HUNGARIAN AGRICULTURAL ENGINEERING
N° 38/2020 37-48
Published online: http://hae-journals.org/
HU ISSN 0864-7410 (Print) / HU ISSN 2415-9751(Online)
DOI: 10.17676/HAE.2020.38.37
Received: 25.08.2020 - Accepted: 15.11.2020

PERIODICAL OF THE COMITTEE OF AGRICULTURAL AND BIOSYSTEM ENGINEERING OF
THE HUNGARIAN ACADEMY OF SCIENCES
and
SZENT ISTVÁN UNIVERSITY
Faculty of Mechanical Engineering

EFFECT OF SELF-CLEANING COATINGS ON SOLAR MODULE REFLECTANCE AND POWER

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Abstract: The pollution caused power loss of solar modules can be reduced by using self-cleaning coatings. When applying these coatings, the basic question is how the coating itself effects on the power of the solar module. The recent paper deal with this. It examines power, reflection capability and power changes due to contamination and self-cleaning of 5 different coated solar modules and compares them with the measured values of an uncoated solar module. Based on the results of laboratory measurements, it can be stated that the effects of photocatalytic thin layer and lotus effect based coatings increase the power of the solar modules by average 2%. The effects of the same contamination reduced the power of all modules, but the power of the coated modules is higher. After spraying with rainwater, the examined coated solar modules operated at nearly 4% more power than the reference, uncoated solar module.

Keywords: photovoltaic, photocatalytic thin layer, lotus effect, reflection, contamination, power

1. Introduction

The use of solar modules is an increasingly important electricity generation option. It can be found in all segments of our lives, including agriculture. The power of a PV module is influenced by numerous factors. The most basic ones are the types of PV module, the orientation, the angle of inclination, geographical and meteorological conditions of the location. Among the meteorological factors, apart from the fundamental role of radiation, the temperature (Skoplaki and Palyvos, 2009; Snaith et al., 2006) and the humidity of the air (Hosseini et al., 2019), but the wind speed (Chandra et al., 2018) also has influence. It is also important to consider the role of shadings (Ishaque, 2011) in the installation. The reflectance and the pollution of the solar modules are also significantly influence the performance of PV systems. The reflectance is reduced by anti-reflective coatings (Prevo et al., 2007; Kumar et al., 2011; Luo et al., 2018), in nowadays the usage of organic possibilities spread (Forberic et al., 2008). The contamination caused power loss and efficiency decrease is quite high, up to 40% (Mani and Pillai, 2010; Adinoyi and Said, 2013). To keep the modules clean is important to achieve the maximum power of the system.

The PV technology is not yet fully matured technology, the latest results of modern physics, materials sciences and nanotechnology generated the continuous development of this area. The application of nanotechnology coatings in various fields is more and more popular (Faustiny et al., 2010; Ganesh et al., 2018). For self-cleaning effect, the photocatalytic thin layers and coatings with lotus effect are the most important at solar modules (Parkin and Palgrave, 2005; Oelhafen and Schüler, 2005; Piliougine et al., 2013; Arabatzis et al., 2018) but CPV modules (Jesus et al., 2018) also has to be taken into the account.

Photocatalytic thin layers absorb photons and create a number of chemical reactions. Chemical redox reactions and reduction of organic materials are catalysed by electron-hole pairs generated in the layer by photons. The anatase crystalline phase of TiO_2 is the primary material used for catalytic applications. Photocatalytic thin layers are used for the decomposition of organic contaminants and energy applications include dye-sensitized solar cells and artificial photosynthesis (Hwang et al., 2008; Snaith, 2013; Malinkiewitz et al., 2014; Jeon et al., 2014). The base of the lotus effect is the hydrophobicity, which helps self-cleaning process (Koch and Barthlott, 2009). Dirt particles are picked up by water droplets due to the micro- and nanoscopic architecture on the surface, which minimizes the droplet's adhesion to that surface. In this study the effects of several Hungarian-developed layers on the solar module reflectance and power are studied and compared. The powers of the modules are compared in clean, contaminated and after self-cleaning states.

2. Module and coatings

A 4 W power polycrystalline solar module with 156x156 mm^2 area without cover, as uncoated and 5 modules of the same type, 1 with photocatalytic thin layer and 4 with lotus effect coated were compared. In some measurements the uncoated module covered with rainwater and with glass layer also were examined. The coatings were applied on the surface of solar modules by the developer companies. The main features of the studied thin layers are as follows:

- The **Nanopro** is a photocatalytic self-cleaning coating, developed by NanoPro Ltd for solar modules. The main materials of the coating are 0.5% TiO_2, 0.5% WO_3 and 2% SiO_2. The coating was prepared by spraying.
- The **Nanobase**, is a lotus effect nanotechnology coating, which was developed by Nanobase Ltd., this hydrophobic layer has been rolled onto the solar module surface.
- **Hardbody**, **Bodyguard** and **Misteryjuice** are the fantasy names of coatings which are the self-developed coatings for self-cleaning of different surfaces of cars, made by Wolf Chemistry Ltd., working base is the lotus effect. The SiO_2 based nano ceramic coatings are super hydrophobic. The dry matter content and the distribution of the solid and liquid components are the differences between the 3 coatings. The coatings were applied to the solar modules by rubbing with sponge.

Images taken from the surface of uncoated (natural) and the exposed coatings by microscope (BIM135M-LED microscope 3,0 MPMicroQ microscope camera, 100x magnification) are shown in Fig. 1.

