Effects of different parameters on energy – Exergy and power conversion efficiency of PV modules

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\textbf{ABSTRACT}

Due to increase in the amount of electricity generated from solar energy, the installation of a solar energy facility based on the photovoltaic collector has accelerated. However, work-life of these power plants is planned for 25 years. In this 25 years period, there are many parameters that can affect the PV collector efficiency. The authors of this study observed many solar power plants and some of these parameters were determined. Many researchers investigated the effect of the wind load, load test and dust on the surface of the collectors. However, authors of this study investigated cleaning process and dust damage effect carried by the wind. Examples used in the experimental were evaluated according to a concept which is before and after. Before, measurements of current, voltage, power and energy-exergy, power conversion efficiencies of the example, which is the PV module, had determined and all these values were determined again after applying parameters which are cleaning process and dust damage effect carried by the wind. Results show that serious decrease in efficiency parameters is obtained. Energy, exergy and power conversion efficiency of the PV module are determined as 2.19\%, 1.46\% and 1.44\% for after the wind-dust test, respectively. The maximum decrease in energy, exergy and power conversion efficiencies occur 17.87\%, 19.37\% and 19.62\% due to using a squeegee for the cleaning process, respectively.

1. Introduction

Awareness of renewable and usage of these sources is increasing day by day. When solar power plants based on PV collector are compared to other renewable energy sources, they have many advantages than any other renewable energy sources. These advantages are low operating cost, silent working, low first investment cost according to other renewable energy sources. Studies which focus on innovative and R & D (Research and Development) of the solar cell are carried out by many researchers. The latest data show that good results are obtained in solar cell efficiency. According to data from NREL (National Renewable Energy Laboratory), the efficiency of solar cells has exceeded the value of 45\%. This situation shows that future of the solar energy is very bright and solar energy will be an important part of power generation in the near future. However, there are effects of many different parameters on the PV collector efficiency and effects of these parameters are seen in the application. Some of them are dust, wind load, the load which occurs effective loads on collector surface wind and snow load that accumulates on the surface of the collector and so on. In the literature review, there are many studies which are related the impact of dust and another contamination parameter on the solar photovoltaic performance [1]. Studies have been carried out in consideration of many parameters such as dust, irradiation intensity, cooling fluid mass flow rate and humidity [2]. The operation temperature of the PV cell is one of the parameters which affect the efficiency of the PV module. Effects on the efficiency of the PV cell or module in different solar radiations and cell temperature were studied and the PV cell temperature has been found to have significant effects on efficiency [3]. It was observed that efficiency of the PV cell decreased by 0.06\% per 1 Celsius of cell temperature [4]. The efficiency of the PV module has been determined under standard test conditions. The PV module efficiency is determined at a certain constant temperature and radiation value in standard test conditions. While the efficiency of the PV module is determined, manufacturers of PV module use these standard test conditions. In these conditions, the temperature of the PV module is 25°C and solar radiation is 1000 W/m\(^2\). However, the PV module does not work under standard test conditions, the efficiency of the PV module is depending on the different solar radiations in the application. In some studies, the efficiency of the PV module on different solar radiations was investigated. Obtained results show that energy efficiency changes

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approximately between 18.8% and 19.9%, and exergy efficiency changes approximately between 13.6% and 16% on different solar radiations [3]. In application, many parameters have an effect on efficiency and electrical characteristic of the PV module. One of these parameters is a mechanical load. This mechanical load occurs due to snow, wind and during transportation of the PV panel. Researchers studied on tensile stresses of solar cells and stress analysis of PV modules. They used silicon wafer-based PV modules for stress analysis [5].

