INVESTIGATION OF THE IMPACT OF ATMOSPHERIC POLLUTANTS ON SOLAR MODULE ENERGY EFFICIENCY

by

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Soiling is a term used to describe the deposition of dust (dirt) on the solar modules, which reduces the amount of solar radiation that reaches the solar cells. This can cause a more difficult operation of the entire photovoltaic system and therefore generation of less electric energy. This paper presents the results of the influence of various pollutants commonly found in the air (carbon, calcium carbonate – $CaCO_3$, and soil particles) on the energy efficiency of solar modules. Scanning electron microscope investigation of carbon powder, $CaCO_3$, and soil particles which were applied to solar modules showed that the particles of carbon and $CaCO_3$ are similar in size, while the space between the particles through which the light can pass, is smaller in carbon than in $CaCO_3$. Dimensions of soil particles are different, and the space between the soil particles through which the light can pass is similar to $CaCO_3$. Solar radiation more easily reaches the surface of solar modules soiled by $CaCO_3$ and soil particles than the surface of the solar modules soiled by carbon. The efficiency of the module soiled by carbon on average decreases by 37.6%, the efficiency of the module soiled by $CaCO_3$ by 6.7%, and the efficiency of the module soiled by soil particles by 6.8%, as compared to the clean solar module. The greatest influence on reducing the energy efficiency of solar modules by soiling exerts carbon, and the influence of $CaCO_3$ and soil particles is similar.

Key words: *soiling, dust, solar module, efficiency, carbon, $CaCO_3$, soil*

Introduction

Much time and money has been spent on improving the components to make photovoltaic (PV) systems reliable during their exploitation. One fact almost not at all taken into account when examining the majority of PV systems is the impact of the deposition of particles of dust or dirt on the surface of solar modules that are exposed to solar radiation [1-11].

The performance of the solar modules is influenced by various factors such as the material the module is manufactured of, the angle of inclination of the solar module (angle at which it is set - tilt angle), the intensity of the solar radiation reaching the surface of the module, soiling of the module surface, module temperature, *etc*. Soiling is a term used to describe the deposition of dust (dirt) on the solar modules, which reduces the amount of solar radiation reaching the solar cells. Soiling of solar modules is often a problem in areas where rain does

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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 cause difficult operation of the entire PV system and therefore much less electricity generation [12-14].

This paper presents the results of the impact of various pollutants that are commonly found in the air (carbon, $CaCO_3$, and soil particles) on the solar modules energy efficiency.

Dust

Dust denotes a mixture of different pollutants that are typical for a particular geographic area. The word dust is a general term for any particulate matter 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 behaviour 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 behaviour of dust are air humidity (moisture), speed and direction of wind, *etc*. [10].

The 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 due to air pollution [1, 10].

The composition of the dust reflects the characteristics of the region it comes from [10]. Dust is mostly composed of organic minerals (*e. g.* sand, clay, and eroded limestone) and particles arising from the combustion of fossil fuels, but dust may also contain small amounts of pollen and fungi, bacteria, vegetation, microfibers, *etc*. [1]. Air pollution is higher in urban areas due to the high population density and industrial activities, and particles formed as a product of the combustion of fossil fuels and construction activities are mostly present in it [1]. In rural areas in the dust particles of various types of fertilizers, windblown soil particles or plant matter particles can be found [10].

Many studies have examined the impact of the dust on the solar modules performance, but only a few have examined the effect of different types of particles (dust pollutant type) on the performance of solar modules. Studies have examined mainly the impact of various pollutants indoors, but rarely outdoors [1, 10, 15-18].

Worldwide a large number of studies have investigated the impact of dust on the energy efficiency of solar modules. In these studies it was concluded that all types of dust adversely affect the energy efficiency of solar modules, but most influence was exerted by ash, limestone, $CaCO_3$, red soil and sand [19].

