FACTA UNIVERSITATIS
Series: **Physics, Chemistry and Technology** Vol. 15, N° 2, 2017, pp. 57 - 69
https://doi.org/10.2298/FUPCT1702057R

INVESTIGATION OF THE ENERGY EFFICIENCY OF HORIZONTALLY MOUNTED SOLAR MODULE SOILED WITH $CaCO_3$

UDC 621.311.243

Ivana S. Radonjić*, Tomislav M. Pavlović

Department of Physics, Faculty of Science and Mathematics, University of Niš, Niš, Serbia

Abstract. *Soiling is a term used to describe the deposition of dust (dirt) on solar modules, which reduces the amount of solar radiation reaching the solar cells. Deposition of dust on solar modules can make the operation of the entire PV system - more difficult and, therefore, lead to the generation of less electric energy. Soiling of solar modules also influences solar modules parameters (short-circuit current, open-circuit voltage, maximum power, fill factor and efficiency). This paper presents the results of the investigation on the impact different quantities of calcium carbonate ($CaCO_3$) deposition have on the energy efficiency of horizontally mounted solar modules. The short-circuit current, power and efficiency decrease with increasing the mass of $CaCO_3$ deposited on the horizontally mounted solar module. The open-circuit voltage and fill factor very slightly increase with increasing the mass of $CaCO_3$ deposited on the horizontally mounted solar module. Upon soiling with 1 g of calcium carbonate, the solar module efficiency decreased by 4.6% in relation to the clean solar module, upon soiling with 2 g of calcium carbonate it decreased by 6.0%, and upon soiling with 3 g of calcium carbonate it decreased by 12.9% in relation to the clean solar module. It can be concluded that the power and energy efficiency of the solar module decrease due to the increased amount of calcium carbonate.*

Key words: solar module, soiling, dust, calcium carbonate, efficiency

1. INTRODUCTION

The performance of solar modules is influenced by various factors such as the material the module is manufactured of, the angle of inclination of the solar module, as well as the external factors depending on the module's surrounding environment such as the intensity of the solar radiation reaching the surface of the module, soiling of the

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Received: June 7th, 2017; accepted: November 29th, 2017.
* **Corresponding author**: Ivana S. Radonjić
Department of Physics, Faculty of Science and Mathematics, Višegradska 3, 18000 Niš, Serbia
E-mail: r_ivana_fizika@yahoo.com

module surface, module temperature, environment temperature, relative air humidity, wind speed and direction, etc. (Cano, 2011).

Soiling is a term used to describe the deposition of dust (dirt) on solar modules, which reduces the amount of solar radiation reaching the solar cells. The soiling of solar modules often causes a problem in areas where rain does not fall for the whole month. Due to the deposition of dust on the solar modules, a reduction in the intensity of solar radiation falling on the solar cells occurs. This can make the operation of the entire PV system difficult leading to much less electricity generation (Cano, 2011; Djordjevic et al., 2014).

This paper presents the results of the investigation on the impact different quantities of calcium carbonate ($CaCO_3$) have on the energy efficiency of solar modules.

2. DUST

Dust denotes a mixture of different pollutants that are typical for a particular geographic area (ash, calcium carbonate, sand, mud, clay, cement, etc). The term dust is a general term for any particulate matter with the diameter of less than 500 μm. Important characteristics of dust are the size and distribution of its particles, density, shape, chemical composition, etc. The size and shape of dust particles, as well as the behavior of deposits and the rate of accumulation of dust, depend on the geographical location, climate conditions and urbanization of the specific location. Important environmental conditions that can affect the performance and behavior of dust are air humidity, speed and direction of wind, etc. (Sarver et al., 2013).

Dust gets into the air in different ways: it can be lifted and carried by the wind (windflaws), it can be lifted due to the movement of pedestrians and vehicles, it can occur from vehicle exhausts, from the volcanic eruptions and, in general, air pollution (Darwish et al., 2015; Sarver et al., 2013).