The authors of this study observed many installations of the solar power system and staff set foot on the panel surface during the assembly process of the solar power system. This situation showed that mechanical load can occur due to many reasons. Serious mechanical loads can cause a micro crack in PV cells and efficiency of the PV module can decrease for these reasons. One of the most studied topics in the literature is the dust effect. Dust deposition on the surface the PV modules effects efficiency, because solar radiation cannot pass through dust. The dust on the surface of the PV module reflects or absorbs solar radiation. Absorption and reflection depend on the nature and amount of the dust deposited on the collector surface. Some studies were focused on different type dust effect deposited on the PV collectors. Effects of dust occur due to air pollutants which are red soil, ash, sand, calcium carbonate and silica. Results showed that PV voltage and power reduced according to pollution type and amount of accumulation on the surface of the dust [6]. In the literature, studies which carried out the very long time period for determining dust effects on the efficiency of the PV module can be found [7]. Also, researchers studied on dust accumulation effects on the surface of the PV modules. Factors such as dust settlement were determined as dust properties, glazing characteristics, ambient temperature and humidity, PV system tilt-angle and orientation, wind velocity and site characteristics [8,9]. Obtained results showed that dust on the surface can be cleaned by natural effects such as rain and wind in a dry location, but daily energy losses can occur higher than 20% in a long time without rain [2]. Not only, dust is a problem for solar power plant based on PV modules, but also it causes undesirable problems for concentrated PV systems and concentrated solar power systems [10]. In the literature, many review studies can be found about dust effects on efficiency and electrical characteristic of the PV modules [11]. This situation shows that study on dust effects has a trend. In the literature, many analyses have been carried out such as X-ray diffraction (XRD), optical transmittance using (UV–vis), photoluminescence (PL) spectroscopy and atomic force microscopy (AFM) by researchers [12,13]. Very detail and useful results obtained from those analysis can be determined.

In this study, a different approach is developed. Many solar power plants were observed by the authors and factors which affect efficiency parameters were determined. Operation conditions are very important for investment protection. Choosing of wrong operation conditions can cause energy and financial losses. The work-life of the solar power plants is planned for 25 years. In this 25 years period, there are many parameters that can affect the PV collector efficiency. The authors of this study observed many solar power plants and some of these parameters were determined. The authors of this study investigated cleaning process and dust damage effect carried by the wind. Examples used in the experimental were evaluated according to a concept which is before and after. Before, measurements of current, voltage, power and energy-exergy, power conversion efficiencies of the example, which is the PV module, had determined and all these values were determined again after applying parameters which are cleaning process and dust damage effect carried by the wind. In this perspective, cleaning process and damage of dust carried by the wind are determined and examined.

2. Experiment methodology

In this study, cleaning process and dust damage effect carried by the wind are considered for determining effects on PV modules. Especially, these parameters affect module efficiency in operating conditions and were determined by examining several solar power plants. The work life of PV collectors is between 20 and 30 years. Also, work life of the PV depends on operating conditions. Generally, employees clean PV collectors once a week. If work life of the PV collector is assumed 25 years [14–16], PV collectors will be cleaned 1300 times. In this period, choosing wrong cleaning methods, using unsuitable cleaner material and chemicals can damage on the surface of the PV collectors and effects efficiency of the PV modules. As previously stated, many solar power plants based-PV collector were observed and cleaning materials used in these facilities were determined. The authors of this study classify in two part which are chemicals and tools in this process. Chemicals using in the cleaning of the surface of the PV collectors are detergent, network water, pure water and liquid soap. Tools and chemicals used in cleaning process were applied on the surface of the PV modules. Experimental measurements of samples which have same and homogeneity properties had carried out for determining efficiencies parameters of them and then the authors tried to damage on the surface of the PV module with tools using in the cleaning process. The dust which is accumulation on the surface of the PV collectors was collected and a muddy water was prepared with this dust. The samples were tried clean in this muddy water via using glass razor, squeegee, chamois, velour, and sponge. Chemicals used in cleaning can leave residues on the surface if no good rinsing is done. Detergent, liquid soap, pure water, and network water had sprayed on the surface of the PV modules and residues of these chemicals on the surface of the PV module were observed. The experimental measurements procedure was applied to these examples according to the concept of before and after. The section described so far has described the testing process for collector cleaning. It has been previously stated that a lot of research has been carried out on the effect of dust accumulation on the collector. However, study about dust damage effects cannot be found in the literature. Serious wind speed values are seen in many places where solar power plants were installed. The wind which has high-speed value can be carried dust and this dust can hit the collector surface at high speed. This event can seriously damage the surface of the PV module. Generally, solar power systems have been installed in rural areas where are not suitable for agriculture. The wind effect in these areas is quite high because factors or obstacles which decrease wind speed cannot be found. In the Turkey, highest wind speed was measured as 176 km/h in 1978 [17]. The authors of this study determined average wind speed which is 28 km/h and Fig. 1 shows experimental setup installed for determining of damage which occurs by dust carried by the wind. All variables such as wind speed, the distance between the nozzle and the PV module and amount of dust were constant in the test procedure. Only, collector angle was changed as 90°, 80°, 70°, 60°, 50°, 40°, 30° and 20° and dust damage effects were observed on the surface of the PV module samples. Measurements in all of the experiments were carried out by using semiconductor characterization analyzer and PV solar simulator. Model of semiconductor characterization system produced by Keithley Company is 4200-SCS. Properties of the semiconductor characterization system are DC current-voltage (I–V) range 10 aA–1 A and 0.2 μV–210 V, pulsed I–V range ± 40 V (80 V p-p), ± 800 mA, 200
Msa/Section, 5 ns sampling rate, capacitance-voltage (C – V) range 1 kHz – 10 MHz, ± 30 DC bias. The solar simulator has been used to obtain different solar radiations which are changing 200–1000 W/m². Using PV solar simulator is AAA – class. Properties of the PV module used in the experiments are shown in Table 1. Methods and models used for determining efficiency parameters of the PV module are explained under the following headings.

