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The effect of snowfall and icing on the sustainability of the power output of a grid-connected photovoltaic system in Konya, Turkey

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Abstract: When the module surface is covered with various factors such as snow and icing which prevent the solar irradiance from reaching the photovoltaic cells, the power production of the system and its performance decrease. The purpose of this study is to determine the energy production losses of a grid-connected photovoltaic plant due to snowfall and icing. The effect of snowfall and icing has been examined on a photovoltaic system consisting of a hybrid inverter with two separate maximum power point tracking inputs and 36 monocrystalline modules, which are mounted on the supporting system horizontally in the south direction and at a constant tilt angle of 30°. The plant area is located in a priority and snowy region (Konya,Turkey) where large-scale photovoltaic system installations are carried out. In order to evaluate the effect of snowfall, the minute resolution data of the hybrid inverter which provides connection to the grid is used. The change over time of the power generated by the two arrays of the plant was examined comparatively. For comparison, one of the arrays was continuously cleared. The recorded data was used to determine the expected energy output of the array covered with snow. Besides, the solar irradiance and ambient temperature data obtained from the meteorological station were used to accurately identify and evaluate the effects of snowfall with digital images recorded in the site area.

The results showed that surface clearing of modules had a significant positive effect on the power output of the system. In the array entirely covered with snow, the daily energy loss exceeds 93%. In months of heavy snowfall, the monthly energy loss is 18% depending on time of being covered with snow of the modules. When the production data of 2017 and 2018 is evaluated, it is seen that the total energy loss of the plant varies between 1% and 2%.

Key words: Hybrid inverter, icing, photovoltaic, snowfall

1. Introduction

Power generation and yield of photovoltaic (PV) solar power systems widely differ in summer and winter months depending on the time of insolation. In addition to the low insolation time in winter season, snowfall and icing events cause a serious decrease in the power generation of PV plants that supplied power for the grid. Investors who want to maintain their current earnings throughout the year make the installation above the specified capacity to compensate for the power generation losses. This situation leads to an increase in the power given to the grid when the bad weather conditions become normal and in investment costs as well. The power system authorities do not allow exceeding the contract capacity signed with the distribution company; no payment

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is made to investors of the PV plants that supply power for the system above the contract capacities. Thus, exceeding the capacity results in loss of their earnings. For this reason, accurate estimation of energy production and losses is extremely important for both the investors and the grid.

The performance of PV plants differs among similar installations which are located close to each other on the same latitude [1]. Climatic variables such as snowfall, icing, irradiance, temperature, cloudiness rate, as well as operating conditions such as dirt and dusting lead to considerably different results from the estimated performance value of a particular plant. There are widely used software tools to determine the appropriate site and the system design and yield before the installation of a plant. These simulation packages [2] use the atmospheric variables such as irradiance, temperature, humidity, and wind speed as input. However, these variables differ from year to year, especially due to global warming [3]. Therefore, performance is evaluated by selecting appropriate data characterizing the region from the existing meteorological database based on long-term observation. These data are obtained from meteorological satellite and ground observation stations [3, 4]. However, various reasons such as the cloudiness in the sky or snow and icing on earth cause incorrect or incomplete data recording of the meteorological satellites and measuring devices [1, 4–6]. In addition to the difficulty of obtaining suitable meteorological data for each PV installation site, the yield estimates which do not contain any information related to snowfall and which are based on only a few meteorological data are higher than expected. In order to increase the accuracy of regional estimations, information about meteorological measurement and snowfall was handled together with the system design and the effects of snowfall were tried to be modelled [7, 8]. One of these models [8] has been recently adapted for an existing simulation program developed for renewable energy projects [9].

The use of a comparative PV module or array pairs to determine the losses caused by snowfall is one of the preferred methods in the literature and this study. In the state of California (Truckee), USA, annual production loss for uncleared modules with tilt angles of 0°, 24°, and 39° was estimated as 18%, 15%, and 12%, respectively [10]. Using the same method, the contribution of clearing snow cover on a PV system in the Czech Republic to the yearly yield was determined as 1.4% [11].

