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

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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

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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

Table 1
Share, best achieved efficiency and characteristics of the currently available photovoltaic cells.
Source: Own collection

Generation	Plant/solar cells	Market share	Efficiency (%)	Notes	Reference
I (Crystalline Si)	Si (crystalline)	85–90%	22–26	Most widespread, reliable, affordable price	[6,10,33,34]
	Si (multicrystalline)		18–20		
II (Thin-film)	Amorphous Si	10–15%	14–15	Cheapest	[6,10]
NEXT	Poly-Si thin film		16		
	II–VI Compound thin film		18.8	Compromise between price and reliability, radiation resistance	
	Concentrator tandem		32–33		
Space	GaAs		23–26	Highly reliable, high price	[6,33]
	InP		22		
	Tandem		33		
New materials	TiO_2	Under 1%	11	Rapid development, serious potential	[6]
	Carbon		3–4		
	Dye		9–15		[10,33,35]
	Organic		2–9		[6,11,33,36]
	C3 plants	–	3,5	–	[7]
	C4 plants	–	4,3	–	
	microalgae	–	5–7	–	

characteristics, power point tracking, i.e., inverters also play a significant role in reaching the proper performance level [18].

By realising the potential in solar energy, the most diverse utilisation methods have been developed, ranging from solar-powered aircraft [19] to hydrogen production [20], disinfection of drinking water [21], wastewater management [22] and desalinisation technology [23]. The type of photovoltaic modules have to be taken into consideration in all cases, as it significantly affects the amount of energy to be produced.

Today, as a result of the increased efficiency of technology, the manufacturing costs and retail price of components of photovoltaic modules are becoming more affordable, resulting in reduced payback periods on the investment.

As a result of technological development and the above described reduction of investment costs, there was a huge increase in the penetration of photovoltaic systems around 2000. During the last decade, there were periods when the acquisition cost of an installed system decreased by 40% a year, while there was a 40–90% increase of the total installed capacity [24–26]. It can be concluded that the investment cost of photovoltaic systems has approached the lowest possible cost level, unless of course significantly more developed manufacturing technology can be applied or newer and less expensive raw materials become available. Simultaneous production of heat and electricity may contribute to further potential for development [27]. For efficient and economic operation of solar systems, it is essential to size the systems properly by stochastic modelling of [28].

The only significant problem of photovoltaic module technology is the storage of the produced electric energy which is often very expensive and, in other cases, connection must be established to the electrical grid to provide buffer capacity (e.g. in the case of household-sized power plants). As opposed to photovoltaic module systems, energy storage has been solved by nature since the beginning in the form of photosynthesis. The process of photosynthesis, which also has an energy storage function, could provide a basis for comparison with generally widespread, synthetic photovoltaic modules. Moreover, it could have a crucial significance in the practical use of the photovoltaic module cooling method examined by the authors of this paper.

Photosynthesis is the natural method of converting solar energy to chemical energy, during which the plant incorporates and stores water and carbon dioxide in its own system while it produces oxygen [14,29]. This process – which is the basis of biomass production – is performed by plants at different levels of efficiency [30].

The theoretical limit of the light use efficiency of photosynthesising organisms is around 12%. Of these, the highest efficiency is reached by intensive field crops such as C3 plants (produced in temperate climate zones, 3.5%), C4 (tropical) plants (4.3%) and algae (5–7%) [7]. Of the various photosynthesising organisms, microalgae are able to achieve the highest yield [14]. Since algae can reach a more favourable photosynthetic efficiency, their intensive production technology calls for a significant amount of electric energy in order to maintain effective and productive operation. This energy need can be covered by renewable energy sources, such as solar energy, more specifically with water cooled photovoltaic modules. The significant water requirement of cooled photovoltaic module-based energy production is a second point of relevance. This water demand can be fully covered by the water produced during wastewater purification with algae.

Systems integrating various sustainability elements are expected to become more preferred in the future. Schaubroeck et al. [31] performed examinations aiming at energetic self-sufficiency, while there are also technical literature resources focusing on the integration of high energy need wastewater purification and photovoltaic module energy production [32].

In parallel with the rising competition of the photovoltaic module market, researchers also constantly deal with new raw materials and research and development activities focusing on increasing efficiency [11]. In addition to the classic, most frequently used silicon-based solar cells, there are numerous other types in use or in the experimental phase. Organic solar cells are based on photosynthesis and they produce energy by incorporating organic matter. Table 1 shows the efficiency of each photovoltaic cell type. For comparison reasons, the table also shows the efficiency of plant photosynthesis and other explanatory information.

As can be seen in Table 1, the reliable and affordably priced silicon-based crystalline has the highest share (more than 85%) in the world market. Accordingly, the analysis described in this paper also focuses on this photovoltaic module type.

Recently, there has been an intensive research and development activity aiming at hybrid solar cells. In this case, the word 'hybrid' has two possible meanings. Accordingly, there are two types of solar cells. One of them is used if the equipment used for the utilisation of solar energy produces electricity and also makes it possible to utilise the resulting heat energy [37,38]. According to the technical literature sources, the phrase 'hybrid solar cells' may refer to the construction of solar cells, i.e., the given solar cell type might contain organic and inorganic constituents [39].

It is important to emphasise that plant photosynthesis is not electric energy production, but the production of organic matter which constitutes plants as energy production calls for further transformation in power plants at an efficiency level of around 30–45%. For this reason, this process cannot be directly compared to

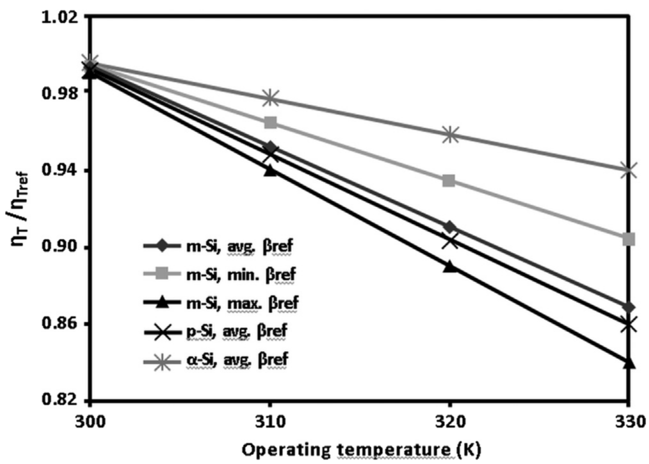

Fig. 1. Correlation of η_T/η_{Tref} in the case of silicon-based PV modules.
Source [16].

the efficiency of the energy production provided by classic photovoltaic modules. However, plants – as opposed to photovoltaic modules – are able to store solar energy. At the same time, electric energy able to be readily mobilised is produced as a result of the photo-electric transformation process of photovoltaic modules [7].

