transportation				
Total gross (EUR)	7136	8749	8631	7912	14,352
Required additional material and equipment for cooled solar PV systems	Reversed osmosis water cleaner, industrial magnetic valve, pipes with joint elements, spray heads, household water pump, filters, dilatational tank, intelligent digital thermostat with temperature sensor, costs of installation and transportation.				
Total gross (EUR)	874	1048	1092	1092	1136

Table 6
Characteristics of monocrystalline solar modules during cooling in summer.

Time interval (h)	Average global irradiation (W/m^2)	Average wind speed (m/s)	Air temperature (°C)	Relative moisture content of air (%)	Average temperature decrease of vaporized module (°C)	Performance excess as a result of cooling		Changing of performance in the case of 1 °C decrease of the temperature of vaporized module (%)
						Average (%)	CV (%)	
9–10	437.3	0.1	27.5	36.8	4.6	3	19.7	0.7
10–11	579.3	0.1	27.9	37.9	7.5	3.5	17.7	0.5
11–12	780.3	0.2	30.4	36.3	11.9	6.8	13.2	0.6
12–13	894.2	0.3	30.1	36	14	7.3	16.6	0.5
13–14	959.5	0.3	33.4	33.2	13.9	8	17.3	0.6
14–15	919.1	0.2	35.1	32.4	15.3	8.5	17.5	0.6
15–16	833.5	0.2	35.2	31.8	16.3	8.8	15	0.5
16–17	672	0.1	34.3	34.7	13.2	6.7	17.1	0.5
17–18	509.1	0.2	30.9	34.1	12.1	5.4	19.4	0.4
Average								0.5
CV, %								10.8

Table 7
Characteristics of polycrystalline solar PV modules during cooling.

Time interval (h)	Average global irradiation (W/m^2)	Average wind speed (m/s)	Air temperature (°C)	Relative moisture content of air (%)	Average temperature decrease of vaporized module (°C)	Performance excess as a result of cooling		Changing of performance in the case of 1 °C decrease of the temperature of vaporized module (%)
						Average (%)	CV (%)	
9–10	422.5	0.2	28.1	38.6	6.2	4.2	10.6	0.7
10–11	560	0.1	27.4	39	7.8	4.3	18	0.6
11–12	777.3	0.5	31.3	36.6	13.8	7.3	16	0.5
12–13	888.8	0.3	31.2	35.7	16.3	7.8	18.9	0.5
13–14	951	0.3	32.1	33.9	17.6	9.4	15.4	0.5
14–15	922.9	0.2	34.7	33.2	19.5	7.7	19.8	0.4
15–16	836.6	0.2	34.3	33	18.2	8.3	18.5	0.5
16–17	682.4	0.2	34.7	33	17.6	7.4	19.2	0.4
17–18	517.4	0.1	31.3	35.8	14.4	7.2	16.5	0.5
Average								0.5
CV, %								15.6

of elements were suitable for analysing the estimated operational time periods of the cooling system. Results of this study support the data of Chandrasekar et al. (2015), Radziemska and Klugmann (2002), Skoplaki and Palyvos (2009) as an average performance improvement of 0.5% in relation to 1 °C of temperature decrease of the sprayed water could be detected in the cases of monocrystalline and polycrystalline solar panels, as well.

The pump tank used for the experiment took 3 L of water and used 1.25 W h for cooling one module between ~9 am and 18 pm. Based on the measured water usage values (corrected for the given time periods) we estimated energy consumptions of 1.21 W h, 1.08 W h and 0.96 W h in the cases of 8 h cooling, 7 h and 6 h cooling respectively.

Regarding optimal days of irradiation at all year round and energy need for the operation of the pump is also calculated for daily surplus production the realized annual energy surplus accounts for 2.2% for Hungary (Keszthely and Siófok), 3.3% for Croatia (Šibenik), 3.8% for Spain (Murcia), 6% for Australia (Broome), 3.3% for US (San-Diego) and 5.6% for US (Miami).

3.2. Economic results of the cooling system on the analysed crystalline solar modules

In total considering typical investment costs under the climatic conditions of the studied countries, the electric energy prices and other economic parameters with the calculated and typical annual utilization of the cooling system the economic indexes of the cooling system are unfavourable compared to those of the reference solar power plant without cooling (Table 8).

Differences among the studied countries, however, are significant. Investment costs are lowest in Hungary, but payback indexes hardly reach the economic level. The cooling system increases payback time by 2.4 years.