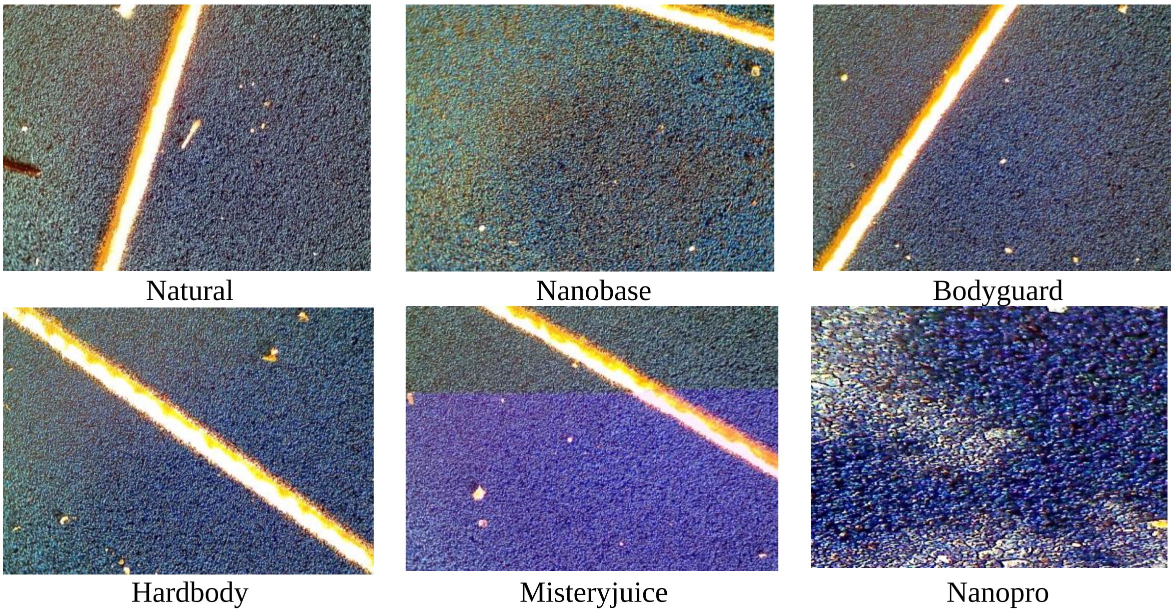

Fig. 1. Images of uncoated and coated solar panels made by microscope

During the measurements the properties of the natural module, the solar modules with the presented coatings and some cases the properties of a natural solar module covered with water and with a 2 mm thick normal glass were compared.

3. Measurements and results

3.1. Maximum power

For the comparability of power, the same boundary conditions were applied in each case. The relatively small solar modules were under the same uniform artificial illumination. The continuous spectrum light of a normal, 40 W bulb reached the different solar modules from the same, 22 cm distance at the same position, perpendicularly to the center of the modules. For to determination the power, values of voltage and current are required at different load resistors. For the current measurement the internal resistance of the ammeter was too large due to the small inner resistance of the solar modules. The problem was solved by inserting a shunt. A small, but finely variable resistor was a metal wire. During the data gathering a NI USB 6009 AD converter unit was used and a computer with LabVIEW program collected the data. The schematic diagram and photograph of the measuring system are shown in Fig. 2. and Fig. 3.

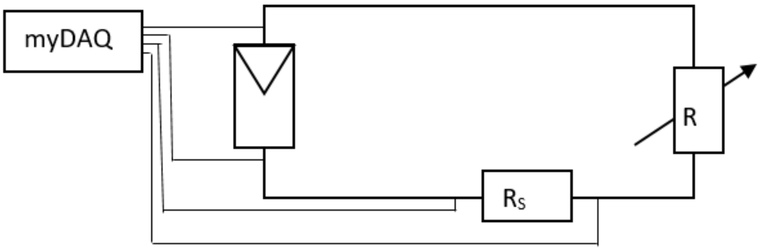

Fig. 2. Sketch of the power measurement

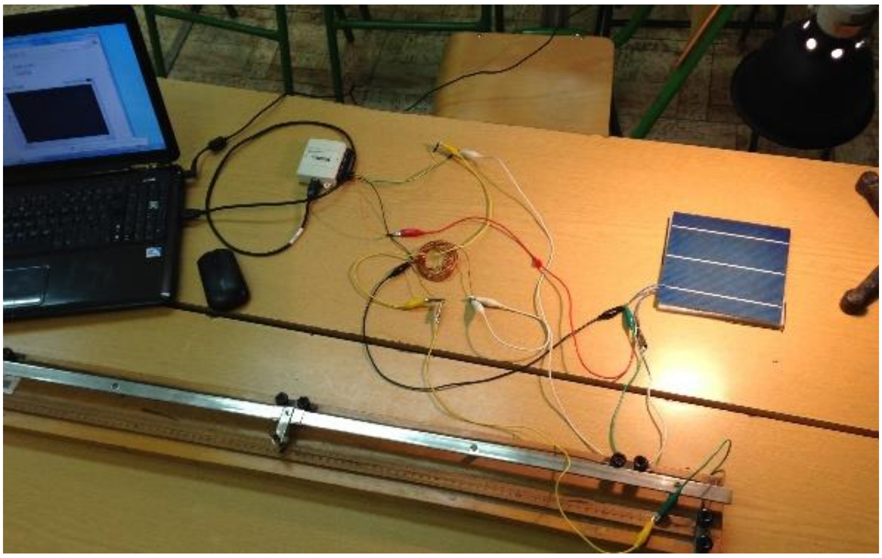

Fig. 3. Photo about the measurement system

For each solar module, 3-3 I-V characteristics were recorded. The maximum powers were determined based on these characteristics. The maximum power determined by the measurement data, taking into account the law of error propagation, contains less than 5% error. As a sample, the uncoated (natural), the water and glass layer covered natural solar modules I-V and P-V characteristics are shown in the Fig 4. and Fig. 5.