Bio-photovoltaic cells (BPV) use an innovative technology based on photo-bioelectrochemical processes which may provide new opportunities to utilise solar energy by making use of the photosynthetic activity of autotrophic organisms. Currently, the energy production efficiency of this technology is low. However, according to various technical literature sources, there is a significant potential in this technology after the electrochemical interaction of plants and artificial material is understood and properly researched. It is a further positive aspect that this technology has low material costs. In a study performed by De Caprariis et al. [40], the algae species *Chlorella Vulgaris* was used to create an energy-producing bio-photovoltaic cell. In the paper, the authors point out the energy production potential lying in eukaryote organisms, especially the use of photoautotrophic microorganisms.

Due to the significant technological innovation, the generation which follows crystalline photovoltaic modules was expected to gradually gain ground with an increasing market share. However, these expectations proved wrong, as the global market share of these photovoltaic module types – including thin film solar cells – decreased from 15% (2009) to 10% (2013). “Thin films (TF) are based on cadmium telluride (CdTe), copper-indium-gallium-selenide (CIGS), or amorphous silicon (a-Si), plus some variants [10].”

In addition to the thin film technology, which has a 10% global market share, there are constant research and development activities related to various materials, manufacturing procedures and innovative technologies. These efforts include the development of organic photovoltaic modules or modules manufactured with nanotechnology. Efficiencies of 11% for organic cells and 12% for dye-sensitised cells have recently been achieved [10]. The different generations of photovoltaic module technology and the novel development directions were summarised by Badawy [41] and Hosenuzzaman et al. [6].

In addition to finding new raw materials and developing manufacturing technology, the development of photovoltaic module technology can advance mainly in the field of cooling photovoltaic modules and energy efficiency improvement. For this reason, this paper describes the authors' experiments in this field.

2.2. The impact of cooling on performance

The efficiency of using solar energy reaching the Earth can be affected by several factors. In the case of photovoltaic modules, the fluctuation of module temperature arising from the change of daily temperature is one of the main factors [42,43]. On warm days, module temperature may reach up to 60–70 °C. The energy production of photovoltaic modules drastically decreases above a specific module temperature. The various cooling technologies provide solutions to this phenomenon.

According to [44], the performance of photovoltaic systems greatly depends on operation temperature. In general, it can be stated that photovoltaic systems transform only 4–17% of incoming solar energy to electric energy, while the majority is transformed into heat energy without being utilised [45]. The produced heat is not only lost, but it causes further losses both in the short and the long run, because it reduces the amount of electric energy which can be produced with the system. In the short run, high module temperature limits the momentary energy production, while the long-term effect results in increased ageing of the photovoltaic module [46,47]. While the short circuit current (Isc) increases slightly with increasing temperature, the open circuit voltage (Voc) decreases significantly (about 2.3 mV/C) with increasing temperature [48]. The reduction of efficiency could be different depending on the type of the photovoltaic module. In the case of silicon-based crystalline modules, efficiency generally decreased by 0.35–0.8% as a result of 1 °C increase in temperature [49–52].

Skoplaki–Palyvos performed a correlation analysis based on the basic data of several research projects of silicon-based solar cells and found that there is a linear correlation between temperature and efficiency (Fig. 1). The effect of the temperature coefficient on the efficiency of various silicon-based PV module types is shown in Fig. 1., where the Evans–Floschuetz ratio η_T/η_{Tref} is plotted against the operating temperature. In harmony with the relevant technical literature sources, a 10 °C increase in temperature results in a 3–5% loss of performance [16].

The ratio of η_T/η_{Tref} as predicted by the Evans–Florschuetz efficiency correlation for typical silicon-based PV module types. Evans–Florschuetz PV efficiency correlation coefficients $\eta_T=\eta_{Tref}[1-\beta_{ref}(T-T_{ref})]$. Where:

η_{Tref} = the module's electrical efficiency at the reference temperature
β_{ref} = temperature coefficient,
T = temperature (K)
T_{ref} = reference temperature

Of the various factors determining the performance of a given solar cell, the influence of temperature has been researched by many researchers and research groups. In the research performed by Zaoui et al. [53] and Bahaidarah et al. [44], the conducted practical measurements were accompanied by modelling in order to determine the correlation between temperature and performance. Based on the results of Zaoui et al., a single °C unit increase of temperature results in a 0.45% reduction of performance. The activity of Chandrasekar et al. [12] shows that 1 °C increase of temperature usually causes a 0.5% reduction of efficiency of crystalline photovoltaic modules. Of the various thin film technologies, this reduction ranges between 0.21% and 0.36% in the case of amorphous silicon (a-si), cadmium telluride and copper-indium-gallium-diselenide (CIGS) [51,54–56]. As a result, the method of spraying should be examined primarily in the case of crystalline photovoltaic modules, since a 1 °C increase in temperature results in a 0.5% reduction of efficiency. In the experiment conducted by Bahaidarah et al., the module temperature was reduced to 20% with a heat exchanger which resulted in a 9% increase of efficiency

[44]. Odehand and Behina [57] examined the cooling effect of water flowing off the surface of the solar cell, during which the module was cooled down from 58 °C to 26 °C. The energy produced by the cooled photovoltaic module increased by 4–10%. As regards air-based cooling, Teo et al. [58] performed experiments of cooling the back of solar cells with a fan in 2012. This solution resulted in a 12.5% increase of efficiency and 30 °C decrease of temperature [12]. These findings show that cooling results in the highest increase of efficiency on the module type examined in this paper (silicon-based photovoltaic modules).

Our standpoint with regard to the efficiency ranking which was set up on the basis of the further technical literature data of solar cell cooling for the users, considering water and electricity demand as well as electricity production:

- sprinkling water cooling with draining (most effective)
- sprinkling water cooling without draining
- refrigerant based cooling
- air-based cooling.

In parallel with the universal use of photovoltaic systems and the constant extension of installations, the research and development activity is focused on avoiding the above described short- and long-term reduction of efficiency. For this reason, various active and passive cooling methods can be performed in order to control the operation temperature of the photovoltaic module [12,59–61]. According to [12], four groups of cooling techniques can be distinguished as follows: air based, water based, refrigerant based [62] and heat pipe based technique. A heat pipe (HP) is a simple cooling device with a working fluid and an energy recovery unit to use the waste heat generated by electronics to drive the cooling fluids [63]. Heat pipe technology, as one of the widespread alternative of passive cooling solutions, currently has an important role in cooling electronic devices of various size – including photovoltaic cells [63,64], fuel cells [65], solar thermal power plants [66], but it also plays a major role in the passive cooling of even nuclear power plants [67].

This paper focuses on water based (sprinkling) and refrigerant based procedures. It can be stated that evaporation during the sprinkling method results in a significantly reduced operation temperature of the photovoltaic module in comparison with an uncooled photovoltaic module operating under identical circumstances [48].

In addition to the photovoltaic module temperature reduction effect of sprinkling, the reduction of reflection is a further advantage. In conventional photoelectric systems, reflection loss during operation may reach up to 8–15% [68]. Sprinkling with water could be used to reduce this loss, as water's refractive index of 1.3 could increase both the light permeability of the module and the efficiency of energy production [48].