Due to the difficulty in keeping a specific module group constantly clear and the problems encountered in practice, estimated production values based on meteorological data to determine losses are compared to actual production values. For a test system with 0°, 15°, 39°, and 45° tilt angles in the state of Michigan (Calumet), USA, it was found that energy losses ranged from 29% to 34% for ground-mounted modules and from 5% to 12% for ground-raised modules [12]. In Germany, the annual loss of yield caused by snow cover varies from 0.3% to 2.7% for a grid-connected PV system where the frameless PV modules are mounted on the roof with a 28° tilt angle [13].

The installed power capacity based on PV solar energy of Turkey reached 5062.9 MW level at the end of 2018. The share of these investments within total installed power capacity increased to 5.71%[1]. PV industry investments have achieved a growth of about 608.15% within the last two years in Turkey. Even though the interest in PV applications has been increasing, no studies have been carried out to determine the losses caused by snowfall which reduces power generation. In the current performance studies, performance losses caused by snowfall are not included in the assessments [14, 15]. Therefore, a snowy region (Konya, Turkey) which is prioritized in PV solar energy investments has been chosen as a working area to resolve this research deficiency.

[1]Turkish Electricity Transmission Corporation (2019) [online]. Website http://www.teias.gov.tr/sites/default/files/2019-01/kurulu_guc_aralik_2018.pdf [accessed 02 05 2019]

2. Case study city: Konya, Turkey

The Central Anatolia Region in Turkey, producing electrical energy based on PV technology, is one of the areas where most of the on-grid and off-grid PV system installations are done. Owing to its climate characteristics, the investment incentives, and support mechanisms, this region has become one of the most attractive places for investment. Manufacturers are trying to increase the production capacity to meet the needs of the new PV solar energy investments and the existing PV plants. This situation shows that the PV solar energy sector and investments in the region will increase further in the following years.

Konya is located in the south of the Central Anatolia Region. Average monthly irradiation and sunshine duration of the region are 4.69 kWh/m^2 per day and 7.3 h, respectively. These values are above the average of Turkey (4.34 kWh/m^2 per day and 6.6 h for 2011–2018)[2]. Maximum irradiation and sunshine duration were obtained in June and July, respectively. May is the month in which precipitation in the form of rain occurs and the cloudiest days are seen. During winter (November–March), the irradiation and duration of sunshine are the lowest; snowfall and icing are the highest. Snowfall which may begin at the end of November and continue until the end of March causes a decrease in yield obtained from the PV plants installed in this region. A research conducted on Konya shows that the number of snowy days is 12, the snow thickness is about 40 cm [16] and the time of snow staying on the ground varies between 17.5 and 35.3 days. Long-term climate data of the region(1929 − 2018) is given in Table 1[3].

Table 1. The climate data for Konya,Turkey.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average monthly radiation(kWh/m^2-day)	2.27	3.03	4.6	5.5	6.65	7.19	7.13	6.28	5.14	3.73	2.69	2.13
Average sunshine time (hour)	3.3	4.7	5.9	7.1	8.9	10.6	11.6	11.2	9.5	7.2	5.3	3.2
Average temperature (°C)	–0.2	1.4	5.6	11.1	15.8	20.1	23.5	23.2	18.5	12.5	6.3	1.7
Average minimum temperature (°C)	–4.2	–3.3	–0.2	4.3	8.6	12.6	15.8	15.6	10.9	5.9	0.8	–2.4
Average maximum temperature (°C)	4.6	7.0	11.8	17.5	22.3	26.6	30.1	30.2	26	20	13	6.6
Average number of precipitation days	9.9	8.4	8.8	9	10.6	6.6	2.2	1.5	3.1	6.1	6.6	10

3. System overview

3.1. The grid-connected PV power production plant

The grid-connected PV energy production plant and power system components are shown in Figure 1. The PV solar plant consists of a total of 36 modules in two arrays, a battery pack and a hybrid inverter that converts DC

[2]Turkish State Meteorological Service (2019) [online]. Website https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?k=parametrelerinTurkiyeAnalizi [accessed 01 07 2019]

[3]Turkish State Meteorological Service (2019) [online]. Website https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?k=A&m=KONYA [accessed 01 07 2019]

current into AC current. The plant was installed in the backyard of the Technical Sciences Vocational School at Konya Technical University in Konya, within an area of approximately 350 m^2. The elevation of the bottom edge of the modules is about 70 cm and the installation area of the modules is about 60 m^2. This plant is located at the 38.029649 N latitude and 32.50487 E longitude, at 1031 m above sea level.