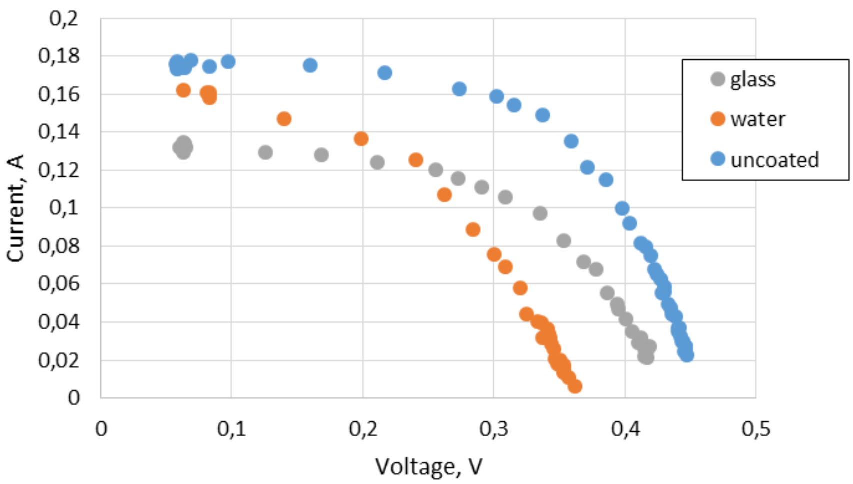

Fig. 4. I-V characteristics

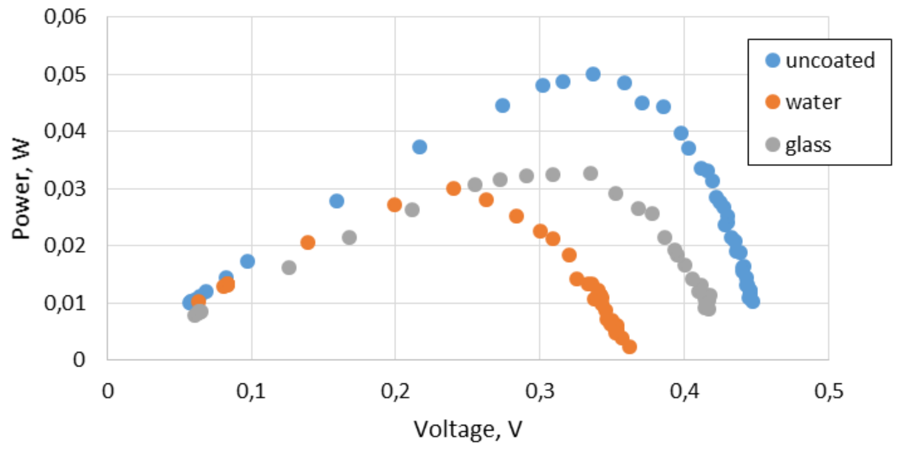

Fig. 5. P-V characteristics

Based on the results, it can be stated that both the water and the glass layer reduced the power. The maximum power of PV modules coated with various self-cleaning nanotechnology coatings were determined by the above described measurements. In case of the uncoated solar module, at the applied illumination the maximum power was 0.05 W. Compared to this the maximum power of the coated modules (based on the average of 3 readings, too) can be seen in Fig.6.

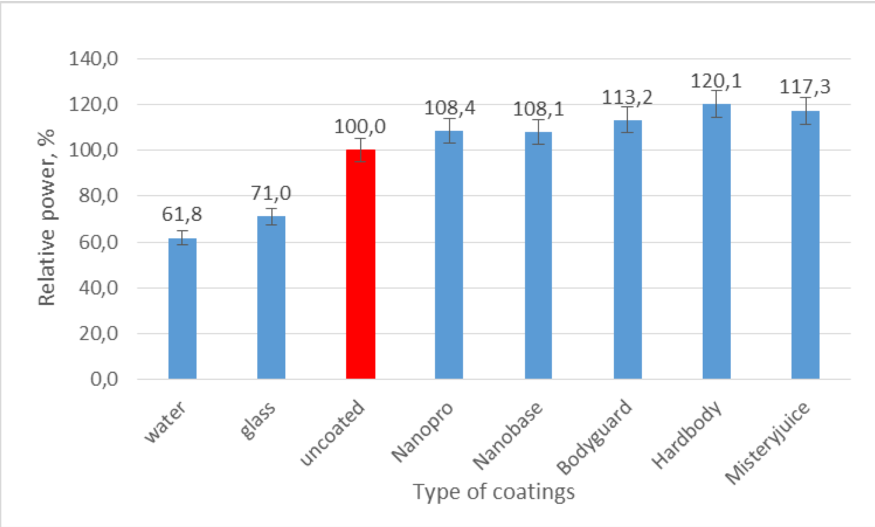

Fig.6. Relative effect of the coatings

The diagram shows that the nanotechnology coatings slightly increased the maximum power of the solar modules. The examined modules are not enclosed, so the coatings are directly on the solar module surfaces. The surface of the solar module is rough. The different coatings are constructed from different binders and are otherwise related to the surface which results the difference between the light entering the surface of the solar module and thus resulted the difference in the powers.

3.2. Optical effects

The difference in the energy utilization of the solar modules is caused by coatings which modified the optical properties of the modules. The optical effects how the solar radiation passing through a layer are summarized in Fig. 7.