Surface cooling with water was examined by [51], who measured the changes in module temperature and capacity as a result of using constant – 4.4 $\mathrm{l\,min^{-1}\,m^{-2}}$ – water doses with sprayers. Furthermore, they observed that the water flow on the module surface and evaporation resulted in a cooling effect of 680 W h, which significantly reduced the module temperature. This method made it possible to achieve a 10.3% daily improvement of efficiency in comparison with the non-cooled photovoltaic module. The experiment also covers an economically significant factor, i.e. the capacity and efficiency of the water pump, which is responsible for water circulation [69]. Abdolzadeh and Ameri [48] obtained data, which show the increasing efficiency of sprinkling during the examination of the efficiency improvement of a water pump system operating on solar energy by applying sprinkling. The test resulted in a 17% improvement of energy, as a consequence of the increasing average cell efficiency (+3.26%) in comparison with a standard module. There has been numerous research projects aiming at the cooling of photovoltaic systems which concentrate sunlight, all of which concluded that high temperature has an efficiency reduction impact [70].

2.3. Regulation of the purchase of electric energy in Hungary

Temporary 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 current season. Off grid systems can overcome this disadvantage only to a limited extent and they call for especially costly electric current storage equipment. In Hungary – similarly to many other EU Member States – it is possible for even residential customers with household-sized power plants to feed the energy produced with photovoltaic modules into the national grid, in addition to purchasing energy. The consumed amount of energy and the amount fed into the system are collated every year and only the difference has to be financially settled. If there is extra consumption, the consumer pays, but in the event of extra production, the power company pays the consumer. This way, the national grid also has an energy storage role from which both parties benefit:

- This represents an advantage for consumers since they can be self-sufficient even with smaller sized photovoltaic systems and they do not have to face the costs and losses of storage.
- The electricity company meets the legal requirements, the owner of the photovoltaic system continues to pay the network access fee and there is no need to develop the grid in order to provide the security of supply due to the current small number of such systems.
- The state could be interested in the macroeconomic benefits of green energy production (such as enterprise development, indirect job creation and the subsequent budgetary income, meet obligations related to renewable energy production, environmental aspects).

The pre-requirement of entering the household sized power plant (HSPP) system is a maximum of 50 kVA capacity and primarily refers to consumption by residential consumers, small enterprises and public institutions. If the capacity of the photovoltaic system is higher than 50 kVA, certification and feeding is arranged based on the rules referring to small power plants (SPP). At the same time, the price of energy produced by photovoltaic varies widely depending on capacity and own consumption [71]:

- HSPP system, energy production lower than own consumption: 12.1 €c/kW h
- HSPP system, energy production higher than own consumption: 6.2 €c/kW h
- small power plant system: 10.4 €c/kW h.

The economic analysis of this paper does not include the second, less economical arrangement, as we assume that the owner of the photovoltaic system is interested in purchasing and operating an economically rational sized photovoltaic system and makes a decision accordingly.

3. Methods

The applied analytical methods are described in three separate subsections. The description of the experimental circumstances of photovoltaic module cooling will be followed by the methods of economic and statistical analysis.

3.1. Photovoltaic module cooling examinations

During the performed research, the impact of two cooling methods (sprinkling and refrigerant based) were examined in comparison with a non-cooled control photovoltaic module. Identical measurement circumstances were provided for the photovoltaic modules during 9–17 h-long measurements and measurements which needed less time. The angular offset was 35° and south orientation was applied in order to completely avoid shade during the measurement periods. The types and capacities of the used photovoltaic modules were identical and their technical parameters can be summarised as follows:

- Type: Mono-Si (Model SM636-50)Rated Maximum Power (Pm): 50 W
- Size: 680 × 510 × 35 mm
- Weight: 4.4 kg.

A dummy load equipped with maximum power point tracking (MPPT) control technique was used for photovoltaic modules and the voltage and amperage signals were conducted to the input of the measurement data logger. In this way, it was possible to measure parallel the temperature and capacity of the photovoltaic modules and to maintain the bias point voltage of the photovoltaic modules in the entire range of operation. The purpose of doing so was to keep the actual capacity at its maximum level, as well as to avoid the change of efficiency arising from incoming solar radiation and temperature changes.

The system was cooled by using a thermostat (type: Omron E5CN) sensing the surface temperature of the photovoltaic modules. Water was injected into the sprinkler head through an ion exchange resin water softener while constant cooling was performed. Pt-100 sensors were used to reach the desired temperature. These sensors were connected to a 4–20 mA remote transmitter mounted into a waterproof box, from which the voltage signal was transmitted into a Picolog measurement data logger.

At the measurement site of the city of Keszthely (Hungary), the water supply needed for cooling the photovoltaic modules was provided by a water pressure tank from a garden well, using filtered groundwater following water softening. In order to ensure low pressure, a pressure reducer was built into the system connected to the water pressure tank. To reduce the amount of sprinkling water, the sprinkler head was operated non-continuously and impulsively during further measurements (using several sprinkler heads, less energy and water). The purpose of this method was to reduce the amount of excess water, i.e. to sprinkle just the amount needed for evaporation. The equipment and measurement processes used during the experiments are shown in Fig. 2.

Since the impact of photovoltaic module cooling arises in warm and sunny weather, the measurements were carried out on summer days (between 30th May and 4th July 2014). The details of the performed examinations could be summarised as follows:

On 30 May 2014, a non-cooled comparative analysis was performed with the control and the cooled photovoltaic modules with identical environmental conditions. The data of the analysis contained the measurement performed each second between 09:30 and 16:00 (6.5 h, 23,400 data). The purpose of the analysis was to reveal whether the technical parameters and placement of the