El-Shobokshy and Hussein [20] were among the first to examine the effects of dust on the energy efficiency of PV systems. In this research, three types of *laboratory-defined* dust which are often present in the atmosphere such as limestone, cement, and carbon were used. El-Shobokshy and Hussein [20] have concluded that the degradation of PV module perfor-mance depends not only on the deposition of dust, but also on the type of dust and its particle size distribution. The accumulation of finer dust (dust particles of smaller size) on the surface of the solar modules has a much greater negative impact on their performance than the accumulation of the coarser dust (dust particles of larger size). Finer dust particles are distributed homogeneously (more uniformly) than the coarser dust particles so that the space between the particles, through which light can pass within the finer dust is smaller than in the coarser ones. It was also noted that the type of dust affects the performance of solar modules. For example, carbon particles absorb solar radiation more easily than limestone and cement do [19].

Cleaning and maintaining

To enhance the energy efficiency of solar modules, it is obligatory to perform their occasional cleaning to remove all the dirt deposited on their surfaces. There are general recommendations for the proper cleaning and maintenance of solar modules depending on the climate conditions in which they are operating [19].

Cleaning of solar modules is performed in different ways, using different means. The most effective means of cleaning solar modules is water. To remove sticky or muddy dirt one uses water under pressure or a brush. In rainy periods, rain removes all the dust from the solar modules. However, in rain-free periods (*e. g.* in summer) the accumulation of dust on the surface of solar modules in some areas of the world can cause daily losses exceeding 20%.

To water clean solar modules different automation systems are used such as systems with nozzles, systems with brushes, *etc*. Nozzles systems can use fixed or sliding nozzles. In systems with a brush, a system with fixed nozzles is added to a movable brush which can slide or rotate on the surface of the solar module.

All these systems are fully automated and contain sensors that control their operation (determining the appropriate time for the cleaning and the proper amount of water required for cleaning). These systems clean the solar modules and at the same time perform their cooling. Due to the cleaning of solar modules in this manner, their efficiency is increased to 15% [21].

Experiment

The experiment was conducted to compare the power of the clean and soiled solar modules with three pollutants: $CaCO_3$, carbon, and soil particles. The experiment used the same amount of pollutants of 2.7 g per module to determine which of these pollutants has the greatest impact on the solar modules energy efficiency. For solar modules soiling carbon is used because it is obtained from the combustion of fossil fuels, $CaCO_3$ is used because it usually enters the composition of dust in urban areas, and soil is used because a large number of PV power plants are placed directly on the ground and soil particles carried by the wind can easily deposit on the solar modules.

The research was conducted in the Laboratory for Solar Energy at the Faculty of Science and Mathematics in city of Nis, Serbia. In the experiment two identical monocrystalline silicon Isofoton solar modules ISF-60/12 were used, placed side by side on the roof of the faculty, fig. 1. Solar modules are set at the optimum angle of 32° for the area of Nis and are facing south. Table 1 gives technical characteristics of ISF-60/12 solar modules. At the start of the experiment, on September 14, 2015, at 10:53 a. m. the power of both solar modules in clean condition was measured and measured values for both modules were the same *i. e*. 42.2 W.

Figure 1. Two identical monocrystalline silicon solar modules ISF-60/12 on the roof of the Faculty of Science and Mathematics in Nis, used in the experiment

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

Dimensions (size)	776 × 662 × 39.5 mm
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 °C, AM 1.5, 1 m/s)	47 °C
Maximum system voltage	760 V

To determine the power of solar modules a MiniKLA device from Mencke and Tegtmeyer, Hameln, Germany, was used. During the measurements maximum power point values, P_{mpp}, of solar modules were recorded.

The solar radiation intensity incidence on the solar module set at the optimum angle was measured by Sunny Web Box from SMA, Niestetal, Germany.

At each measurement, always performed on a clear day, first both solar modules were cleaned to remove all dirt. Thereafter, left module was uniformly soiled by spraying the same quantity of water, always containing 2.7 g of each respective pollutant. Every part of the left module was sprayed with the same quantity of water containing the appropriate pollutant. Then, enough time was left for sprayed water to evaporate so that the temperature of both solar modules is the same. The area of one solar module is $A = 0.514$ m^2 so the concentration of the certain pollutant on the surface of the solar module is always equal 5.253 g/m^2.

For the observation of the particles of dissolved powder of carbon, $CaCO_3$, and soil, a scanning electron microscope (SEM) JEOL JSM-5300 (Japan) was used.