Dust composition reflects the characteristics of the region where it comes from (Sarver et al., 2013). Dust is mostly composed of organic minerals (eg. sand, clay and eroded limestone and the particles arising from the combustion of fossil fuels, but dust may also contain small amounts of pollen, fungi, bacteria, vegetation, microfibers, etc. (Darwish et al., 2015). Air pollution is higher in urban areas because of the higher population density and industrial activity, and they contain in particular particles which are formed as a product of combustion of fossil fuels and the construction activities (Darwish et al., 2015). In rural areas, dust can contain particles from various kinds of fertilizers, windblown soil particles or particles originating from plants (plant matter) (Sarver et al., 2013).

Many studies have investigated the impact of dust on the performance of solar modules, but only a few have examined the effect of different dust pollutant type. Geneally, the influence of different pollutants is tested in a closed space, indoors, and rarely outdoors (Darwish et al., 2015; Mani and Pillai, 2010; Mekhilef et al., 2012; Sarver et al., 2013).

Worldwide, a large number of studies have been carried out to investigate the impact of dust on solar modules energy efficiency. The studies have concluded that due to the solar module’s surface soiling less amount of sun rays reach solar module cells, so the soiled solar modules generate less power than the clean ones. It can also be concluded that the soiled module temperature is lower than the clean module temperature. The experiments used various types of dust: carbon, cement, limestone, calcium carbonate, ash, red soil, silica, sand, sandy soil, clay, mud, talc, fine and coarser mode of air born dust, etc. Most of the research referred to in the literature deal with artificial dust, and only a small number with natural dust (Radonjić et al., 2015). The studies have concluded that any dust type adversely affects the energy efficiency of solar modules, but the greatest impact is ascribed to ash, limestone, calcium carbonate, red soil and sand (Radonjić et al., 2015).

Hereinafter, we will present the results of the impact of varying amounts of calcium carbonate ($CaCO_3$) on the energy efficiency of horizontally-mounted solar modules.

3. Solar Cell Parameters

Solar cell characteristics include short-circuit current (I_{sc}), open-circuit voltage (U_{oc}), maximum power (P_{mpp}), fill factor (FF) and efficiency (η).

Short circuit current (I_{sc})

A short circuit current (I_{sc}) is the maximum current of the solar cell at zero voltage. If the solar cell is short-circuited, the circuit will flow the short-circuit current I_{sc}, which is proportional to the intensity of the solar radiation incident.

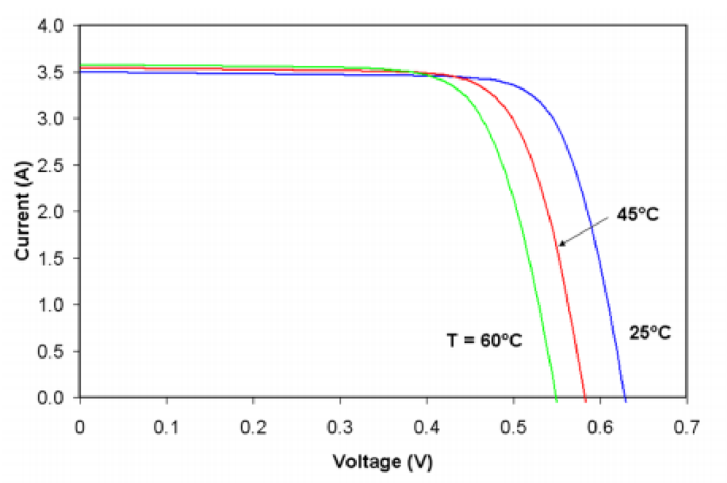

Fig. 1 The impact of monocrystalline silicon solar cell temperature on its current-voltage characteristic

With the increase of the solar cell temperature the short-circuit current increases very slightly (Carr and Pryor, 2004; Honsberg and Bowden, 1999; Makvart and Castaner, 2003; Makvart and Castaner, 2005; Pavlović and Čabrić, 2007).

Open-circuit voltage (U_{oc})

Open-circuit voltage (U_{oc}) is the maximum voltage on the solar cell ends in the open circuit (I=0). Open-circuit voltage decreases with increasing the temperature of the solar cell.