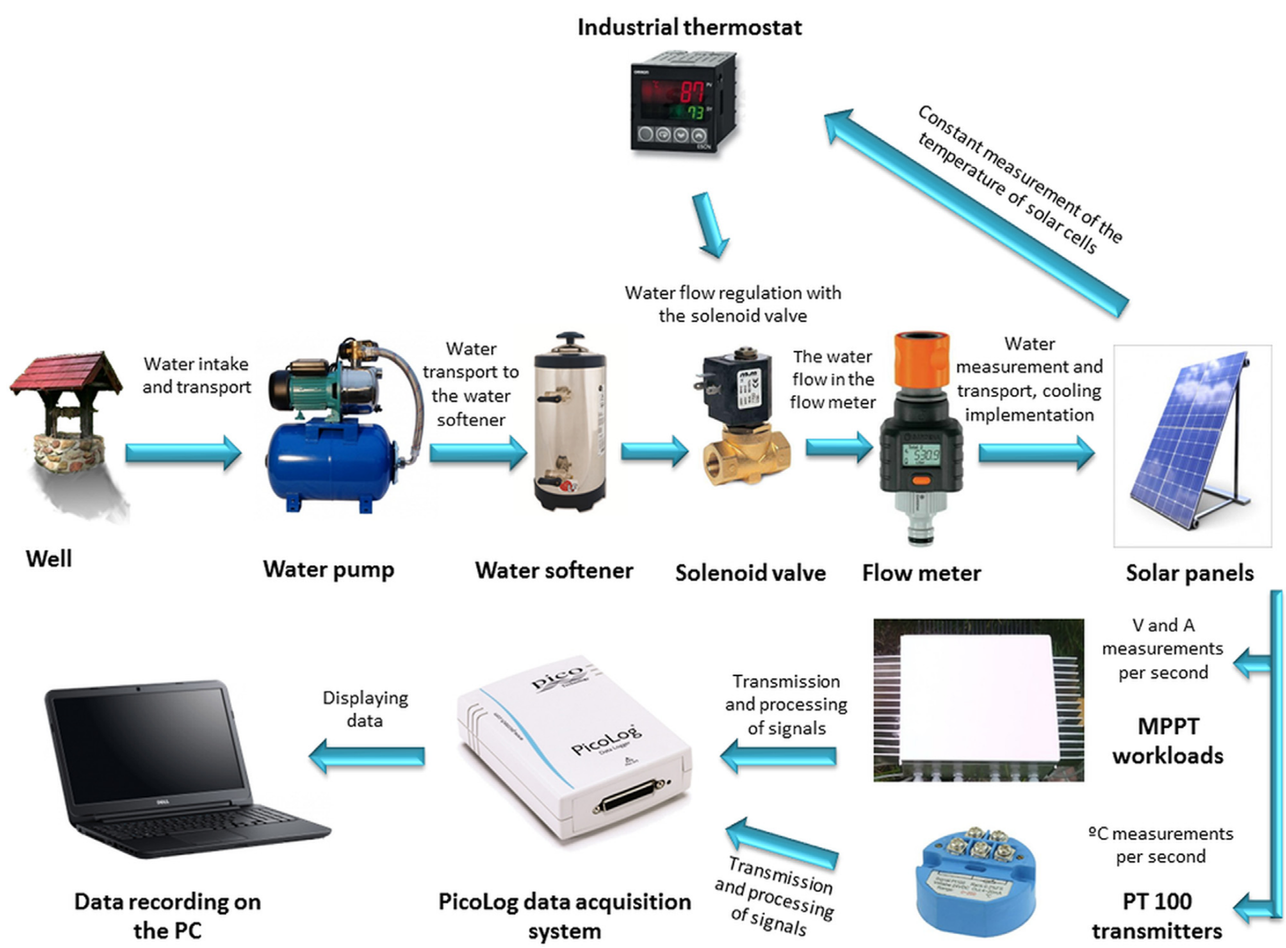

Fig. 2. Schematic diagram of the applied research system.
Source: Own construction.

photovoltaic modules are identical, i.e. whether they have identical capacity without cooling.

In order to show the correlation between the temperature and actual performance of the photovoltaic module, short-term measurements were carried out on two occasions during periods of summer temperature and undisturbed sunlight (12.30–13.03 on 4th June 2014 and 12.30–12.39 on 4th July 2014). In both cases, the photovoltaic module was sprinkled during the first 325 s. After this period the sprinkling ended and cooling was provided only by the evaporating medium. The 2000- and 511-s-long time series were meant to facilitate the analysis of cooling duration and the quickness of cooling impact.

As a next step, the performance of sprinkling cooling was examined against the control (non-cooled) photovoltaic module. Accordingly, the difference in temperature of the two modules was compared to the difference in performance. The aim of examination was to demonstrate the change of performance as a result of one unit change of the difference between the module temperatures of the two variants in the case of usual summer temperature. Examinations were carried out for 5 days (7th, 9th, 13th, 14th and 15th June 2014), during which period the weather was clear most of the time. Within each day, data were measured for 8 h (between 09.00 and 17.00), during the period when radiation and environmental circumstances were identical in the case of each photovoltaic module. Therefore, five times 28,800 data could be compared. In addition to the actual air temperature values, the temperature, voltage and amperage of photovoltaic modules were logged each second, while water consumption was documented once per hour.

During the course of measurement, the temperature of cooling water varied between 17 and 19 °C. Thermostat controlling the sprinkled photovoltaic cell turned on at a surface temperature of 30 °C and it turned off once the surface cooled down to 28 °C. The sprinkled water cooled the photovoltaic module further, evaporated from its surface and once the surface temperature increased to 30 °C, the system turned on again. 15 sprinkler heads and 5 drip appliances had been installed for cooling purposes previously. The best result was obtained by a low-pressure Gardena sprinkler head, resulting in the most homogeneous water surface on the measured photovoltaic module at 0.3 l/min water consumption and 1.4 bar pressure.

Finally, a three-way comparative analysis was performed between the control modules, the ones cooled with sprinkling and the ones equipped with a heat exchanger logging the data every second of a 8-h-long interval (between 09.00 and 17.00) between 19th and 22nd June 2014. In this case, the logged data was identical to that of the previous examination and the performance of each variant was compared to each other in pairs, expressed in percentage. The aim of this method was to rank the different variants and to perform a temporal examination. Thermostat controlling the photovoltaic module equipped with a heat exchanger turned on water circulation when the cooling water temperature was 25 °C and it turned off at 20 °C. Once the surface of the photovoltaic module was 25 °C, the cooling system switched on again. In both cases, the aim was to maintain an optimal temperature of 20–25 °C, which can be regarded optimal for cooling photovoltaic modules.

3.2. Economic and statistical analyses

The performed economic calculations focused on the difference between the extra capacity to be obtained with cooling and the financial expenses (electricity, water) needed for cooling under the current Hungarian legislation circumstances by comparing the rational HSPP system and the larger sized small power plant system. Using average data and readings obtained on days with various weather, income analysis and three types of average efficiency analysis were performed in relation to the following indexes:

- efficiency of the cooling method: energy and water need of cooling divided by the total output to be obtained by cooling
- efficiency of the combined system: electricity and water need of producing one unit extra output (kW h) divided by the extra output to be obtained by cooling
- economic efficiency: ratio of the previous two efficiency indexes expressed in money. This parameter was calculated in the case of both examined plant sizes.

In addition to the performed comparative analysis, sensitivity analyses were performed to demonstrate how much extra capacity and change in the price of electricity could justify the operation of this system in the summer period. Since no data are available for the whole year, it was not possible to perform calculations referring to the operation for a whole year or the length of the payback period of the cooling system, but it is a definite future purpose to establish a database needed for such analysis. Due to the lack of operational data for the whole year, depreciation costs were not involved in the cost calculations, since this type of expense depends on the extent of system use when calculating prime cost.