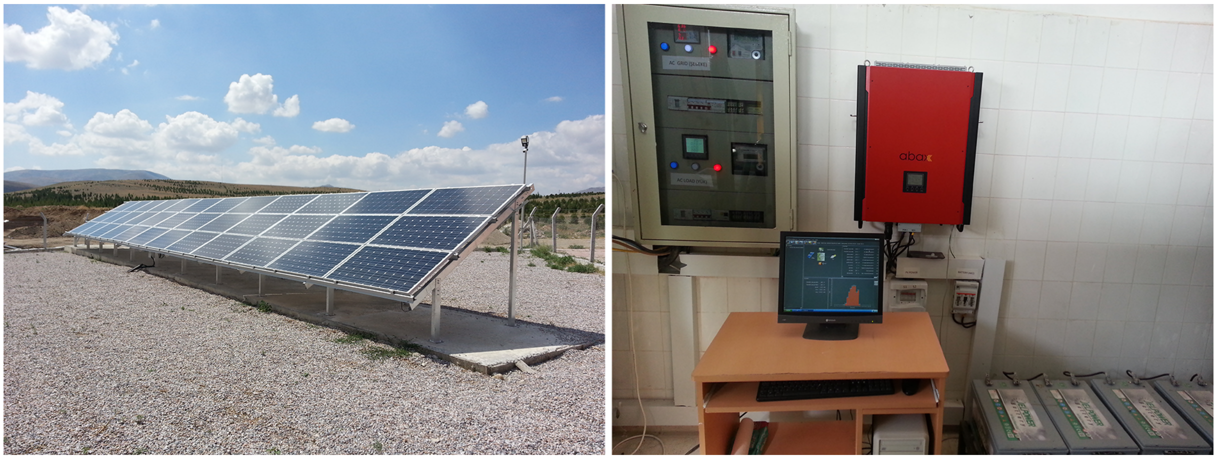

Figure 1. PV plant area and power system components.

3.2. The PV modules

The 60-cell modules with monocrystalline structure used in this study are produced domestically. These modules are produced by Endustriyel Electrical-Electronic Company[4] located in Konya. PV modules are mounted on the supporting system horizontally in the south direction and at a constant tilt angle of 30°. One of the arrays consists of 18 modules having 265 W output power. The other array consists of 8 modules having 270 W output power and 10 modules having 265 W output power. The module specifications are given in Table 2.

Table 2. PV module performances at STC conditions (1000 W/m^2; 25°C; AM 1.5 G)

Model	M60−265	M60−270A
Maximum (0−3%), P_{mp}	265 W_p	270 W_p
Open circuit voltage, V_{oc}	39.17 V	39.05 Volt
Short circuit current, I_{sc}	8.638 Amps	9.301 Amps
Voltage at maximum power, V_{mp}	31.57 V	31.3 Volt
Current at maximum power, I_{mp}	8.394 Amps	8.626 Amps

3.3. The hybrid inverter

Power management of the PV plant is performed by using an ABAX three-phase hybrid inverter with a rated power of 10 kVA. The hybrid inverter offers different configuration options for two basic operating states including on-grid and off-grid depending on the state of the current power source. These features can be disabled or activated by the interface software of the inverter according to the intended use. It is necessary to

[4]Endustriyel Electrical-Electronic Company (2019) [online]. Website https://endustriyel.com/en [accessed 01 07 2019]

look at the data sheet for the operation modes of the inverter depending on different system requirements[5]. The hybrid inverter is equipped with two separate array inputs to reduce the effects of partial shading and clouding events on overall performance. There are serially connected 18 modules in each array. Moreover, the inverter is equipped with maximum power point tracking (MPPT) system in order to obtain maximum power output from arrays. The number of modules in each array was chosen in such a way that the total output voltage of the array would not exceed the operating voltage of the MPPT during the entire year.