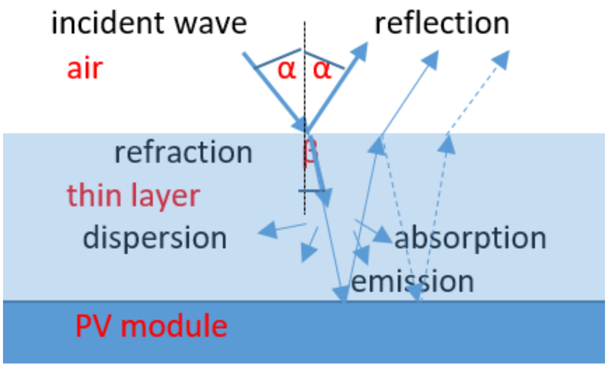

Fig. 7. Optical effects

The appearance of thin layers on the module surfaces may change over the light transmission and the reflections and these changing resulted in the change of the power. Reflection and transmission of the light beam through the boundaries of two mediums is determined by the Fresnel equations (Hecht, 2002), which can be used to determine the amplitudes of reflection and transmission on the several frequencies, based on the refractive indexes and the incidence angle, considering the interferences of multiple reflection too. If the layer is already on the solar module, than the reflection may be well-researched from the optical properties. The reflection is direction and wavelength dependent quantity. During the illumination a standard bulb with 100 W electric power was used. The module's reflected light spectrum was determined by the Ocean Optics spectrometer. Based on the signal coming into the spectrometer via the optical cable, the spectrometer gives intensity every 0.36 nm between 340 and 1026 nm, which can be measured and recorded using the Overture program which run on the connected computer. The experimental layout is shown in Fig. 8.

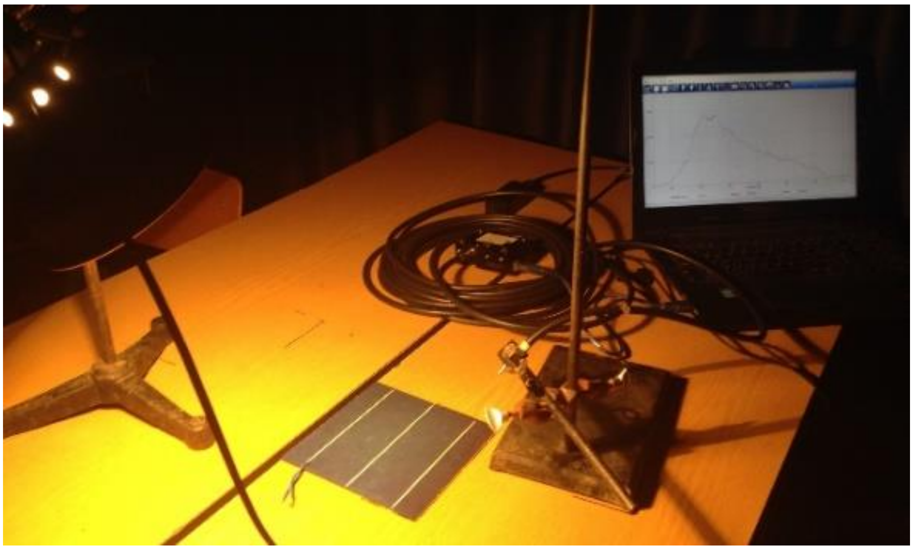

Fig. 8. Experimental layout for measuring the reflected spectrum

The measurements were performed under the same boundary conditions (same continuous spectrum light source; location and direction of the illumination, solar modules and sensor of the spectrometer). Examples of spectra made in the different reflection directions are shown in Fig. 9. and Fig. 11. The Fig. 10. and 12. show the intensity differences of natural and coated solar modules reflected lights as a function of wavelength at 41° and 52° incidence angles. Based on the experimental data, it can be stated that at the wavelengths below 550 nm each coating reflectance is lower than that measured on the uncoated solar module. In areas with more than 550 nm wavelength, Nanobase and Nanopro coatings reflect better than the uncoated solar modules. The characteristic of the curves is the same, the major difference is found only at the Nanopro coating, which can be explained by the fact that this coating is working with another principle. The direction sensibility of spectrum intensity is very high.