The open-circuit voltage (U_{oc}) changes logarithmically with solar radiation intensity. Reduction in the intensity of solar radiation twice as much means the short circuit current will be reduced twice, and the open-circuit voltage by about 5%. It can be said that the open-circuit voltage is constant with changing solar radiation intensity, unless the value of the solar radiation intensity is less than 100 W/m^2, when there is a substantial reduction in the open-circuit voltage.

The negative impact of temperature rise is most pronounced in the open-circuit voltage. In practice, the solar cell temperature rise is always associated with an increase in the intensity of the solar radiation incident. The intensity of the incident radiation depends on numerous parameters such as the incident angle of solar radiation, time of the day and year, weather conditions, etc. (Carr and Pryor, 2004; Honsberg and Bowden, 1999; Makvart and Castaner, 2003; Makvart and Castaner, 2005; Pavlović and Čabrić, 2007).

Maximum power (P_{mpp})

Solar cell power is obtained as the product of voltage and current. In the knee of current-voltage characteristics of the solar cell, there is an optimum operating point that represents the maximum power (P_{mpp}) of the solar cell in given conditions:

$$P_{mpp} = U_{mpp} \cdot I_{mpp} \quad (1)$$

where I_{mpp} and U_{mpp} are current and voltage corresponding to the maximum power of the solar cell (Carr and Pryor, 2004; Honsberg and Bowden, 1999; Makvart and Castaner, 2003; Makvart and Castaner, 2005; Pavlović and Čabrić, 2007).

Fill factor (FF)

The fill factor indicates how a real solar cell approaches the ideal solar cell. The fill factor (FF) is defined by the following expression:

$$FF = (I_{mpp} \cdot U_{mpp}) / (U_{oc} \cdot I_{sc}) \quad (2)$$

For an optimal operating point the fill factor is less than one. The values of the fill factor usually range between 0.7 and 0.9.

In case two I-U curves have the same values of the short circuit current I_{sc} and the open-circuit voltage U_{oc}, the solar module with a higher value of the fill factor will have higher power. It should be noted that any damage that affects the fill factor reduction at the same time causes a reduction in the output power of the solar module. The solar cell temperature rise causes a decrease in the fill factor (Carr and Pryor, 2004; Honsberg and Bowden, 1999; Makvart and Castaner, 2003; Makvart and Castaner, 2005; Pavlović and Čabrić, 2007).

Solar cell energy efficiency (η)

The energy efficiency of a solar cell (η) is defined as the ratio of the maximum power P_{mpp} and the intensity of solar radiation I_s which falls on the solar cell surface S:

$$\eta = P_{mpp} / (I_s \cdot S) \quad (3)$$

The energy efficiency of the solar cell can be calculated using the following expression (Carr and Pryor, 2004; Honsberg and Bowden, 1999; Makvart and Castaner, 2003; Makvart and Castaner, 2005; Pavlović and Čabrić, 2007):

$$\eta = (I_{mpp} \cdot U_{mpp}) / (I_s \cdot S) = (FF \cdot I_{sc} \cdot U_{oc}) / (I_s \cdot S) \tag{4}$$

4. Experiment

4.1. Experimental setup

The research was conducted at the Laboratory for Solar Energy at the Faculty of Sciences and Mathematics in Nis, Serbia. In the experiment we used two identical Isofoton ISF-60/12 solar modules, individual power of 60 Wp each, made of monocrystalline silicon (Fig. 2). The solar modules were mounted horizontally next to each other on the roof of the Faculty building. Table 1 gives the technical characteristics of ISF-60/12 solar modules.

Fig. 2 **A s**ystem of two identical solar modules ISF-60/12, each of individual power of 60 Wp, horizontally mounted, southward facing

Table 1 Technical characteristics of ISF-60/12 solar module

Dimensions (size)	776 × 662 × 39.5 mm^3
Weight	6.5 kg
Cell type	Si monocrystalline
Power of the module	60 Wp
Module efficiency	11%
Maximum power current	3.47 A
Maximum power voltage	17.3 V
Open circuit voltage	21.6
NOCT (800 W/m^2, 20^oC, AM 1.5, 1m/s)	47^oC
Maximum system voltage	760 V

In the experiment the powers of the horizontally positioned clean and calcium carbonate ($CaCO_3$) soiled solar module were compared. Varying amounts of calcium carbonate were deposited on the horizontal module in order to determine its impact on the energy efficiency of the solar modules. For the solar module, soiling $CaCO_3$ was used because it is most often a part of dust in urban areas.