2.1. The single diode Rs – Model

In the literature, different circuit models can be found, some of those models are the ideal single diode model, the single diode Rs – model, the single diode Rs – model and the two – diode model. Fundamental and details about those models can be found in reference [18]. The single diode Rs – model is considered in this study and this model is shown in Fig. 2. Difference between the single diode Rs – model and the single diode Rs – model is that the single diode Rs – model is more accurate according to cell temperature variant [19]. In this study, effects of cell temperature are not considered, because many studies have been made in the literature on different cell temperature and in the case of cooling the PV modules, the variation in PV module efficiency and electrical characteristic values were investigated by researchers [19]. The current-voltage relation for the Schottky barrier solar cell is expressed by the Eq. (1) [5].

\[
I = I_{ph} - I_s \left( \exp \left( \frac{q(V + IR_s)}{akT} \right) - 1 \right)
\]

where \( I_{ph} \) is photocurrent, \( I_s \) symbolizes saturation current, \( a \) indicates diode ideality factor, \( R_s, V, T \) and \( q \) are series resistance, voltage, temperature and electron charge (\(-1.60217646 \times 10^{-19}\) C), respectively. \( k \) is Boltzmann’s constant (\(-1.380653 \times 10^{-23}\) J/K). The I-V characteristics of the solar cell can be determined by using Eq. (2) [19,20],

\[
V_{oc} = \left( \frac{aV}{q} \right) \ln \left( \frac{I_R}{I_s} \right)
\]

where \( I_R \) is short circuit current and \( V_{oc} \) is open circuit voltage. Experiments were carried out different solar radiations which are 200–400–600–800–1000 W/m². Obtained results are a discussion in result and discussion part of this study. Detail about theory and others models can be found in Ref. [19,20].

2.2. Methodology for the efficiency parameters of the PV module

Efficiency parameters of the PV module indicate that efficiency of the PV module shows the ability to obtain electrical energy from solar radiation energy. In this perspective, energy and exergy efficiency parameters can be considered for the efficiency parameters of the PV modules. The temperature of the PV module is kept constant (25 °C) in all experiments. Eq. (3) can be used for determining the energy efficiency of the PV modules [19].

\[
\eta_{en} = \frac{P_{max}}{G} \frac{V_{oc}}{A}
\]

G indicates solar intensity and A is an illuminated area of the PV module in Eq. (3). In the calculation of exergy efficiency must be considered maximum current and voltage. Also, exergy value of solar intensity must be determined. Exergy efficiency of the PV module can be calculated as follow:

\[
\eta_{ex} = \frac{I_{max}V_{max}}{G \alpha A}
\]