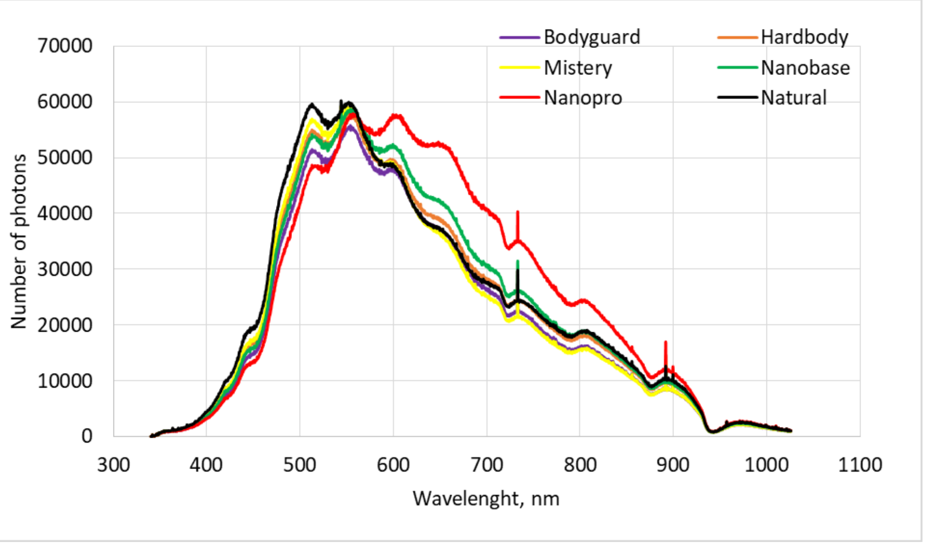

Fig. 9. Solar modules reflected spectra, at 41° incidence angle

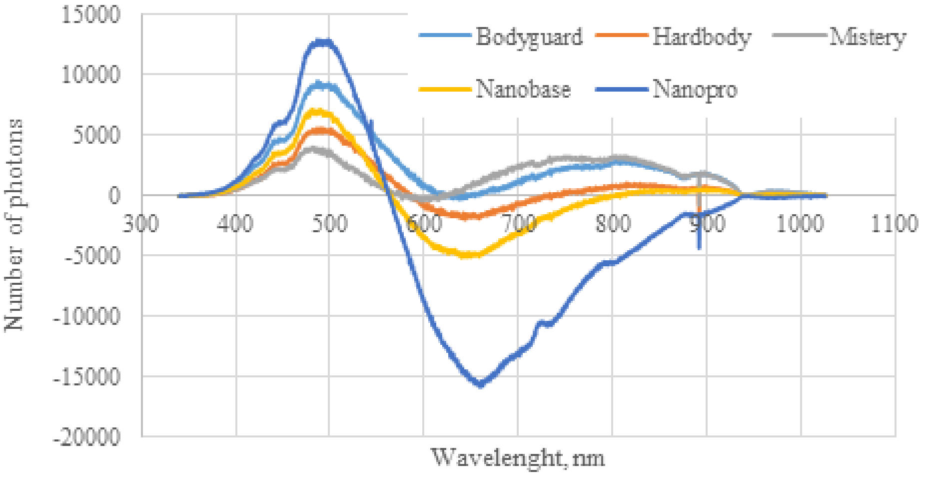

Fig. 10. Intensity difference between the coated and natural spectrums, at 41° incidence angle

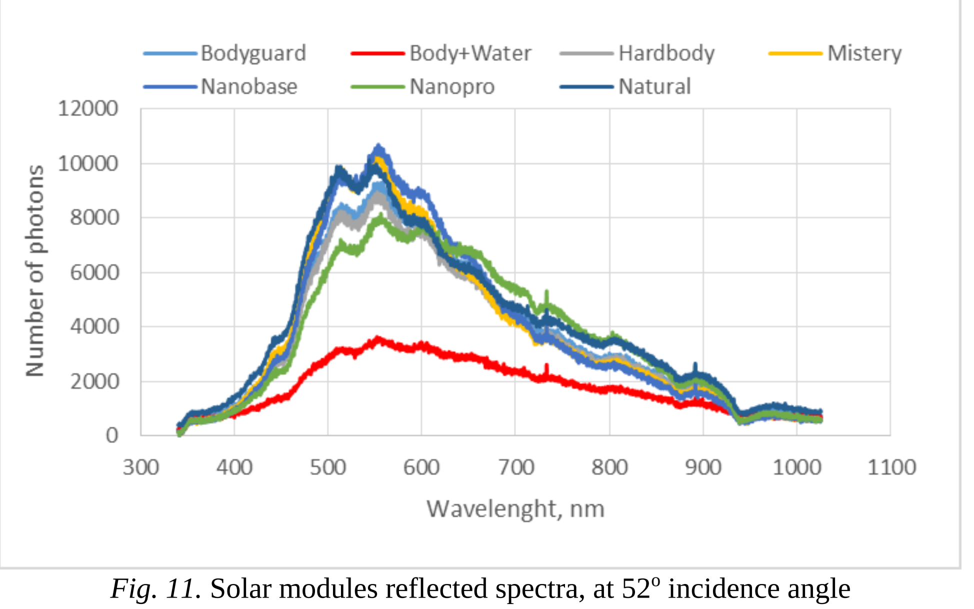

Fig. 11. Solar modules reflected spectra, at 52° incidence angle

Fig. 11. shows the reflection of the aqueous Bodyguard coating (Body+Water) also. It is well observed the reflectance reduction, but the characteristics of the spectrum do not change. The reason of reflectance reduction is that the water droplets in the form of small spheres on the hydrophobic surface significantly reduce the reflection.

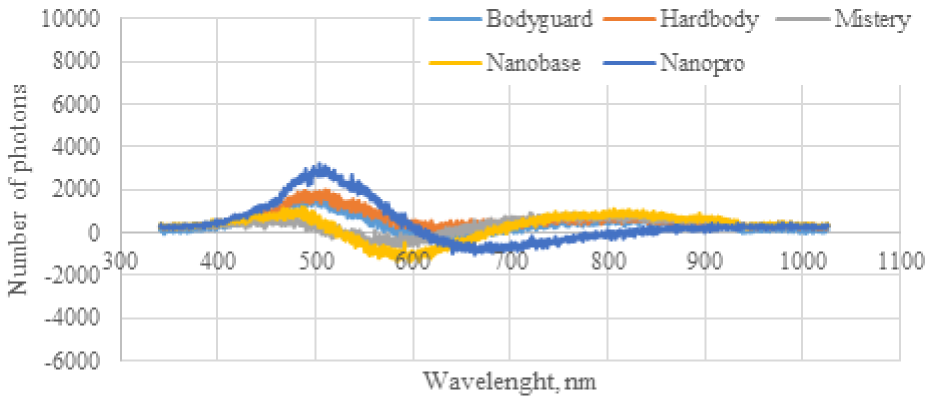

Fig. 12. Intensity difference between the coated and natural spectrums at 52° incidence angle