4.2. Measuring equipment

To determine the current-voltage characteristics of the solar modules, a MiniKLA device from Mencke & Tegtmeyer (Germany) was used. During the measurements the values of the short-circuit current (I_{sc}), open-circuit voltage (U_{oc}), working point power (P_{mpp}), and the fill factor (FF) of the solar modules were recorded.

The solar radiation intensity incidence on the solar module set at the optimum angle was measured with Sunny Web Box (SMA, Germany).

For the observation of $CaCO_3$ particles a scanning electron microscope JEOL JSM-5300 (Japan) was used.

4.3. Calculation of solar radiation intensity falling on horizontally mounted surface

Bearing in mind that during the experiment solar radiation intensity falling on the horizontal surface was not measured, it was set for its calculation. When one knows the value of solar radiation intensity that reaches the surface oriented towards the south and set at an angle in relation to the horizontal plane (I_m), then the values of solar radiation intensity that reaches the horizontal surface (I_h) can be calculated using the following expression:

$$I_h = I_m \cdot (\sin\alpha) / \sin(\alpha + \beta) \tag{5}$$

where α-is the elevation angle of the Sun (the altitude of the Sun), and β-is the angle at which the solar module is tilted relative to the horizontal surface.

The elevation angle α is calculated using the relation:

$$\alpha = 90 - \varphi + \delta \tag{6}$$

where φ- is latitude, and δ- is the declination angle of the Sun given by the relation:

$$\delta = 23.45^o \cdot \sin[360 \cdot (284 + d) / 365] \tag{7}$$

where d-is the number of the days in a year.

The height of the Sun in the sky changes during the day and during the year. Solar radiation intensity was measured on 5 August 2016 for an optimally oriented surface, and for the horizontal surface was calculated by the formula (5) - (7). The height of the Sun in the sky depends on the day of the year when the measurement was performed, as well as on the latitude of the place where the measurement is performed. Given the fact that the measurement was carried out on 5 August 2016 i.e. during summer, the Sun was high in the sky and the declination angle δ was 16.6^o.

4.4. Measurement

On 5 August 2016 the influence of different amounts of $CaCO_3$ on the energy efficiency of the horizontally mounted solar module was investigated.

On the measurement day, 5 August 2016, two horizontally mounted solar modules were cleaned first to remove any dirt. During the measurement, the right solar module was clean and not soiled at all. The left module was uniformly soiled by spraying a certain amount of water containing 1 g of calcium carbonate followed by the first measurement at 12:10. The surface of one solar module was $S=0.514\ m^2$ so the concentration of calcium carbonate on the soiled solar module before the first measurement was 1.945 g/m^2. After the first measurement, the left module was additionally uniformly soiled by spraying a certain amount of water containing 1 g of calcium carbonate, so that the concentration of calcium carbonate on the soiled solar module before the second measurement was 3.891 g/m^2, and at 12:20 the second measurement was performed. After the second measurement, the left module was additionally uniformly soiled by spraying a certain amount of water containing 1 g of calcium carbonate, so that the concentration of calcium carbonate on the soiled solar module before the third measurement was 5.837 g/m^2, and at 12:30 the third measurement was performed.

4.5. Results

SEM images with different magnification of $CaCO_3$ particles taken from a soiled solar module are given in Figures 3 and 4.