A formula was used to determine the efficiency of solar modules:

$$\eta = \frac{P}{I A} \tag{1}$$

where P is the power of solar modules, I – the intensity of solar radiation, and A – a surface of the solar module.

Carbon

On September 16, 2015, the impact of carbon on the energy efficiency of monocrystalline silicon solar modules was examined. Figures 2 and 3 show SEM images of carbon particles used in the experiment at different magnifications.

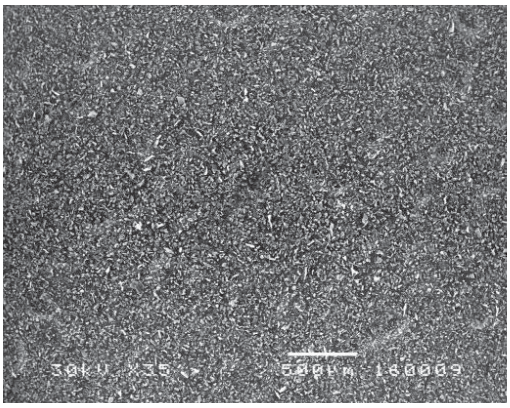

Figure 2. The SEM image of carbon particles at 35x magnification

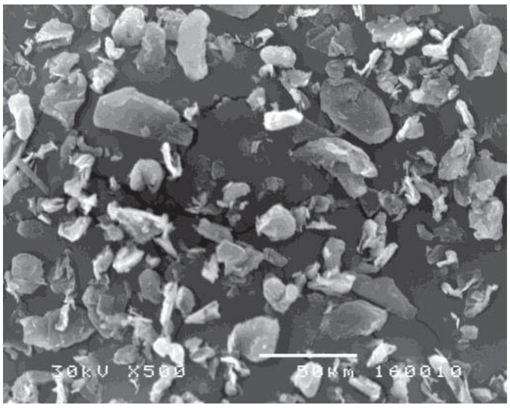

Figure 3. The SEM image of carbon particles at 500x magnification

Figure 2 shows that the carbon particles are distributed homogeneously and densely so that the space between the particles through which the light can pass is very small. Figure 3 shows that the carbon particles have a leaf structure, are of small thickness, with a diameter of about 30 μm.

Left module was soiled with carbon while the right module remained clean. In the period from 11:00 a. m. to 1:00 p. m. every 10 minutes the power of the clean and carbon soiled modules was measured by MiniKLA device. Table 2 gives the values of the measured power for the clean and carbon soiled solar module. That day in the period from 11:00 a. m. to 1:00 p. m. a mean value of the solar radiation intensity on the solar module, set at the optimum angle, was 948.8 W/m^2.

Table 2 gives the values for the solar radiation intensity incidence on the solar module set at the optimum angle, I, the power of the clean, P_c, and the carbon soiled solar module, P_s, power reduction due to the solar module soiling, ΔP, the efficiency of the clean, η_c, and carbon soiled solar module, η_s, and the reduction in efficiency due to the solar module soiling, $\Delta\eta$, on September 16, 2015.

The data in tab. 2 show that the difference in power between the clean and carbon soiled module ranges from 14.7 W to 16.9 W, or from 35.8% to 39.9%. Power of the carbon soiled module was on average reduced by 37.8% compared to the clean solar module. The clean solar module in the period from 11:00 a. m. to 1:00 p. m. generated 92.7 Wh of electricity and the carbon soiled module generated in the same period 57.55 Wh of electricity. The difference in efficiency between the clean and carbon soiled module ranged from 35.4% to 39.8%. The efficiency of the carbon soiled module was reduced on average by 37.6% as compared to the clean solar module.

Table 2. The solar radiation intensity incidence on the solar module set at the optimum angle (*I*) on September 16, 2015