In addition to descriptive statistical indexes, data analysis was performed using a two sample paired *t*-test, one-way and two-way ANOVA [72]. All statistical analyses were conducted using SPSS 22. The paired *t*-test was used to compare two population means where we had two samples in which observations in one sample could be paired with observations in the other sample. A larger *t* value (for a consistent degrees of freedom) was more likely to attain statistical significance by deviating farther from the mean of the normal distribution [73]. The basic principle of ANOVA is to test for difference among the means of the population by examining the amount of variation within each of these samples relative to the amount of variation between the samples [74]. The two-way ANOVA technique is used when the data are classified on the basis of two factors. As required by ANOVA, the assumptions of approximate normality and equality of variances were fulfilled [72]. One-way and two-way ANOVA Tukey post hoc multiple means comparison were used [75]. In addition, linear regression models with a single or two explanatory variables were also performed for data analysis purposes [76,77]. The linear regression model was $Y=\beta_0+\beta_1\times_1+\varepsilon$ where β_0 was the intercept (constant); β_1 was the slope of the regression model; ε was the error term of the model. If the β_1 value is higher, it means that one unit change of the Predictor has a higher impact on the Dependent Variable. The negative indicator of parameter β means that the changing increase of the predictor will result in the reduction of the dependent variable. R^2 is the determination coefficient which expresses how many percentages the dependence from the predictor variable explains from the whole variability of the dependent variable. In the case of a model where R^2 is higher, the fitting of the model is also better. During the regression analysis, in addition to testing the model, the various parameters also need to be tested. *T* value is used for this purpose, as it shows whether the given parameter β deviates significantly from zero. High *t* value shows that the given parameter β is suitable for estimating the dependent variable in the regression model [72].

4. Results and discussion

This section describes the technical and economic outcomes of the two types of photovoltaic cooling methods and the related development opportunities.

4.1. Control analysis of the photovoltaic modules used in the experiments

Based on the performed measurements, it was observed that the difference in capacity of the examined photovoltaic modules is minimal without cooling, while the highest difference was 0.16% in the case of average performance, 0.51% at the maximum values and 1.11% at the minimum values in comparison with the control. The above described results are also shown as a result of the one-way ANOVA (Table 2).

The average data of the energy produced by all three photovoltaic modules were nearly identical (30.308–30.356 Ws) and the result of the F test was 2.53 (df=2, $P=0.08$), which shows that there is no significant difference between the performance of the examined photovoltaic modules without cooling. Consequently, it can be concluded that the findings obtained with the two types of cooling solely result from the impact of the applied sprinkling and refrigerant based cooling.

4.2. The impact of air temperature and sunlight on the actual performance of photovoltaic modules

The extent to which air temperature and direct solar radiation affects the energy output of the control (non-cooled) photovoltaic modules was also examined. During this analysis, days with the lowest and highest output (13th and 22nd June) were compared, using the available data. The fitting of the regression model was strong-average ($r=0.61$) and the coefficient of determination shows that the two factors have a 37% influence on performance (Table 3).

Based on the parameters of the model (Table 4), it can be concluded that a 1 °C increase in air temperature in the examined temperature range (18–29 °C) improves actual performance by 1.58 W and there is a probable need to perform cooling at higher temperatures. On more cloudy days, the average expected reduction in performance is 9.8 W and it is statistically significant ($P=0.001$).

Using a two-way ANOVA, it was concluded that the joint impact of days of different weather and sprinkling cooling on performance is statistically significant ($P<0.001$), even though there is a very weak correlation ($R^2=0.17$, Table 5).

4.3. Impact speed of sprinkling cooling

The performed short-term analyses convincingly showed that evaporation removes heat more effectively in the warmest period than water circulation. Figs. 3 and 4 show that 500 min are enough for the photovoltaic module to reach a temperature of 30 °C.

Table 2
One-way ANOVA on the amount of energy produced by the three examined photovoltaic modules.
Source: Own calculation

Denomination	*N*	Mean	Std. deviation	Std. error
Control PV WS	23,401	30.308	2.371	0.016
Sprinkling PV WS	23,401	30.328	2.300	0.015
Refrigerant based PV WS	23,401	30.356	2.333	0.015

	Sum of squares	df	Mean square	*F*	Sig.
Between groups	27.603	2	13.80	2.53	0.08
Within groups	382,682.646	70,200	5.45		
Total	382,710.249	70,202			

df: degree of freedom, F: value of F test, Sig: level of significance.

Table 3
ANOVA of the regression model.
Source: Own calculation

Model	Sum of squares	df	Mean square	*F*	Sig
Regression	1,847,255.96	2	923,627.98	17,072.96	$P<0.001$
Residual	3,116,041.19	57,599	54.10		
Total	4,963,297.14	57,601			

Dependent Variable: Control PV energy Ws; Predictors: Days, Air temperature C.
df: degree of freedom, F: value of F test, Sig: level of significance.

The use of sprinkling cooling was used on two undisturbed, sunny summer days. As a result of sprinkling cooling, the temperature of the photovoltaic module decreased from 40 °C to below 35 °C in 105 s and to below 30 °C in 154 s and it was lower than the initial value even at the last measurement (2046 s). Consequently, the effect of the 325-s-long sprinkling was persistent for more than half an hour compared to the control photovoltaic module, while its efficiency was higher than 80% (40 W performance) between seconds 125–881, followed by an efficiency higher than 70% (35 W), exceeding the initial value (Fig. 3.).

A similar, but shorter control measurement was performed one month later under similar circumstances in order to evaluate the speed of cooling. In this measurement, the initial temperature of the photovoltaic module was much higher before cooling, while its performance was significantly lower (56 °C, 28 W). As a result of cooling, the temperature of the photovoltaic module decreased below 35 °C in 275 s (i.e. during sprinkling) and to 30.2 °C at the end of measurement (in 512 s). The efficiency of the photovoltaic module was constantly above 80% (40 W) starting from the 167th second and above 90% (45 W) at the end of the measurement (from the 478th second) (Fig. 4).

Therefore, a clear negative correlation was observed in both cases under permanent radiation circumstances.

4.4. The impact of temperature difference on actual performance

The data obtained during the 5 days of analysis can be classified into two groups. During the first two sunny and warm days, the linear line fitting to the obtained data characterised the impact of the difference in temperature very well. Based on this function, it can be concluded that one unit of difference in temperature resulted in a performance difference of 0.62–0.64 W (1.2–1.3%) of the same direction. More cloudy days (days 3–5) resulted in much smaller change (0.42–0.49 W) (Table 6).

4.5. Comparing the actual performance of the control photovoltaic module to the water sprinkling and refrigerant based cooling

Figs. 5 and 6 show that there can be extreme fluctuations in the short run due to the change of sunny and cloudy periods. This observation is also reinforced by the fact that weather was warmer and sunnier on 22 June 2014 than on 19 June 2014.

If extreme data are disregarded, the following conclusions can be made:

- The actual performance of the sprinkling cooling method exceeds that of the other two methods (by 19% and 25% (control) and by 13% and 18% (refrigerant based cooling), on the two measurement days, respectively).
- On average, the refrigerant based method produced 2% and 10% more energy than the control.
- The extra performance related to the sprinkling water cooling method was nearly constantly 15–17% higher than that of the refrigerant based cooling.
- The extra performance of both cooling types can be characterised with a parabolic curve, showing minimal values in the morning and the evening and a much higher difference during the day.