\( \alpha \) indicates exergy of solar intensity and it can be determined by Eq. (5),

\[
\alpha = \left( 1 + \frac{1}{3} \left( \frac{I_{max}}{I_{sun}} \right)^4 - \frac{4}{3} \left( \frac{I_{max}}{I_{sun}} \right) \right) G
\]

where \( T \) symbolizes temperature both ambient and surface of Sun. The temperature of the Sun is 5600K [5]. The maximum power output is calculated by using Eq. (6) [21,22].

\[
P_{max} = V_{oc}I_{max}FF
\]

FF is filled factor and it is one of the important performance indicators. The fill factor can be expressed by [9]:

\[
FF = \frac{P_{max}V_{max}}{I_{max}V_{oc}}
\]

In many studies, power conversion efficiency is considered, because it indicates maximum accessible electrical power for resistance terms. The power conversion efficiency is calculated by using Eq. (8) [9].

\[
\eta_{pc} = \frac{\int V_{oc} I(V)dV}{GA_{pc}}
\]

Results obtained from analysis and tests are shared next part of this study.

3. Result and discussion

In this study, cleaning process and damage of dust carried with wind are examined effects on energy, exergy, and power conversion efficiency parameters. Results obtained from the analysis are examined in two subtitles which are cleaning process and wind – dust. Firstly, photos of the samples which are the PV module are illustrated and then graphics of efficiency parameters are presented according to the concept of before – after.

3.1. Cleaning process

The PV-based solar energy systems are installed in the roof sections of industrial establishments and industrial wastes pollute the surface of collectors. Staff responsible for operating and cleaning the solar power plant have no information about the right method for the cleaning process. There are very little information and experienced staff about the points to consider regarding the cleaning of the PV collector. Chemicals and tools used for cleaning of surface the PV modules were determined by the authors of this study. Detergent is used for many cleaning applications and this cleaning chemical is preferred for
cleaning of difficult stains and dirt. Bird droppings, sticky pollen, different chemistries that are difficult to clean can accumulate on the collector surface and detergent is used for cleaning these unwanted pollutants. If the surface cleaned with detergent is not rinsed well, the wastes of these chemicals accumulate on the surface. When Fig. 3 is examined, the residue of the detergent can be seen on a surface according to the concept before and after. Fig. 3 shows residues chemicals using in cleaning applications of the PV module. As can be seen, pure water gives the best result, because it doesn’t form a residue on the surface. Liquid soap forms residue as be detergent. Network water contains many substances such as chlorine and so on. When network water is a phase change, lime accumulates on the surface. These residues are obstructing the sun’s radiation and efficiency of the PV module effects from this situation. Fig. 5 shows damages of the using tools in the cleaning process of PV module. Glass razor is used to clean hard and dry pollutants like bird droppings. The dust which is accumulation on the surface of PV collectors was collected, and a muddy water was prepared with this dust. The samples were tried clean in this muddy water via using glass razor, squeegee, chamois, velour, and sponge. At the end of the cleaning process, damage on the surface can be seen in Fig. 5. In the user manual, data and information are module efficiency, highest power output, material & workmanship and linear power output warranty, dimensions, I – V curves, dimensions, electrical characteristics at normal operating cell temperature and standard test conditions, temperature and mechanical characteristics, maximum ratings, system design, and packaging. Information about operation and maintenance of the PV module must be in these brochures. Especially, information about the cleaning of the PV module must be shared in operation and maintenance part of the brochures. Information about the cleaning of the PV module can be found on the internet, but the information about cleaning process given by the producer of the PV module will be trustier than information on the internet. When cleaning chemicals used in the cleaning process of PV module are examined, energy, exergy, and power conversion efficiencies were determined according to the before and after concept. Fig. 4 shows that using detergent effects on efficiency parameters. Obtained results show that energy, exergy, and power conversion efficiencies decrease at rate 23.66%, 15.47%, and 15.66%, respectively. As can be seen in Fig. 4, the chemical wastes of the detergent on the surface prevent or reflect solar radiation and efficiency parameters of the PV module decrease. The pure water is used for cleaning process and results obtained from the experiment can be seen in Fig. 4. In general, pure water is suggested for cleaning of the