t [h]	I [Wm^{-2}]	P_c [W]	P_s [W]	ΔP [%]	η_{c*} [%]	η_{s*} [%]	$\Delta\eta$ [%]
11:00	833	41.3	25.5	38.3	9.6	6.0	37.5
11:10	862	42.6	26.3	38.3	9.6	5.9	38.5
11:20	886	42.4	25.5	39.9	9.3	5.6	39.8
11:30	911	42.7	26.7	37.5	9.1	5.7	37.4
11:40	935	43.7	27.2	37.8	9.1	5.7	37.4
11:50	954	45.0	27.7	38.4	9.2	5.6	39.1
12:00	966	44.9	27.7	38.3	9.0	5.6	37.8
12:10	979	43.0	26.9	37.4	8.5	5.3	37.7
12:20	989	41.9	26.3	37.2	8.2	5.2	36.6
12:30	994	41.9	26.2	37.4	8.2	5.1	37.8
12:40	1003	43.2	26.6	38.4	8.4	5.2	38.1
12:50	1009	41.9	26.3	37.2	8.0	5.1	36.2
13:00	1014	41.1	26.4	35.8	7.9	5.1	35.4
	$I_{avg.}$ = 948.8	$P_{c,\,avg.}$ = 42.7	$P_{s,\,avg.}$ = 26.5	$\Delta P_{avg.}$ = 37.8	$\eta_{c,\,avg.}$ = 8.8	$\eta_{s,\,avg.}$ = 5.5	$\Delta\eta_{avg.}$ = 37.6

Efficiency η_c and η_s are calculated using eq. (1)

Calcium carbonate

On September 14, 2015 the influence of $CaCO_3$ on the energy efficiency of the mono-crystalline silicon solar modules was examined. Figures 4 and 5 show SEM images of $CaCO_3$ particles used in the experiment at different magnifications.

Figure 4 shows that the particles of $CaCO_3$ are distributed homogeneously, but the space between the particles through which light can pass is larger than that of carbon particles. Figure 5 shows that $CaCO_3$ particles have a cubic structure, and their diameter is about 30 μm.

Left module was $CaCO_3$ soiled while the right module remained clean. In the period from 11:20 a. m. to 1:20 p. m. every 10 minutes the power of the clean and $CaCO_3$ soiled modules was measured by MiniKLA device. Table 3 gives the values of the measured power for the clean and $CaCO_3$ soiled solar module. That day in the period from 11:20 a. m. to 1:20 p. m. a mean value of the solar radiation intensity on the solar module, set at the optimum angle, was 983.6 W/m^2.

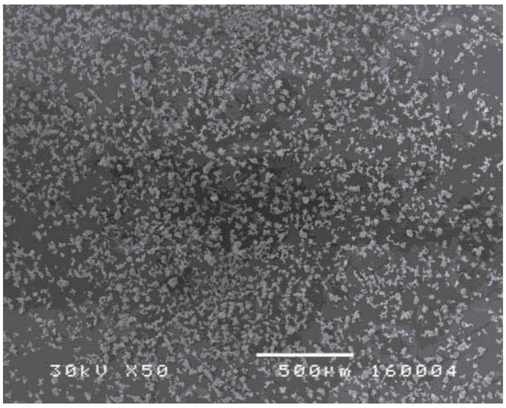

Figure 4. The SEM image of $CaCO_3$ particles at 50x magnification

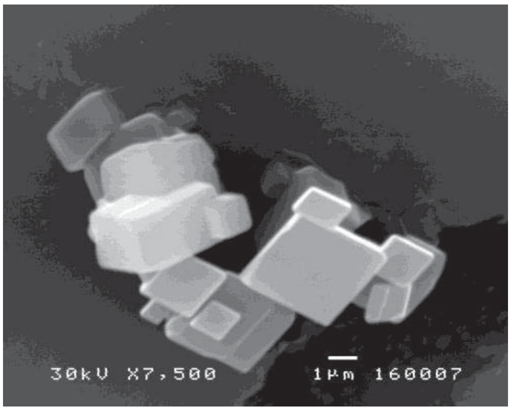

Figure 5. The SEM image of $CaCO_3$ particles at 7500x magnification

Table 3 gives the values for the solar radiation intensity incidence on the solar module set at the optimum angle, I, the power of the clean, P_c, and the $CaCO_3$ soiled solar module, P_s, power reduction due to the solar module soiling, ΔP, the efficiency of the clean, η_c, and $CaCO_3$ soiled solar module, η_s, and the reduction in efficiency due to the solar module soiling, $\Delta\eta$, on September 14, 2015.