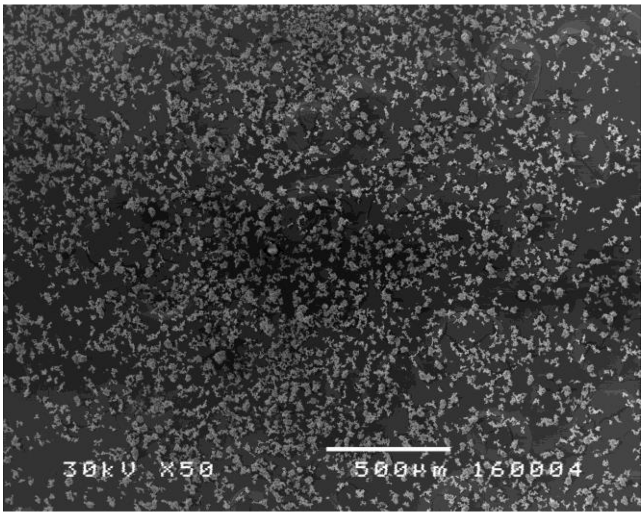

Fig. 3 SEM image of $CaCO_3$ particles at magnification of U=50×

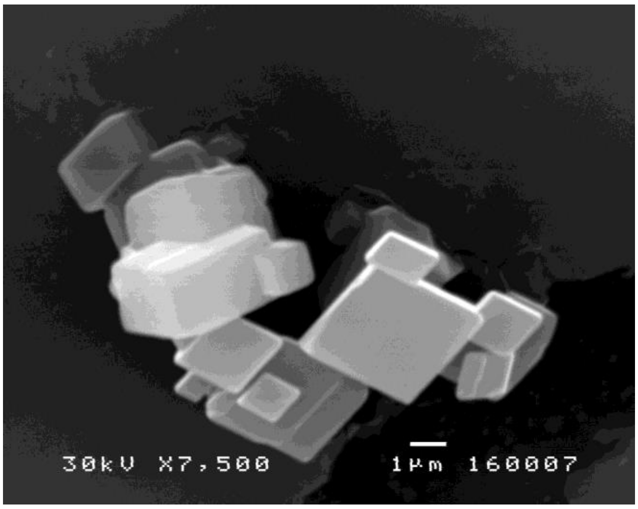

Fig. 4 SEM image of $CaCO_3$ particles at magnification of U=7500×

Figure 4 shows that $CaCO_3$ particles have a cubic structure diameter of about 30 μm.

Solar radiation intensity that falls on the horizontally mounted solar module ($I_{horizontal}$), the mass of $CaCO_3$, the power of the clean (P_c) and the $CaCO_3$ soiled solar module (P_d), power reduction due to the solar module soiling (ΔP), the efficiency of the clean (η_c) and the $CaCO_3$ soiled solar module (η_d) and the reduction in the efficiency due to the solar module soiling ($\Delta\eta$) on 05.08.2016, for the horizontally mounted solar modules are given in Table 2.

Table 2 Solar radiation intensity that falls on the horizontally mounted solar module ($I_{horizontal}$), the mass of $CaCO_3$, the power of the clean (P_c) and the $CaCO_3$ soiled solar module (P_d), power reduction due to the solar module soiling (ΔP), the efficiency of the clean (η_c) and the $CaCO_3$ soiled solar module (η_d) and the reduction in the efficiency due to the solar module soiling ($\Delta\eta$) on 5 August 2016 for the horizontally mounted solar modules

t (h)	$I_{horizontal}$ (W/m^2)	m (g)	P_c clean (W)	P_d soiled (W)	ΔP (%)	η_c clean (%)	η_d soiled (%)	$\Delta\eta$ (%)	Normalized P (%)	Normalized η (%)
12:10	902.8	1	40.7	39.0	4.2	8.8	8.4	4.6	95.8	95.4
12:20	918.9	2	39.4	37.0	6.1	8.3	7.8	6.0	93.9	94.0
12:30	919.8	3	40.4	34.8	13.9	8.5	7.4	12.9	86.1	87.1

Due to the horizontally mounted solar module soiling with 1 g, 2 g, and 3 g of $CaCO_3$ the solar module efficiency was reduced by 4.6%, 6.0%, and 12.9%, respectively as compared to the clean module (Tab. 2).

The current-voltage characteristics of the horizontally mounted solar module depending on the soiling on its surface with different amounts of $CaCO_3$ is given in Fig. 5.