Table 4
Parameters of the regression model.
Source: Own calculation.

Model	Unstandardised coefficients		Standardised coefficients	t value	Sig.
	β	Std. error	Beta		
Constant	−18.08	0.35		−52.28	$P<0.001$
Air temperature °C	1.58	0.01	0.37	111.64	$P<0.001$
Days	9.83	0.06	0.50	159.30	$P<0.001$

Dependent Variable: Control PV energy Ws; Predictors: Days, Air temperature °C. Sig: level of significance.

Table 5
Two-way ANOVA model of Control PV energy (Ws).
Source: Own calculation

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	9,342,090	13	718,622.37	6230.03	$P<0.001$
Intercept	313,193,943	1	313,193,943.40	2,715,206.99	$P<0.001$
Days	5,865,333	6	977,555.62	8474.83	$P<0.001$
Sprinkling	2,792,120	1	2,792,120.04	24,206.04	$P<0.001$
Days*sprinkling	684,637	6	114,106.17	989.23	$P<0.001$
Error	46,508,350	403,200	115.35		
Total	369,044,384	403,214			
Corrected total	55,850,441	403,213			

Dependent Variable: Control PV energy Ws; Predictors: Days, Sprinkling, Sig: level of significance. $R^2 = 0.17$

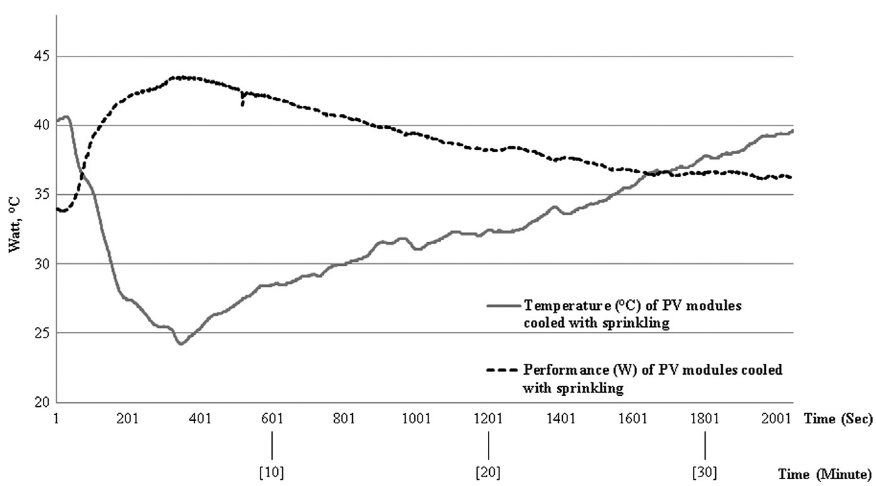

Fig. 3. Correlation between the temperature and performance of photovoltaic modules (12:30–13:03, 04/06/2014).
Source: Own calculation.

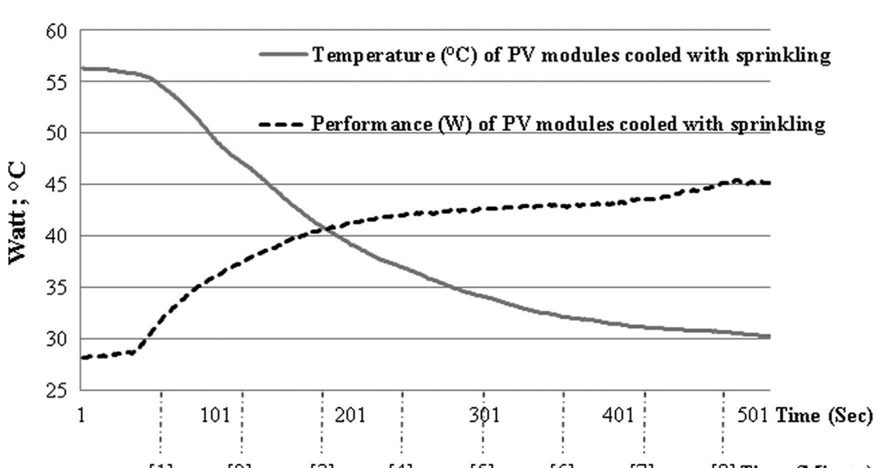

Fig. 4. Efficiency of the sprinkling cooling of photovoltaic modules (12:30–12:39, 04/07/2014).
Source: Own calculation.

The difference in paired energy outputs was also expressed in Ws using a paired sample *t* test (Table 7). The observed tendencies were identical to the above described relative data. The difference between both technologies and the control was statistically significant ($P < 0.001$). Furthermore, the sprinkling water technology also resulted in a statistically significant extra output ($P < 0.001$) in comparison with the refrigerant based cooling.

Altogether, it can be concluded that the increased efficiency achieved with sprinkling water cooling during the performed experiments and the speed of cooling greatly exceeded the technical literature data which is probably due to the higher amount of water used. Further analyses are planned to be performed in order to determine the optimal amount of water.

4.6. Economic evaluation of the examined cooling methods

When comparing the two examined cooling methods, it should be emphasised from the economic aspect that the sprinkling water technology has a much lower electricity need and results in a much higher improvement of efficiency, but there is a rather high water need in comparison with the refrigerant based cooling method. The amount of water can probably be reduced by using more sprinkler heads in order to decrease unnecessary leaking, so that the loss of water could be reduced to evaporating water alone. Water costs should be reduced in the following ways:

- Using rainwater: algae could pose a problem when rainwater is stored in the summer.
- Water from a drilled well: from the economic aspect, one would face the expense of drilling the well, the depreciation cost of the water pump and the cost of electricity used during water uptake. Furthermore, siltation and clogging could pose technical problems and extra expenses.
- Using freely available wastewater which could not be used as drinking water, but contains a negligible amount of dissolved organic and inorganic materials. A good example could be the type of wastewater treatment during which the organic matter content of wastewater is disposed of by applying anaerobic treatment and the inorganic matter content of the fermented organic material is removed with algae. In theory, this type of wastewater is perfectly suitable for cooling photovoltaic modules. Furthermore, wastewater is available in large quantities at such plants and the whole amount of electricity produced by photovoltaic modules can be used by the plant. In addition, wastewater at the connected biogas algae plant could be utilised, as it is possible to convert the operation of this technology into a completely closed loop. At the moment, there are just a few algae plants of industrial scale in operation worldwide, but – based on the authors' own research concerning algae [78] – it is assumed that the advantages of sprinkling water cooling technology can be exploited primarily by involving these plants in the future.

Table 6
The impact of temperature difference on actual performance in the case of sprinkling water cooling and control photovoltaic modules.
Source: Own calculation.