Table 3. The solar radiation intensity that falls on the solar module set at the optimum angle (I) on September 14, 2015

t [h]	I [Wm^{-2}]	Pc [W]	Ps [W]	ΔP [%]	η_c* [%]	η_s* [%]	$\Delta\eta$ [%]
11:20	886	43.9	40.9	6.8	9.6	9.0	6.2
11:30	915	43.8	41.0	6.4	9.3	8.7	6.5
11:40	933	43.9	40.8	7.1	9.1	8.5	6.6
11:50	961	43.6	40.9	6.2	8.8	8.3	5.7
12:00	973	43.5	39.7	8.7	8.7	7.9	9.2
12:10	990	43.7	40.7	6.9	8.6	8.0	7.0
12:20	1006	43.7	40.9	6.4	8.4	7.9	6.0
12:30	1012	44.3	41.3	6.8	8.5	7.9	7.1
12:40	1016	44.2	41.7	5.7	8.5	8.0	5.9
12:50	1022	44.5	41.2	7.4	8.5	7.8	8.2
13:00	1024	44.3	40.6	8.4	8.4	7.7	8.3
13:10	1026	44.4	42.1	5.2	8.4	8.0	4.8
13:20	1023	44.9	42.3	5.8	8.5	8.0	5.9
	$I_{avg.}$ = 983.6	$P_{c, avg.}$ = 44.1	$P_{s, avg.}$ = 41.1	$\Delta P_{avg.}$ = 6.7	$\eta_{c, avg.}$ = 8.7	$\eta_{s, avg.}$ = 8.1	$\Delta\eta_{avg.}$ = 6.7%

Efficiency η_c and η_s are calculated using eq. (1)

The data in tab. 3 show that the difference in power between the clean and $CaCO_3$ soiled module ranges from 2.3 W do 3.8 W, or from 5.2% to 8.7%. Power of the $CaCO_3$ soiled module was on average reduced by 6.7% compared to the clean solar module. The clean solar module in the period from 11:20 a. m. to 1:20 p. m. generated 95.55 Wh of electricity and the $CaCO_3$ soiled module generated in the same period 89 Wh of electricity. The difference in efficiency between the clean and $CaCO_3$ soiled module ranged from 4.8% to 9.2%. The efficiency of the $CaCO_3$ soiled module was reduced on average by 6.7% as compared to the clean solar module.

Soil

On October 30, 2015, the influence of the soil particles on the energy efficiency of the monocrystalline silicon solar modules was examined. Figures 6 and 7 show SEM images of the soil particles used in the experiment at different magnifications.

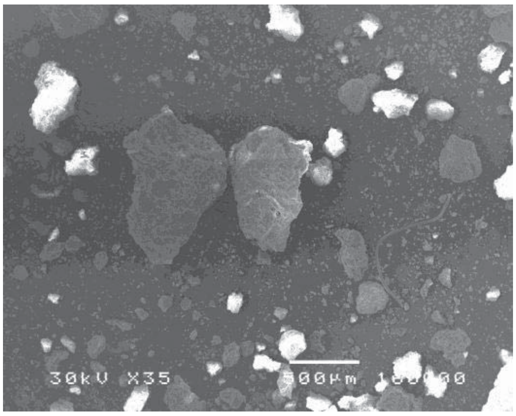

Figure 6. The SEM image of the soil particles at 35x magnification

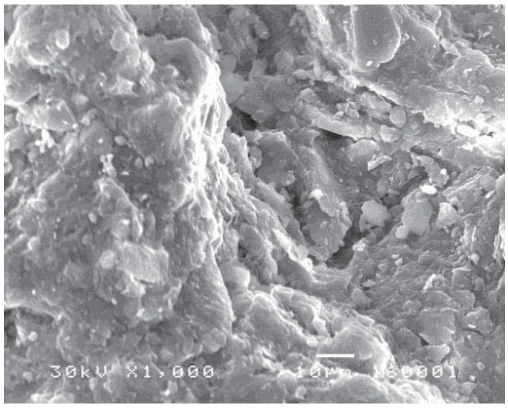

Figure 7. The SEM image of the larger soil particle at 1000x magnification

Figure 6 shows that the soil particles are considerably different ranging in diameter from 20 μm up to 300 μm, and small number of particles is of diameter up to 500 μm. The space between the soil particles through which light can pass is larger than that of the carbon particles.