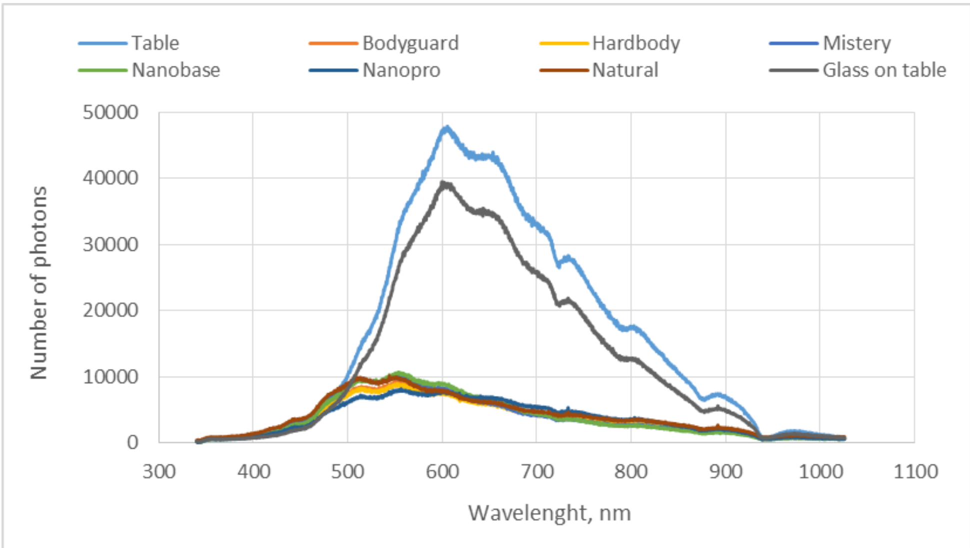

Fig. 13. Spectra, 52° incidence angle

Under the same conditions than was in the Fig. 11, Fig. 13. shows the measured reflected spectra from the table, the glass on the table and the covered solar modules also. From Fig. 13. it can be seen, that the reflection from the table and glass plate is definitely higher than from the natural and coated solar modules. The 550 nm characteristic peak of the solar modules is transmitted to 600 nm in case of the table and the glass on the table.

The energy of the photon is (eq.1):

$$\varepsilon = h \cdot f = \frac{h \cdot c}{\lambda} \qquad (1)$$

where $h=6.62 \cdot 10^{-34}$ Js, the Planck constant and $c=3 \cdot 10^{8}$ m/s is the speed of light in vacuum (air).
In case of $N(\lambda)$ pieces photon, the total incoming energy at the wavelength λ is (eq.2):

$$E = N \cdot \varepsilon = \frac{N \cdot h \cdot c}{\lambda} \qquad (2)$$

The total reflected energy is given from the sum of energies for the whole spectrum (eq.3).

$$E_{total}=\int \frac{N(\lambda)hc}{\lambda}d\lambda = hc\sum \frac{N_i}{\lambda_i} \qquad (3)$$

and similarly in case of natural module (eq.4):

$$E_{natural,total}=\int \frac{N_n(\lambda)hc}{\lambda}d\lambda = hc\sum \frac{N_{ni}}{\lambda_i} \qquad (4)$$

The values of the relative reflectance energies are resulting from the ratio of the two energies. These values are shown at 41° and 52° incidence angles in Fig. 14.

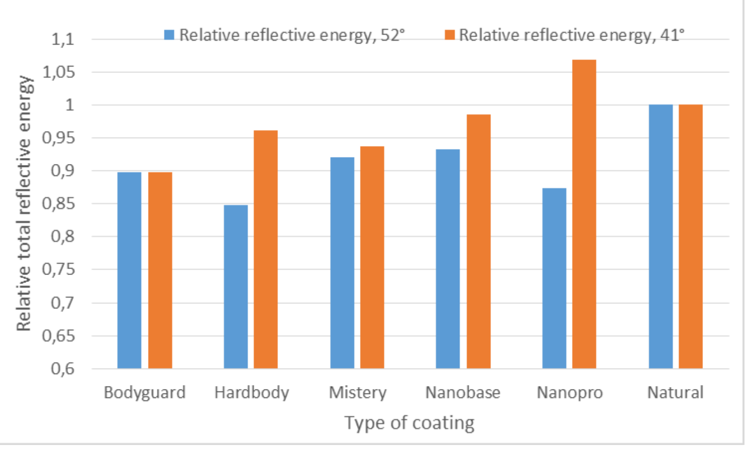

Fig. 14. Relative total reflective energy

The coatings generally reduce the reflection for the entire studied spectrum, the only exception was the photocatalytic Nanopro coating, although the reflectance is sensitively dependent on the angle of incidence as shows the Fig. 14. Fig. 15 compares the relative reflected energy and relative maximum power in case of the different coated solar modules. The references are the values of uncoated module.

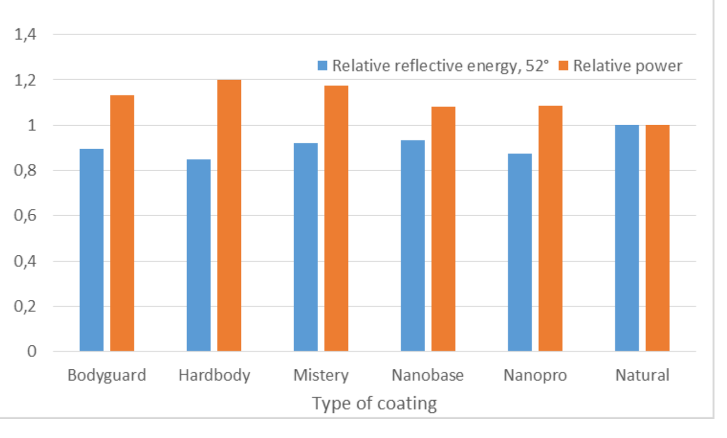

Fig. 15. Relative reflective energies and relative powers

In the Fig. 15. it can be observed, that the relative total reflection and the relative maximum power change in the opposite way, the maximum power increases in case of the reflection increases. Thus, the coatings alone have anti-reflection effects. In addition to the change in reflection capability, other optical factors (e.g. absorption in the coating, dispersion) may also effect the power, and investigation of these effects is another task of the research.