Conditions of solar irradiation and delivery price are relatively high in Croatia and Spain and investment costs are only slightly higher than in Hungary therefore solar PV investments looks exceptionally favourable. Installing a cooling system increases payback time by only half a year and remain below 5 years.

In the case of Australia the annual utilization of the cooling system is outstanding, investment costs and delivery prices are relatively low. As a result of the latter installing the cooling system is not economic.

Costs of investment is most expensive in the US but irradiation parameters are preferable while delivery price for electric energy is only slightly higher than in Australia therefore payback time is worst in Miami and making profit cannot be expected in San-Diego either.

In summary the results of the economic analysis of cooled solar modules show a high correlation with electric energy delivery price at different locations.

Based on the results of investment analysis, investment of both the cooled and non-cooled versions of solar modules can be recommended in the studied European countries (towns) although economic indexes of cooled systems – especially in Australia and

Table 8
Investment-efficiency indexes of studied solar PV systems at the locations involved in the analysis.

Subject	Hungary	Croatia	Spain	Australia	USA San Diego	USA Miami
5 kW solar PV system without cooling						
Net present value (NPV) [EUR]	1620	25,378	22,564	−2268	−4591	−9469
Profitability index (PI)	1.22	3.90	3.61	0.71	0.68	0.34
Discounted payback period (year)	12.2	3.8	4.2	21.0	22.1	44.1
5 kW solar PV system with cooling						
Net present value (NPV) [EUR]	224	24,152	20,623	−6183	−7 99	−13,293
Profitability index (PI)	1.02	3.46	3.12	0.31	0.52	0.14
Discounted payback period (year)	14.6	4.3	4.8	47.9	28.4	105.8

Table 9
Limit values of economic realization/operation of solar PV systems in the studied countries, ceteris paribus.

Subject	Hungary	Croatia	Spain	Australia	USA San Diego	USA Miami
Conditions of a 5 kW non-cooled solar PV system						
Maximum investment cost (EUR)	8756	34,127	31,195	5644	9761	4883
Required ratio of investment support (%)	–	–	–	29%	32%	66%
Conditions of a 5 kW cooled solar PV system						
Maximum investment cost (EUR)	8234	33,949	30,346	2821	8189	2195
Required ratio of investment support (%)	–	–	–	69%	47%	86%
Economic result that could be reached using cooling (EUR)	−522	−178	−849	−2823	−1572	−2688

USA – show a much poorer results than those of non-cooled solar modules (Table 8). In these countries establishment of cooled solar PV systems in the current natural and economic environment could be made competitive only with significant (47–86%) public investment support. Installation of cooling into the system in Croatia can be made economic with a minimal (17%) public investment support (178 EUR). Increasing electric energy prices in the future make the application of solar PV cooling in the studied European countries highly economic in the future. In the two other overseas countries this can be achieved in the case of more drastic economic/technical changes (Table 9).

4. Conclusions

The results achieved confirmed former statements of the literature that there is a high correlation between the change of temperature and efficiency (0.5%/1 °C) in the cases of monocrystalline and polycrystalline solar modules.

Effective application of solar module cooling requires significant investment costs (874–1136 EUR) even in the studied residential size (with 5 kW capacity) that makes non cooled solar PV systems 10–15% more expensive. Intensity of solar irradiation and delivery price of electric energy differs significantly in the studied countries therefore the economic results are significantly different in the studied countries and show strong correlation with the share of green electricity of the given countries.

In conclusion, operation of solar modules with or without cooling is economic primarily in South European countries. Economical installation and operation of solar modules in Australia and the US is mainly impeded by low price for electricity and high installation costs respectively. Cooling of solar modules is not economic in itself in either case, however, with advantageous natural conditions and regulation (Spain, Croatia) it increases only slightly – otherwise fast – payback time. Volume of required investment, however, is much smaller in Hungary (10–50%) than in the rest of the studied countries.

In the case of systems where payback time is ideal cooling from already existing source of water offers a real alternative for increasing the performance of solar modules that cannot be extended due to the lack of space in the European countries involved in the research (Hungary, Croatia, Spain). Currently treated sewage water poor in inorganic and organic matter formed in biogas plant combined with algae systems as free sources of water is not available. This might be important in reducing water costs in cleaned sewage as well. This could have significant role not only in reducing water costs of solar modules but also in the electricity supply of the algae ponds.

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