Left module was soil particles soiled while the right module remained clean. In the period from 11:00 a. m. to 1:00 p. m. every 10 minutes the power of the clean and soil particles soiled modules was measured by MiniKLA device. Table 4 gives the values of the measured power for the clean and soil particles soiled solar module. That day in the period from 11:00 a. m. to 1:00 p. m. a mean value of the solar radiation intensity on the solar module, set at the optimum angle, was 836.2 W/m^2.

Table 4 gives the values for the solar radiation intensity incidence on the solar module set at the optimum angle, I, the power of the clean, P_c, and the soil particles soiled solar module P_s, power reduction due to the solar module soiling, ΔP, the efficiency of the clean, η_c, and the soil particles soiled solar module, η_s, and the reduction in efficiency due to the solar module soiling, $\Delta\eta$, on October 30, 2015.

The data in tab. 4 show that the difference in power between the clean and the soil particles soiled module ranges from 2.6 W to 3.9 W, or from 6.0% to 8.6%. Power of the soil particles soiled module was on average reduced by 7.3% as compared to the clean solar module. The clean solar module in the period from 11:00 a. m. to 1:00 p. m. generated 98.9 Wh of electricity and the soil particles soiled module generated in the same period 91.75 Wh of electricity. The difference in efficiency between the clean and soil particles soiled module ranged from 4.8% to 8.6%. The efficiency of the soil particles soiled module was reduced on average by 6.8% as compared to the clean solar module.

Table 4. The solar radiation intensity that falls on the solar module set at the optimum angle (*I*) on October 30, 2015

t [h]	I [Wm^{-2}]	P_c [W]	P_s [W]	ΔP [%]	η_c [%]	η_s [%]	$\Delta\eta$ [%]
11:00	831	46.2	42.5	8.0	10.8	9.9	8.3
11:10	841	46.4	43.5	6.3	10.7	10.1	5.6
11:20	851	46.9	43.2	7.9	10.7	9.9	7.5
11:30	855	46.8	43.8	6.4	10.6	10.0	5.7
11:40	857	46.4	43.2	6.9	10.5	9.8	6.7
11:50	860	47.0	43.2	8.1	10.6	10.0	5.7
12:00	862	46.7	43.7	6.4	10.5	10.0	4.8
12:10	853	46.6	43.1	7.5	10.6	9.8	7.6
12:20	847	45.6	41.7	8.6	10.5	9.6	8.6
12:30	834	45.3	42.1	7.1	10.6	9.8	7.6
12:40	815	43.5	40.9	6.0	10.4	9.8	5.8
12:50	791	43.0	39.9	7.2	10.6	9.8	7.6
13:00	774	43.1	39.6	8.1	10.8	10.0	7.4
	$I_{avg.}$ = 36.2	$P_{c,\ avg.}$ = 45.6	$P_{s,\ avg.}$ = 42.3	$\Delta P_{avg.}$ = 7.3	$\eta_{c,\ avg.}$ = 10.6%	$\eta_{s,\ avg.}$ = 9.9	$\Delta\eta_{avg.}$ = 6.8%

Efficiency η_c and η_s are calculated using eq. (1)

Comparison of the impact of carbon, $CaCO_3$, and soil on characteristics of solar modules

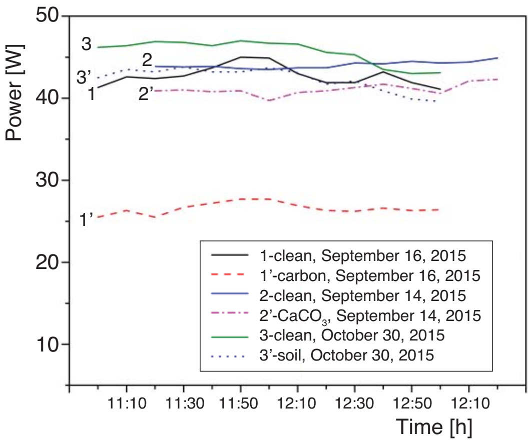

Figure 8. The clean modules power and carbon, $CaCO_3$, and soil soiled modules power as a function of time for appropriate dates wherein the modules are placed at the optimum angle

The SEM examination of carbon, $CaCO_3$, and soil particles showed that the carbon and the $CaCO_3$ particles are similar in size, while the space between the particles through which light can pass in carbon is less than that of $CaCO_3$. The dimensions of the soil particles are different, and the space between the soil particles through which light can pass is similar to $CaCO_3$. It can be concluded that solar radiation more easily reaches the surface of the solar modules soiled by $CaCO_3$ and soil particles than the surface of the solar modules soiled by carbon.