3.3. Effectiveness of self-cleaning

The coatings alone are power enhancers, which is an important result, but with their application the real aim was the self-cleaning of the modules. Coatings are intended to reduce the loss of power due to the contamination on the surface of solar modules. For the investigation the effect quantitatively, the solar modules were made dirty first. The uncoated and coated solar modules were evenly contaminated with a fine meshed (0.02 mm) house dust. Then, the solar module was turned upside down, while most of the dust was fallen down, so as much dirt remained on the surface as it had adhered to the surface properties. All solar module was contaminated with this contamination. Fig. 16. shows the difference of the uncoated solar module in contaminated and clean states.

Fig. 16. The contaminated and clean uncoated solar module

On the pictures of the Fig. 17. the surface of the contaminated solar modules can be seen through a microscope, under the same conditions, as in Fig.1.

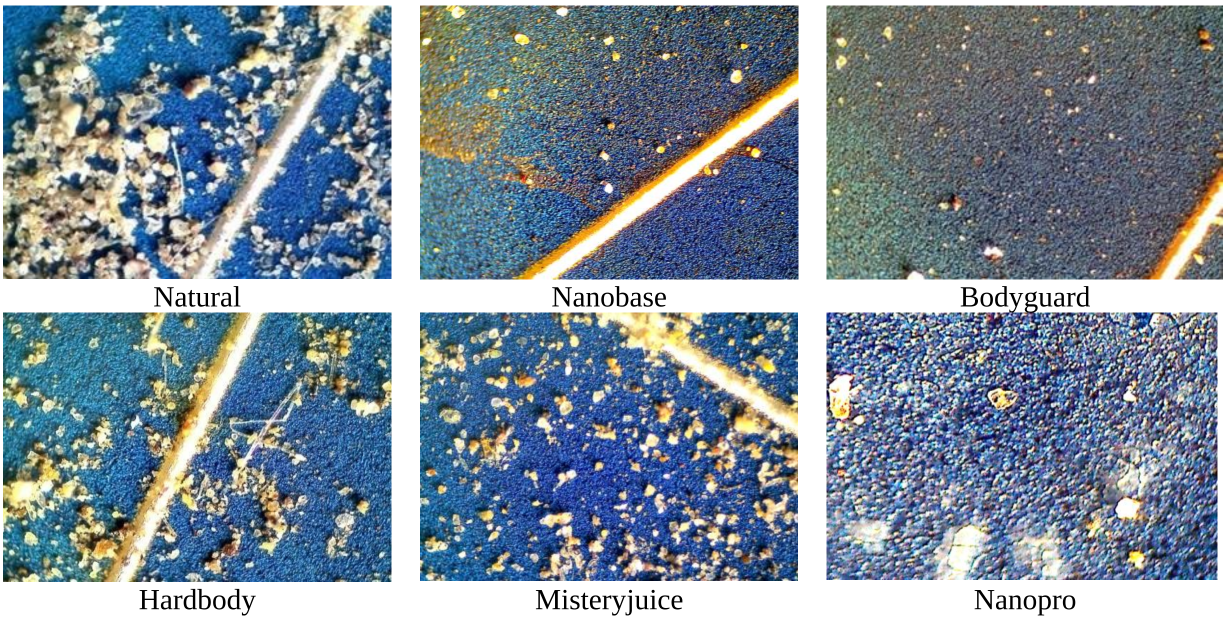

Fig. 17. The contaminated modules

After determining the power of contaminated solar modules, the next step is to examine the effect of self-cleaning. Under real conditions, the photocatalytic layer is activated by light, while the lotus-effect self-cleaning surface becomes effective when it gets wet. In the laboratory, the rain was simulated with 6.55 cm^3 rainwater which was sprayed evenly, perpendicular to the surface. It is corresponding to 0.29 mm rainfall. From the point of view of water depletion, the angle of inclination is important. In this case it was 41.6 degrees, because the optimal inclination angle in Hungary for all year usage is 40-42 degrees. After cleaning, the cleaned state power of the solar modules was determined. Fig. 18. shows solar modules in different states of the investigation: the dusty and cleaned uncoated, and coated (Bodyguard) during the cleaning.

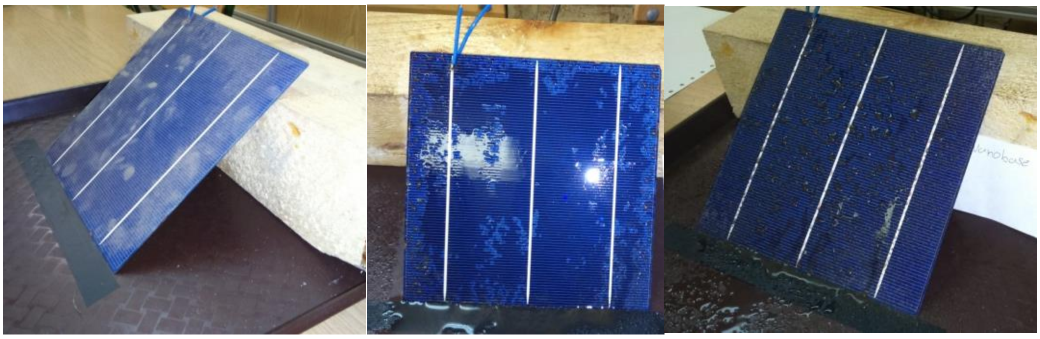

Fig. 18. Solar modules before, after and during the cleaning

It could be observed that in case of the uncoated module the water droplets rather spread on the surface, while for the coated cases regular droplets appeared on the surfaces of the solar modules and the larger droplets rolled down, carrying the dirt with themselves. In Table 1 the relative power-changes of the solar modules in contaminated state relative to the clean one and the relative effect of the cleaning are presented.