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Fig. 3. Residues left on cell surfaces of cleaning chemicals.
PV module, because it not include any contents. Obtained results from this study support this suggestion. For sticky and difficult stains, liquid soap is chosen for cleaning of the PV module in some solar power plant. The main aim of choosing this chemical is that it is used as a solvent for cleaning difficult stains from the surface. When other solvents using for stains are compared with the liquid soap, the liquid soap is cheaper than others and can be found easily. These solvents can be used, but rinse of both solvents and stains must be done very seriously. If contents

![Fig. 4. Change in efficiency parameters according to chemicals used in cleaning.](image-url)
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Fig. 5. Damage of cleaning tools.
of solvents such as liquid soap remain on the PV surface, they affect efficiency parameters as seen in Fig. 4. In Fig. 3, the network water is used for cleaning of the PV module. When no good rinsing process is worked out, lime on the surface which can be seen in Fig. 3 occurs. When efficiency parameters are considered for using network water, the network water can be said unsuitable for cleaning of the PV module. The network water consists of many components. As can be seen in Fig. 3, it causes residuals on the surface. In this case, these residuals have effects negatively on efficiency parameters. When Figs. 3 and 4 are considered, residuals of detergent, network water, and liquid soap prevent solar radiation. These residues accumulate on the surface of the PV module and solar radiation cannot reach the solar cell through the glass. These residues reflect and/or absorb solar radiation. Cleaning of some of these residues from the surface is very difficult such as residues of the network water and cleaning procedure of these residues will be much cost.

Using wrong cleaning tools causes scratches and damages. These scratches and damages are come across on surfaces which are car bodywork and windows. Dust between cleaning tool and surface causes scratches and damages. Tools using the cleaning process of the PV modules are chosen for different purposes. Some of them are used very rarely. For example, glass razor is used for difficult stains. Although these tools are rarely used, they cause serious damage to the surface. As can be seen in Fig. 5, scratches occurring due to using glass razor have negative effects on energy, exergy and power conversion efficiencies of the PV module. It may be said that the squeegee is the most commonly used cleaning tool to clean glass surfaces. It is used for rinse process. However, using this material causes a decrease of efficiency parameters due to scratches on the surface of PV module. Results obtained from using squeegee in Fig. 6. When cleaning tools such as chamois, velour, and sponge are used, effects on energy exergy and power conversion efficiencies can be seen in Fig. 6. In this study, reduction rates of energy, exergy and power conversion efficiencies due to use cleaning tools and chemicals considered by the authors are presented in Fig. 7. Most reduction rates of the energy efficiency occurred at using detergent and reduction rate is determined as 23.66%. When exergy and power conversion efficiencies are considered, the most reduction rates of these efficiencies occur for using a squeegee. The reduction rates obtained for using squeegee are calculated as 19.37% for exergy efficiency and 19.62% for power conversion efficiency. Studies in the literature show that cleaning procedure is a very important parameter for operating costs. Effects of dust accumulating on the surface of the

Fig. 6. Change in efficiency parameters according to tools used in cleaning.
PV modules was explained in the introduction of this study. The dust causes increases cost and efficiency reduction of the solar power plant. Cleaning of dust is much cost [5]. Choosing the right cleaning method will reduce costs. However, wrong methods can cause damages on the surface of the PV modules and the recovery of this damage will bring serious costs. Damages on the surface adversely affect the permeability of the glass and efficiency parameters decrease due to these damages on the surface. These damage occurring due to using of wrong cleaning tools reflect solar radiation, and also they absorb solar radiation. Solar radiation cannot reach to the solar cell. Solar cell produces less electric energy due to these damage occurring due to using of wrong cleaning tools. These comments are supported by results obtained from this study. When Figs. 5 and 6 are examined, it is seen that the efficiency parameters decrease depending on the amount of damage on the surface of the PV module. There is an inverse ratio between damage to the surface and efficiency parameters. As the amount of damage on the surface increases, the efficiencies of the energy, exergy and power conversion decrease.