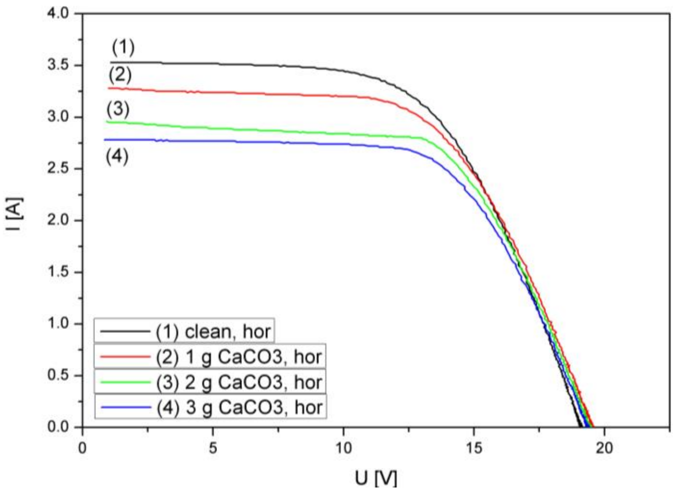

Fig. 5 Current-voltage characteristics of the horizontally mounted solar module depending on the soiling of its surface with different amounts of $CaCO_3$

The figure shows that the increase of the solar module soiling causes the solar module current decrease.

Dependence of I_{sc} on the horizontally mounted solar module surface soiling with different amounts of $CaCO_3$ is given in Fig. 6.

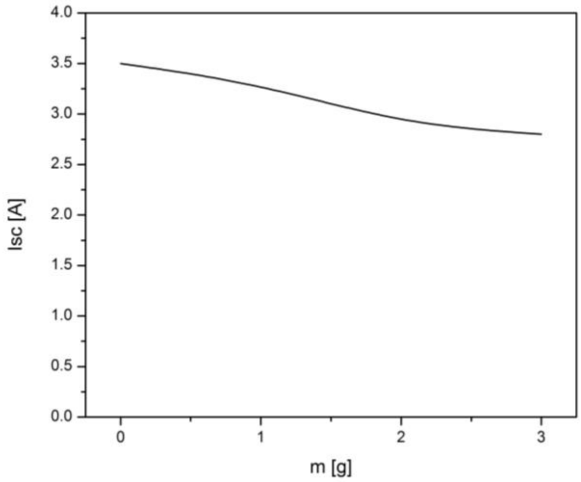

Fig. 6 Dependence of I_{sc} on the horizontally mounted solar module surface soiling with different amounts of $CaCO_3$

Figure 6 shows that I_{sc} decreases with the increasing of the amount of $CaCO_3$ deposited onto the horizontally mounted solar module, which is consistent with the fact that I_{sc} is proportional to the solar radiation intensity incident.

Dependence of U_{oc} on the horizontally mounted solar module surface soiling with different amounts of $CaCO_3$ is given in Fig. 7.

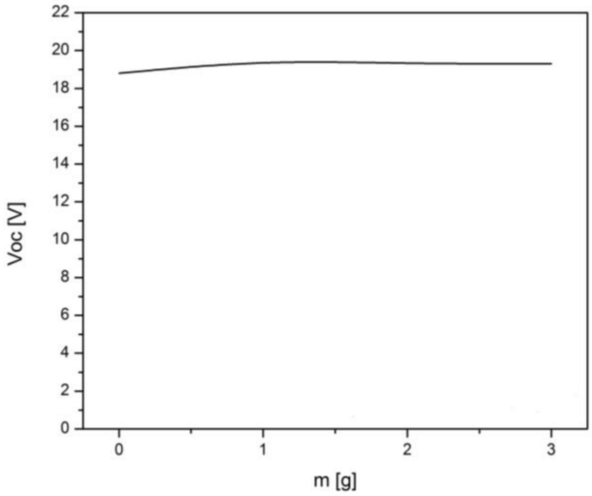

Fig. 7 Dependence of U_{oc} on the horizontally mounted solar module surface soiling with different amounts of $CaCO_3$

Figure 7 shows that U_{oc} very slightly increases with increasing the mass of $CaCO_3$ deposited on the horizontally mounted solar module. This is consistent with the fact that U_{oc} is almost constant with a change in solar radiation intensity.