Figure 8 shows the data for the clean modules power and the carbon, $CaCO_3$, and soil soiled modules power as a function of time for appropriate dates wherein the modules are placed at the optimum angle.

Carbon soiled module power decreased on average by 37.8% compared to the clean solar module, $CaCO_3$ soiled module power decreased by 6.7%, and the soil particles soiled module power decreased by 7.3%.

Figure 9 shows the comparison of the impact of carbon, $CaCO_3$, and soil on the efficiency reduction of solar modules. The efficiency of the carbon soiled module was reduced on average by 37.6% as compared to the clean solar module, the $CaCO_3$ soiled module efficiency was reduced by 6.7% and the efficiency of the soil particles soiled module was reduced by 6.8%.

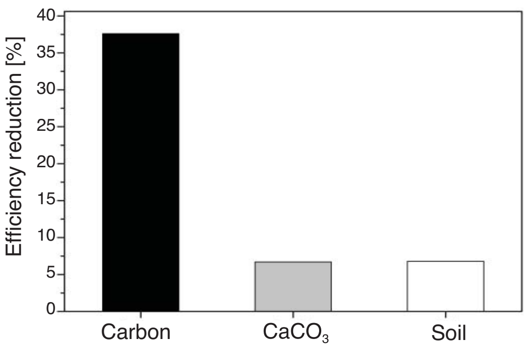

Figure 9. Comparison of the impact of carbon, $CaCO_3$, and soil on the efficiency reduction of solar modules

Conclusions

This paper presents the results of the impact of carbon, $CaCO_3$ and soil particles on the energy efficiency of solar modules. The research was conducted in the Laboratory for Solar Energy at the Faculty of Science in city of Nis, Serbia. In the experiment two identical monocrystalline silicon Isofoton solar modules ISF-60/12, power of 60 Wp each, were used, placed side by side on the roof of the faculty. Solar modules were set at the optimum angle of 32° for the area of Nis and were facing south.

The SEM examination showed that carbon and $CaCO_3$ particles are similar in size but with different dimensions than soil particles. The space between the soil particles through which light can pass is similar to $CaCO_3$, but is bigger than that of carbon. Solar radiation more easily reaches the surface of the solar modules soiled by $CaCO_3$ and soil particles, than the surface of the solar modules soiled by carbon.

Carbon soiled module power decreased on average by 37.8% compared to the clean solar module, $CaCO_3$ soiled module power decreased by 6.7%, and the soil particles soiled module power decreased by 7.3%.

Clean solar module generated on September 16, 2015, in the period from 11:00 a. m. to 1:00 p. m., 92.7 Wh of electricity, and carbon soiled module generated in the same period 57.55 Wh of electricity. Clean solar module generated on September 14, 2015, in the period from 11:20 a. m. to 1:20 p. m., 95.55 Wh of electricity, and $CaCO_3$ soiled module generated in the same period 89 Wh of electricity. Clean solar module generated on October 30, 2015, in the period from 11:00 a. m. to 1:00 p. m., 98.9 Wh of electricity, and soil particles soiled module generated in the same period 91.75 Wh of electricity.

The efficiency of the carbon soiled module was reduced on average by 37.6% as compared to the clean solar module, the $CaCO_3$ soiled module efficiency was reduced by 6.7% and the efficiency of the soil particles soiled module was reduced by 6.8%.

Based on these findings it can be concluded that the power and the total electricity generated by solar modules decrease most due to the carbon soiling, then because of soil particles soiling and the least due to the $CaCO_3$ soiling.

The strongest impact on reducing the energy efficiency of solar modules due to the soiling of their surface has a carbon and the impact of $CaCO_3$ and soil particles is similar.

The obtained results can be useful in choosing the locations of design, construction and operation of grid-off and grid-on solar power plants in urban and other areas.

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