The companies which are responsible for the installation of the solar power plants have no experience in cleaning process or are not considered. After the companies install the solar power plant, they give no information about cleaning protocol to investors of the plant. This situation causes using wrong cleaning tools and chemicals in the solar power plants. 4000 PV modules are needed for installing a solar power plant which has power capacity 1 MW. The surface area of this PV module is 2.5 m². When 4000 PV modules are considered, 10.000 m² area which is surface of the PV modules must be cleaned according to considering cleaning method. This situation shows that cleaning methods and using materials are very important for maintenance and operating costs. In the recent years, a new sector has shown up and this sector is related to cleaning of the solar power plants. Many different approaches and cleaning machines are used by these companies. Also, researchers have studied on cleaning machines for cleaning of the PV modules. Many of these companies suggest using deionized pure water.
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Fig. 8. Dust damage on the surface of the PV modules.
for the cleaning protocol. The staff who are responsible for the operation of the solar power plant should be informed about right cleaning methods or this process must be done by professional companies. Many chemicals which are used for cleaning have many different contents and these chemicals may be damaged the PV module by reacting with components of the PV module. Also, these possibilities must be considered for cleaning process too.

3.2. Wind-dust

The main aim of the wind-dust test is the determining of the damages occurring due to dust carried by the wind. In many locations
installed solar power plant, high wind speed values can be seen. For example, deserts can be a good place for the solar power plant, but in these places, dust storms and high-speed winds can cause damage on the surface of the PV modules. In this perspective, results obtained from the wind-dust test procedure which was indicated in material and method can be seen in this part of the study. Fig. 8 shows dust damage on the surface of the PV modules. These wind-dust tests were carried out at different collector angles which are 90°–20°. In Fig. 8, damage of dust can be seen in detail and after column of it. At every collector angles, energy, exergy and power conversion efficiencies were calculated according to the wind-dust test procedure. For 90° collector angle, efficiency parameters can be seen in Fig. 9. As mentioned before, each
one the PV module may not have same efficiency parameters, so all tests were carried out based on the before-after concept. At 90° collector angle, dust was sprayed on the surface of the PV module according to the wind-dust test procedure. Results obtained from this test can be seen in Fig. 9. Under different solar radiation, energy, exergy and power conversion efficiencies were calculated. When efficiency parameters are considered for 90° and 1000 W/m², energy, exergy and power conversion efficiencies are calculated as 2.53%, 1.70% and 1.68% for before the wind-dust test, respectively. In the same situation, energy, exergy and power conversion efficiency of the PV module are determined as 2.19%, 1.46% and 1.44% for after the wind-dust test, respectively. Energy efficiency of the PV module decreases 13.43% due to damage to the surface of the PV module because this damage on the surface prevents the solar radiation from reaching the collector's cell. Exergy and power conversion efficiencies decrease 14.11% and 14.28%, respectively. For 80° collector angle, results obtained from wind-dust tests are illustrated in Fig. 9. Energy, exergy and power conversion efficiency of the PV module used in the test for 80° collector angle and 1000 W/m² are calculated as 1.87%, 1.11%, and 1.1%, respectively. This situation shows that each the PV module should be evaluated separately because efficiency parameters of the PV modules used in this study have no same. For 80° collector angle and 1000 W/m², energy, exergy, and power conversion efficiencies decrease at rate 14.97%, 11.71%, and 12.72%, respectively. Collector angle is a very important parameter for wind effects and dust effects because depending on the collector angle, the wind effects can be increased or decreased. Efficiency parameters of the PV module can be seen for collector angle 70° and under different solar radiation. In this test, energy, exergy, and power conversion efficiencies decrease at rate 17.82%, 13.22% and 12.6% for 1000 W/m², respectively. Collector angles between 90° and 40° may not be seen in the application, or maybe not preferred according to optimum collector angle. However, the angle at which the wind will affect the collector surface is unpredictable. In similar studies which are examined wind effects, each collector angle must be considered. For collector angle 60°, efficiency parameters are presented in Fig. 9. At each collector angle, damage of the dust carried with wind is determined and it seems that efficiency parameters decrease for collector angle 60°. In the studies which are examined dust accumulation and wind load, collector angle very effects on efficiency parameters [7]. Also, in this study, when collector angle decrease, damage of dust carried with wind decrease too. For example, Fig. 9 presents efficiency parameters for collector angle 50°. Energy, exergy, and power conversion efficiencies decrease at rate 9.54%, 10.34% and 9.94% for collector angle 50° and 1000 W/m², respectively. At collector angle between 90° and 60°, efficiency parameters decrease almost at same rates, but damage effects of dust carried with wind decrease for collector angle 50°. This situation can be seen in Fig. 8. In this Fig., damage, and wear occurring due to dust effects on edge of the PV module. This edge is near to horizontal plane, so dust firstly effects on this edge. Efficiency parameters for collector angle 40° can be found in Fig. 9. The reduction rates for efficiency parameters are determined and energy, exergy, and power conversion efficiencies decrease at rates 8.88%, 8.8% and 9.67% for collector angle 40° and 1000 W/m², respectively. Efficiency parameters for collector angle 30° are shown in Fig. 9. In the wind-dust experimental procedure, last collector angle is 20° and results obtained from this test can be found in Fig. 9. All results can be considered according to the reduced rates of efficiency parameters. Fig. 7 shows the reduction rates of energy, exergy and power conversion efficiencies of the PV modules according to collector angle, damage of dust carried by wind and under different solar radiation. As can be seen in Fig. 10, energy, exergy and power conversion efficiency decrease is very high at rates for collector angles between 90° and 40°. It can be said that damage impact of the dust carried with wind is depend on collector angle. This damage impact may be change due to be many dust types. Also, different type dust may be cause higher or lower damage impact on the surface of the PV module. For solution, a protection wall from damage of dust carried with wind may be considered. In generally, solar power plants are surrounded by wire netting, but aim of these practices is prevent unauthorized entry to solar power plant. When examining many applications used to reduce wind speed, walls which shown in Fig. 11 can be considered for protection from dust carried with wind and wind load. These walls are used for preventing wind and snow at side of highways. As can be seen in Fig. 11, plastic material which is resistant to solar radiation and flexible is used. When plastic material is damaged, changing of it is very easy and cheap. These walls may be solution of problems which are wind load and damage of dust carried with wind. Surface material is glass and this material extremely affect from tools and dust damage carried by the wind. These materials will be effect from dust type, so some preventions must be taken for unwanted situations. Table 2 shows efficiency values for different parameters. In this table, when standard test conditions (1000 W/m² – 25 °C) are considered, efficiency parameters of energy,
exergy and power conversion are illustrated. Results obtained from this study show that surface of the PV modules is very important parameters for the efficiency of them, because residues or damage on the surface can effect efficiency parameters. These residues or damage prevent solar radiation and decrease of efficiency parameters can occur.