3.4. The battery pack and load

The inverter uses the energy generated by the PV system to charge a battery pack and to feed the critical AC load. The remaining power supports the electricity consumption of the school which is synchronized with the grid. The battery pack consists of serially connected 4 long-life 12 V, 200 Ah deep cycle gel type batteries. The battery pack is used to supply the critical load at the AC output of the inverter during power outages in the grid. The load is two LED projector lamps (Helios LMCP 70 W, White, 220 VAC) which are used to light up the plant and a desktop computer which is used to record production data.

4. Methodology

In this study, minute resolution data of the hybrid inverter which provides the connection with the grid was used to evaluate the effects of snowfall and icing. The operating data (power, voltage, frequency, etc.) of the power system components can be obtained visually and numerically through the inverter software without needing experimental setup and measuring devices. This data was closely followed for two years by starting from January 2017, and the change in the power generated by the two arrays of the plant over time was examined comparatively.

During the snowy days, one of the arrays of the plant was continually tried to be kept cleared with a squeegee every half hour (Figure 2). The snow cover accumulated on the other array was not removed. This snow cover was waited to be removed naturally from the module surface as a result of the external environment. The loss caused by snowfall and icing was determined by comparing the power output of PV arrays that were kept cleared and those that were allowed to remain snow-covered. Snow clearing activity was uninterruptedly carried out on holidays and on weekends. The plant area was photographed before and after each clearing operation.

It is possible to apply mechanical scraping, thermal treatment, and deicing fluids to remove snow and ice from the PV module surface [17]. However, each of these methods has its own disadvantage, and their applicability is limited to small-scale PV systems. It is very difficult to keep PV modules clean constantly by using these conventional methods. Cleaning frequency will increase the cost of the activity. There is not a known practical method that can prevent the accumulation of ice or snow on the PV system without damaging its structure and without degrading its performance. For this reason, the mechanical scraping method was preferred in this study as it is more environmentally friendly and cost-efficient compared with other methods. This method is also used in other studies in the literature.

The snow accumulating on the PV system and its components disperses by the effect of the wind both during snowfall and after snowfall. Thus, the thickness of snow on the modules after snowfall was regularly measured from a number of different points.

[5] Voltronic Power Technology Corp. (2019) [online]. Website http://voltronicpower.com/en-US/Product/Detail/InfiniSolar-2-10KW [accessed 29 01 2019]

Figure 2. Snow clearing activity of array with a squeegee.

4.1. Meteorological data

Current and reliable meteorological data are needed for researchers who will evaluate the performance and losses of PV solar systems through experimental and numerical methods [18]. The meteorological information is obtained from national meteorological stations or the measurement devices installed in the site area and from the internet sites of the global environmental organizations which are open to access. Among these options, the most reliable primary data source is the national weather stations because the data are obtained from devices which are calibrated in accordance with the standards.

The meteorological data related to Konya are measured by 54 automatic measuring stations in the region. The nearest meteorological station measuring the global radiation within these measurement stations is the Konya Bahri Dağdaş Meteorological Station (station no: 18213) affiliated to the 8th Regional Directorate of Meteorology. The necessary atmospheric data (global radiation, air temperature) related to the plant area was obtained from this measuring station with 1 min intervals. It is approximately 20 km far from the plant area, and at the same latitude (37.8606 N, 32.5839 E and at 1011 m above sea level).

National meteorological station data presented in this study were used to explain the effects of snowfall and icing on the plant and to correlate these effects with inverter data records. Besides, some of the observations and inspections related to the plant performed by the authors and the photographs of the plant area taken at regular intervals on the snowy days allow interpretation of the results. However, the production data and calculated loss values in this study are entirely based on the inverter data.

5. Results

5.1. Daily energy production losses

Within the operation period including the years of 2017 and 2018, the heaviest snowfall occurred in January 2017. Loss periods having similar characteristics occur during and after snowfall [19]. A small period between January 2 and January 5, 2017 was selected as an example to characterize snow removal events, with the inclusion of changing environment and working conditions. In addition, this four-day period reveals the effects of the fragmented and completely snow-covered work caused by the snow cover accumulated on the modules. The instantaneous power production of the cleared and snow-covered arrays during the day is given in Figure 3 together with the global radiation and air temperature variation graphs in the region. Besides, the images of the plant area taken on different days and at different hours are given in Figure 4.