Dependence of the power obtained by horizontally mounted solar modules on the soiling of their surfaces with different amounts of $CaCO_3$ is given in Fig. 8.

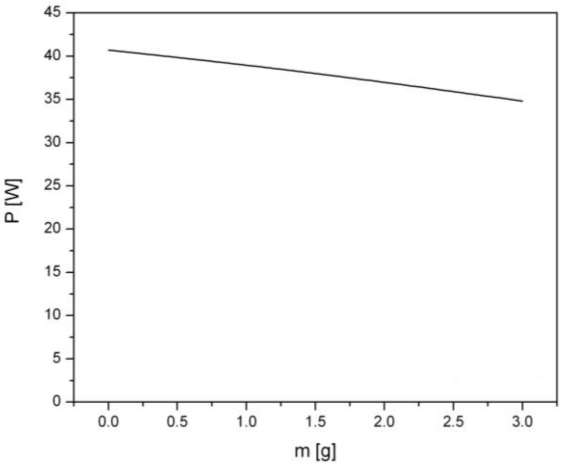

Fig. 8 Dependence of the power obtained by horizontally mounted solar moduleson the soiling of their surfaces with different amounts of $CaCO_3$

Figure 8 shows that the power obtained by a horizontally mounted solar module decreases with increasing the mass of $CaCO_3$ deposited on its surface.

FF dependence on the the horizontally mounted solar module surface soiling with different amounts of $CaCO_3$ is given in Fig. 9.

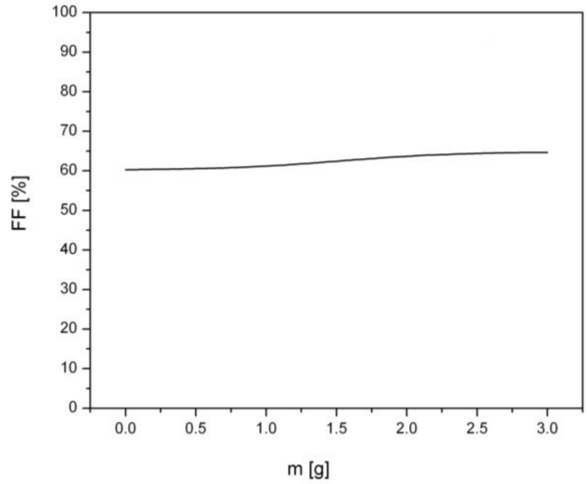

Fig. 9 *FF* dependence on the the horizontally mounted solar module surface soiling with different amounts of $CaCO_3$

Figure 9 shows that *FF* very slightly increases with increasing the mass of calcium carbonate deposited on the horizontally mounted solar module.

The dependence of the efficiency of a horizontally mounted clean and solar module soiled with $CaCO_3$ is given in Fig. 10.

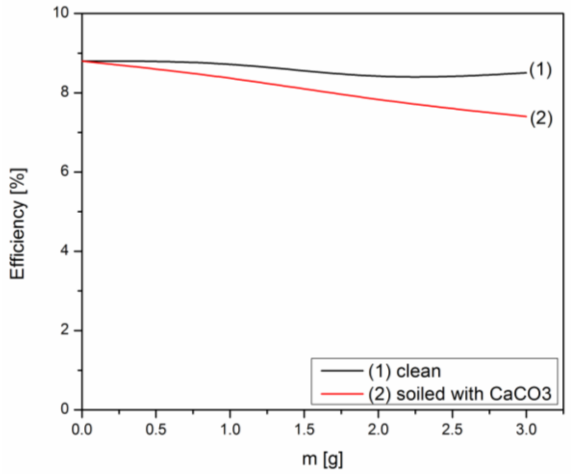

Fig. 10 The dependence of the efficiency of a horizontally mounted clean and solar module soiled with $CaCO_3$

Dependence of the normalized efficiency of a horizontally mounted solar module on the soiling of its surface with different amounts of $CaCO_3$ is given in Fig. 11.