Table 1. The Impact of contamination and cleaning on power

Type of coating	Relative power-change due to contamination, %	Relative power-change due to cleaning, %
uncoated	-16.4%	1.3
Nanopro	-7.3%	2.2
Nanobase	-22.2%	19.4
Bodyguard	-23.2%	22.3
Hardbody	-26.1%	25.7
Mistery	-22.3%	21.4

The Fig. 19. illustrate graphically the values of measured relative powers in clear, contaminated and after cleaning states.

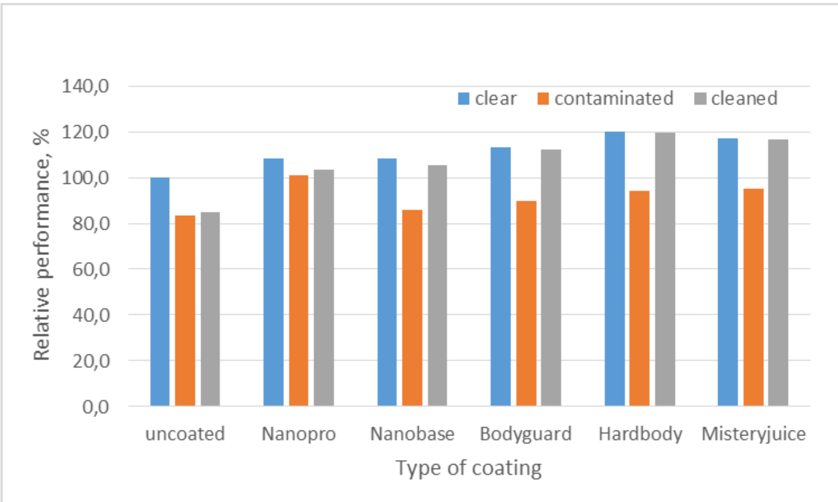

Fig. 19. Clean, dirty and after-cleaning powers compared to uncoated clean solar module power

Based on the data, it can be stated that the power of Nanopro photocatalytic photovoltaic layer decreased the least, which can be explained by the fact that self-cleaning works with the necessary illumination. At lotus effect coatings, the power reduction due to contamination is greater compared to the uncoated solar module, but even in contaminated state, each coated solar module operates at a higher power than the uncoated. The results show the behavior of solar modules in dry, non-precipitation period. Misteryjuice worked the best in contaminated state from coatings using lotus effect, the maximum power was 13.6%

higher than uncoated contaminated solar module. The Hardbody coating was the most sensitive to contamination, the power reduction was 26.1% compared to its clean state. The average power reduction due to contamination in the tested coatings was 20.2%, while the average power growth with the coatings was 13.4%, so the coated solar cells operated on an average of 93.4%, which is 10.2% higher compared to the uncoated reference. After the cleaning with rainwater, the powers were increased. While the power growth of the uncoated and photocatalytic-coated solar modules was only small, 1-2%, for the lotus effect coated modules the simulated rain resulted over 20% average performance growth. The values show that, in the case of uncoated solar modules, the fine dust deposited from the air results in a significant reduction in power and for the removal of this dust the rainwater itself is not enough efficient. As for the contaminating, for the cleaning also the Hardbody coating was the most sensitive. The average power of the coated solar modules after cleaning is 26.5% higher than the reference solar module, which gives almost 4% power surplus by using a self-cleaning coatings, assuming 15% solar module operating efficiency. The result is consistent with the result of Verma et al (2011), who tested 5% efficiency growth by using their anti-reflexive self-cleaning coatings compared to uncoated solar cells. The base of the data, the lotus effect coatings compared to the examined photocatalytic layer are more effective in the case of such precipitation, because after the cleaning they almost returned the initially higher performances. Among the coatings the Hardbody coating was the most effective. Based on power data, the recommended coatings would be the Hardbody for the area where rain often falls, while Nanopro for the areas, poor in the rain. Of course, before application of the coatings beside the power, other factors (e.g. unit price, coating aging, re-applicability) must be taken into the account.

4. Conclusions and proposals

The nanotechnology coatings alone increase the power of the solar modules compared with uncoated one. The surplus was 2%. The reflection spectrum of the examined coated solar modules has similar characteristic curve, the maximum value of the function was found at 550 nm. The coatings reduced the reflection, which depends on wavelengths and angle of incidence. The pollutant has been deposited in different ways and quantities on each solar module, because the coating composition, the application technology and the surface roughness are different. The artificial pollution caused in average 20% decrease in the power. During the cleaning the same amount of water were used under the same conditions. The cleaning caused an average power growth of 18.2%. Among the coatings, lotus-based ones are more sensible for the contaminant, but their self-cleaning is also more effective when exposed to rainwater. Additional tasks: for clarification of coating results coated solar modules under natural conditions should be tested. In addition to the performance growths the testing for durability and economic analysis is another step. As the anti-reflexivity and self-cleaning is also important for the solar collectors and PV/T collectors the examination of coatings can be extended to these devices, too.

Acknowledgements

The authors render thanks the Hungarian NanoBase, NanoPro and Wolf Ltd-s for the layers. This work was supported by the Mechanical Engineering Doctoral School, Szent István University, Gödöllő, Hungary.

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