Date	β_0	β_1	R^2
07/06/2014	2.141	0.619	0.945
09/06/2014	2.497	0.636	0.872
13/06/2014	0.654	0.494	0.813
14/06/2014	0.358	0.485	0.801
15/06/2014	0.496	0.421	0.701

β_0, β_1 : parameter of the regression models. Predictor: Air temperature °C.

On average, energy produced with the help of sprinkling water exceeded the energy output of the control photovoltaic module by 16% (32 W h/day) in 56 h of the seven examined days. This difference reached 34% on the warmest and sunniest day, while it was still 8% even on the least ideal day. Following the deduction of the electric energy needed for cooling, the electric performance was still 12% better while using 22.5 l water per day on average (Table 8).

However, in the case of refrigerant based cooling, this value was lower than the electricity need of the heat exchanger, even though the cooled photovoltaic module produced around 8% (17 W h/day) more energy. For this reason, this solution clearly seems to be not viable from both energetic and economic aspects (Table 9).

In addition to energetic efficiency, the economic impact of both cooling procedures were also examined (Table 10). In general, it can be stated that the Hungarian network prefers small, household sized power plants (maximum 50 kW) to larger systems which feed more energy into the grid. Considering the expected tendencies of the consumer price of regular energy and the purchase price of green energy, the difference between the two plant sizes is expected to grow in the future, which will result in an even more rapid spreading of small sized plants. In 2013, the functional photovoltaic capacity in Hungary was around 35 MW, of which

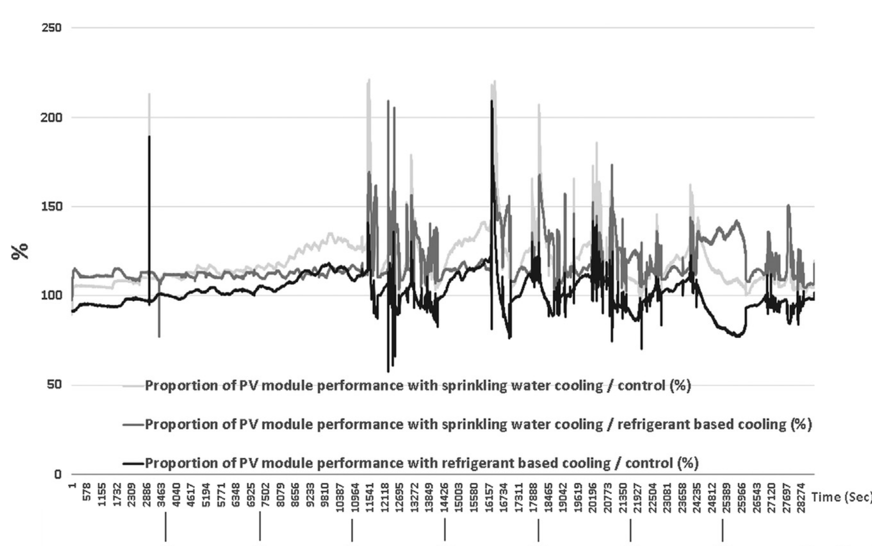

Fig. 5. Performance of different variants compared to each other on 19 June 2014 (%).
Source: Own calculation.

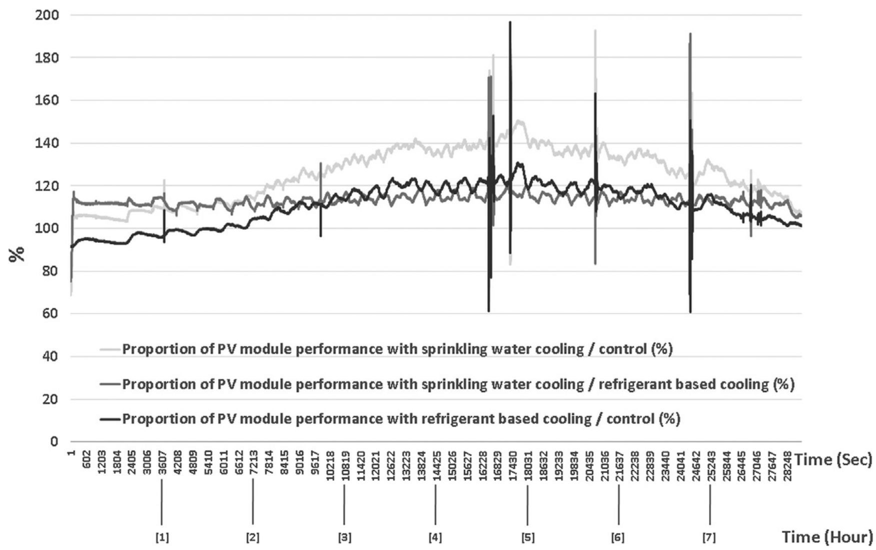

Fig. 6. Performance of different variants compared to each other on 22 June 2014 (%).
Source: Own calculation.

Table 7
Results of the two-sample paired *t* test.
Source: Own calculation.

Denomination	*N*	Mean	Std. deviation	Std. error mean
Measurement date: 19/06/2014				
Perm_Cont_WS	28,801	4.54	3.30	0.02
Perm_HCS_WS	28,801	3.64	1.47	0.01
HCS_Cont_WS	28,801	0.89	2.05	0.01
	t	**df**	**Sig.**	**Mean difference**
Perm_Cont_WS	233.13	28,800	$P < 0.001$	4.53
Perm_HCS_WS	418.23	28,800	$P < 0.001$	3.64
HCS_Cont_WS	74.19	28,800	$P < 0.001$	0.89
	N	**Mean**	**Std. deviation**	**Std. error of mean**
Measurement date: 22/06/2014				
Perm_Cont_WS	28,801	7.67	4.12	0.02
Perm_HCS_WS	28,801	4.36	1.37	0.01
HCS_Cont_WS	28,801	3.31	2.93	0.02
	t	**df**	**Sig.**	**Mean difference**
Perm_Cont_WS	315.73	28,800	$P < 0.001$	7.67
Perm_HCS_WS	537.81	28,800	$P < 0.001$	4.36
HCS_Cont_WS	191.24	28,800	$P < 0.001$	3.31

Sig: level of significance.

Table 8
The impact of sprinkling water cooling on the examined photovoltaic module.
Source: Own calculation.

Sprinkling PV 09:00–17:00	Electric energy produced with control PV module (W h)	Electric energy produced with PV module cooled with sprinkling (W h)	Energy consumed by the pump to access water (W h)	Actual extra energy produced by PV modules cooled with sprinkling compared to the control (W h)	Actual extra energy produced by PV modules cooled with sprinkling compared to the control (%)	Consumed water (l)
07/06/2014	220.4	281.7	9.3	52.0	24	22.3
09/06/2014	209.3	281.5	12.4	59.8	29	29.8
13/06/2014	161.8	187.9	5.5	20.6	13	13.3
14/06/2014	180.4	200.8	3.5	16.9	9	8.4
15/06/2014	203.8	220.8	3.5	13.5	7	8.4
19/06/2014	203.5	239.9	14.9	21.5	11	35.8
22/06/2014	234.0	295.5	19.5	42	18	46.8
Mean	**196.7**	**229.0**	**9.38**	**22.9**	**12**	**22.5**

Table 9
The impact of refrigerant based cooling on the examined photovoltaic module.
Source: Own calculation.