4. Conclusion

In this experimental study, some chemicals and tools using in cleaning process and damage of the dust carried with wind are examined effects on energy, exergy and power conversion efficiencies. The small the PV modules and very sensible solar simulator were used in the experiments. Conclusion obtained from the study can be written as,

- Choosing wrong tools and chemicals used for cleaning of the PV module decrease energy, exergy and power conversion efficiencies of the PV modules. After results obtained from experiments using of cleaning tools show that these materials cause scratches and damages on the surface of the PV modules.
- When cleaning tools are considered for efficiency parameters, the maximum decrease of energy, exergy and power conversion efficiencies occur 17.87%, 19.37% and 19.62% due to using a squeegee for the cleaning process, respectively.
- When the results obtained for chemicals using for cleaning process are examined, it can be seen that the most suitable method is to use pure water.
- Damage of the dust carried with wind is dependent on the angle of the PV module. The results obtained from the study show that energy, exergy and power conversion efficiencies of the PV modules decrease 13% as an average for the angle of the PV module (between 90° and 40°). The damage ratio changes according to the angle of the PV module.
- When efficiency parameters are considered for 90° and 1000 W/m², energy, exergy and power conversion efficiencies are calculated as 2.53%, 1.46% and 1.68% for before the wind-dust test, respectively. In the same situation, energy, exergy and power conversion efficiency of the PV module are determined as 2.19%, 1.46% and 1.44% for after the wind-dust test, respectively.

Different dust types can be used for wind – dust test. Especially, dust taken from similar experiments can be carried out by taking dust samples from the place where the solar power plant is installed. While different cleaning chemicals are considered, it can be determined which one of them react with components of the PV module.

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