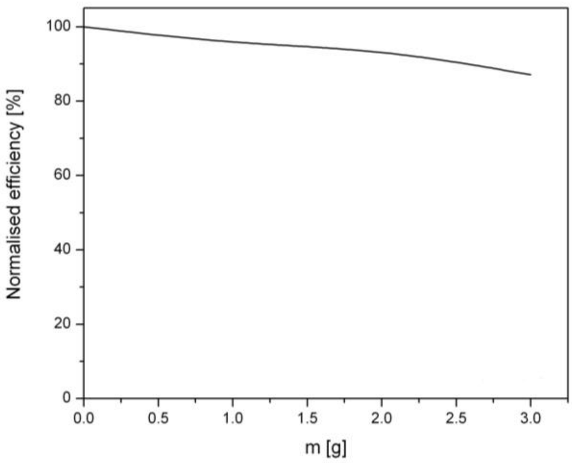

Fig. 11 Dependence of the normalized efficiency of a horizontally mounted solar module on the soiling of its surface with different amounts of $CaCO_3$

Figure 11 shows that the normalized efficiency of the horizontally mounted soiled solar module decreases with increasing the amounts of $CaCO_3$ on its surface.

CONCLUSION

Due to dust deposition on solar modules there is a decrease in the intensity of solar radiation that falls on the solar cells, which can induce a difficulty in the PV system funtioning and, consequently, a lower electricity generation. The research carried out in the world led to the conclusion that any dust (ash, limestone, calcium carbonate, red soil, sand, etc) adversely affects the energy efficiency of the solar modules.

Based on the results obtained in this paper, the following can be concluded:

- Short-circuit current decreases with increasing the mass of $CaCO_3$ deposited on the horizontally mounted solar module, which is in line with the fact that the short-circuit current is proportional to the intensity of the solar radiation incident.
- Open-circuit voltage very slightly increases with increasing the mass of $CaCO_3$ deposited on the horizontally mounted solar module, which is in line with the fact that U_{oc} is almost constant with a change in the intensity of solar radiation.
- The power obtained by a horizontally mounted solar module decreases with increasing the mass of $CaCO_3$ on its surface.
- The fill factor slightly increases with increasing the mass of $CaCO_3$ deposited on the horizontally mounted solar module.
- The efficiency of the horizontally mounted solar module decreases with increasing the amount of $CaCO_3$ deposited on its surface.

The obtained results are important for the practical application of solar modules in solar power plants, outdoors, industry, airports, roads, community facilities, private homes, etc., in our country and worldwide.

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ISPITIVANJE ENERGETSKE EFIKASNOSTI HORIZONTALNO POSTAVLJENOG SOLARNOG MODULA ZAPRLJANOG SA $CaCO_3$

Zaprljanost je termin koji se koristi za opisivanje taloženja prašine (prljavštine) na solarnim modulima koja smanjuje količinu Sunčevog zračenja koje dospeva do solarnih ćelija. Usled taloženja prašine na solarnim modulima može doći do otežanog rada celog PV sistema i do dobijanja manje električne energije. Zaprljavanje solarnih modula takođe utiče i na parametre solarnih modula (struju kratkog spoja, napon otvorenog kola, maksimalnu snagu, fil faktor i efikasnost). U ovom radu su dati rezultati ispitivanja uticaja različitih količina kalcijum-karbonata ($CaCO_3$) na energetsku efikasnost horizontalno postavljenog solarnog modula. Struja kratkog spoja, snaga i efikasnost opadaju sa povećanjem mase $CaCO_3$ nanete na horizontalno postavljen solarni modul. Napon otvorenog kola i fil faktor veoma blago rastu sa povećanjem mase $CaCO_3$ nanete na horizontalno postavljen solarni modul. Efikasnost solarnog modula usled zaprljavanja sa 1 g kalcijum-karbonata opada za 4.6% u odnosu na čist solarni modul, usled zaprljavanja sa 2 g kalcijum-karbonata opada za 6.0% i usled zaprljavanja sa 3 g kalcijum-karbonata opada za 12.9% u odnosu na čist solarni modul. Može se zaključiti da snaga i energetska efikasnost solarnog modula opadaju usled povećanja količine kalcijum-karbonata.

Ključne reči: *solarni modul, zaprljanost, prašina, kalcijum-karbonat, efikasnost*