Refrigerant based cooling 09:00–17:00	Electric energy produced with control PV module (W h)	Electric energy produced with PV module with refrigerant based cooling (W h)	Energy consumed to access water (W h)	Actual extra energy (W h)	Actual extra energy compared to the control (%)	Consumed water (l)
19/06/2014	203.5	210.7	48.2	−41.0	−20	115.6
22/06/2014	233.98	260.52	63.8	−37.3	−16	153.1
Mean	**218.7**	**235.6**	**56**	−**39.1**	−**18**	**134.35**

Table 10
Economic outcomes of the two types of photovoltaic module cooling.

€c	**Value of extra electricity produced with sprinkling cooling**		**Value of water**	**Loss of sprinkling cooling**		**Value of the electric energy balance of refrigerant based cooling**	
Electricity purchase system	KÁT*	EDSZ**		KÁT*	EDSZ**	KÁT*	EDSZ**
€c/unit	12.1 €c/kW h	10.4 €c/kW h	0.19 €c/l	€c/day	€c/day	12.1 €c/kW h	10.4 €c/kW h
Experiment dates							
07/06/2014	0.54	0.63	4.32	−3.78	−3.69		
09/06/2014	0.62	0.72	5.77	−5.15	−5.04		
13/06/2014	0.21	0.25	2.57	−2.36	−2.33		
14/06/2014	0.17	0.20	1.63	−1.45	−1.42		
15/06/2014	0.14	0.16	1.63	−1.49	−1.46		
19/06/2014	0.22	0.26	6.92	−6.70	−6.66	−0.43	−0.50
22/06/2014	0.44	0.51	9.06	−8.62	−8.55	−0.39	−0.45
Mean	**0.34**	**0.39**	**4.56**	−**4.22**	−**4.16**	−**0.41**	−**0.47**

* Compulsory Purchase Tariff (above a capacity of 50 kVA).
** Collective Tariff (below a capacity of 50 kVA).

Table 11
Average efficiency indexes of the two examined photovoltaic module cooling types.

Examined index	**Unit**	**Sprinkling PV cell**	**Heat exchanger PV cell**
Efficiency of the cooling method			
Energy need/total output	W h/W h	0.04	0.24
Water need/total output	l/W h	0.10	–
Total revenue/total expenditure	€c/€c	0.51	4.21
Total revenue/total expenditure	€c/€c	0.60	4.21
Efficiency of the combined system			
Energy need/extra output	kW h/kW h	0.29	3.32
Water need/extra output	l/W h	0.70	–
Additional revenue/additional expenditure	€c/€c	0.07	0.30
Additional revenue/additional expenditure	€c/€c	0.08	0.30

31.21 MW was represented by household sized power plants and the rest belonged to plants whose capacity was above 50 kVA [71].

If proper quality water is freely available (e.g. algaculture), sprinkling water cooling could result in 0.34–0.39 euro cents extra income per day in the case of the examined 50 W photovoltaic module. Considering a typical household sized 5 kW capacity, this extra income is 39 EUR on an average summer day and 72 EUR on an ideal, sunny summer day in comparison with the non-cooled monocrystalline photovoltaic module. In addition to income calculation, the average efficiency of indexes of the two cooling systems were also examined (Table 11). In the case of the sprinkling method, the energetic efficiency is much more favourable than in the case of heat exchanger systems. However, this finding – with the current price proportions and the obtained technical parameters and without reducing water consumption – is not enough for economic operation. The economic efficiency of heat exchanger-based solar cells is due to their water-saving operation which cannot be improved. Also, the energetic efficiency makes it even theoretically impossible to perform economic operation with the examined parameters.

Based on the data shown in Tables 10 and 11 and the examined technical and economic parameters, it can be concluded that both procedures result in economic loss in comparison with the control photovoltaic module. The reason for this loss is the unfavourable energetic efficiency in the case of the refrigerant based method, and the significant water loss in the case of the sprinkling method. In the latter case, the following key issues of economic impact arise:

- increasing price of the produced electricity which also depends on the plant size
- increasing efficiency of the cooled photovoltaic module
- decreasing of the necessary amount of water or its consumer price

Based on these aspects, the following magnitudes of positive change would be necessary to achieve economic results identical to those of the control photovoltaic modules in comparison with the examined case:

- Average weather
  - Compulsory Purchase Tariff: 1360%
  - Collective Tariff: 1170%
- Ideal summer weather
  - Compulsory Purchase Tariff: 800%
  - Collective Tariff: 690%

By perfecting the sprinkling technology, the only problem could arise from the precipitation of inorganic materials which may result in the reduction of irradiation to be utilised by the photovoltaic module and, consequently, in performance loss.

Based on our measurements, the observed changes in cell temperature may play a significantly larger role in enhancing the efficiency of solar cells compared with the previous results in the existing literature ((−) 0.8–1.3%/°C, and (−) 0.35–0.8%/°C, respectively).

It is the aim of our future research projects to perform comparative analyses of three different photovoltaic modules (amorphous silicon, polycrystalline and monocrystalline) by pairing identical type and performance modules without cooling and performing sectioned spraying with identical methods outdoors, under real weather circumstances. It is our further aim to set up a spraying cooling system which would operate without water runoff. In this way, we could focus only on the heat effect resulting from evaporation and we could examine its performance increase impact.

5. Conclusion

Our examinations demonstrate the extra output compared to standard photovoltaic modules under operating circumstances, as well as the energy need of the necessary technical accessories, their costs and economic, technological and environmental protection-related advantages. Consequently, we obtained basic data and empirical correlations which can be used for scaling cooled systems and photovoltaic energy supply systems can be further developed and their efficiency and economicalness improved.

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 circumstances. 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).

During both cooling methods, there was an improvement in performance to a different extent. Water was used as an evaporating medium, removing a significant amount of heat, thereby changing the heat conduction resistance of the structure and increasing the initial thermal inertia of the photovoltaic module. 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 the 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.

The improvement of efficiency in the case of the refrigerant based cooling was basically identical to the parameters of the previous water circulation cooling technologies, while water sprinkling resulted in a much higher increase in performance, compared with the related literature, and a serious amount of water consumption.

Consequently, it can be concluded that the sprinkling water cooling method can be considered to be the best solution from the aspect of energy efficiency, while it is non-competitive from the economic point of view based on the technical and economic parameters examined in this study. From the economic aspect, this method would be justified as opposed to control (non-cooled) monocrystalline photovoltaic modules if either water consumption or water price decreased tenfold or if the price of electricity increased to a similar extent (ceteris paribus). The option of using a heat exchanger revealed that even the extra energy demand of this method is higher than the extra output to be attained; therefore, this solution is not considered to be viable from either energetic or economic aspects.

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