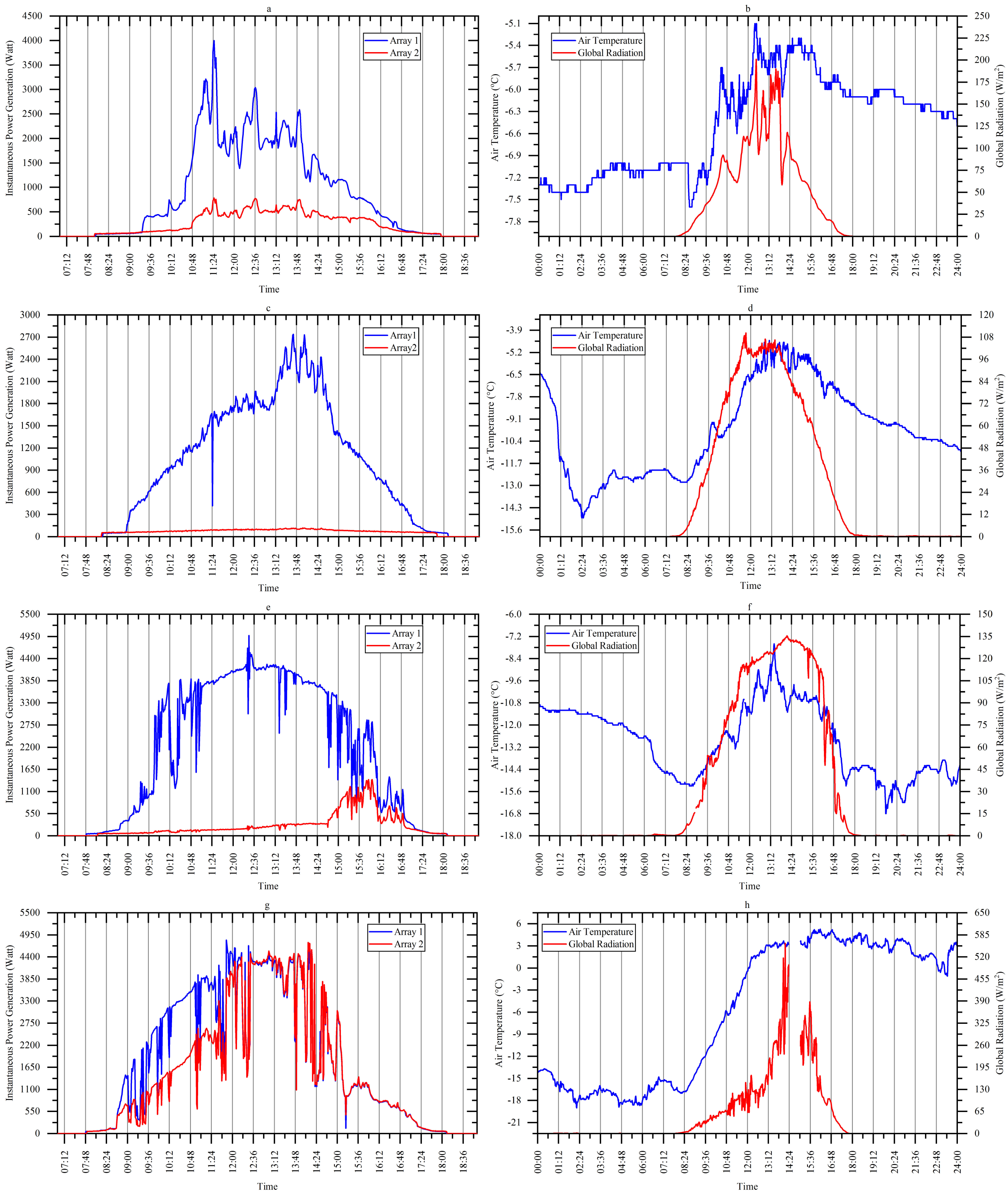

Figure 3. The daily profiles of power outputs from the PV arrays with global radiation and air temperature during the four days from January 2 to January 5, 2017.

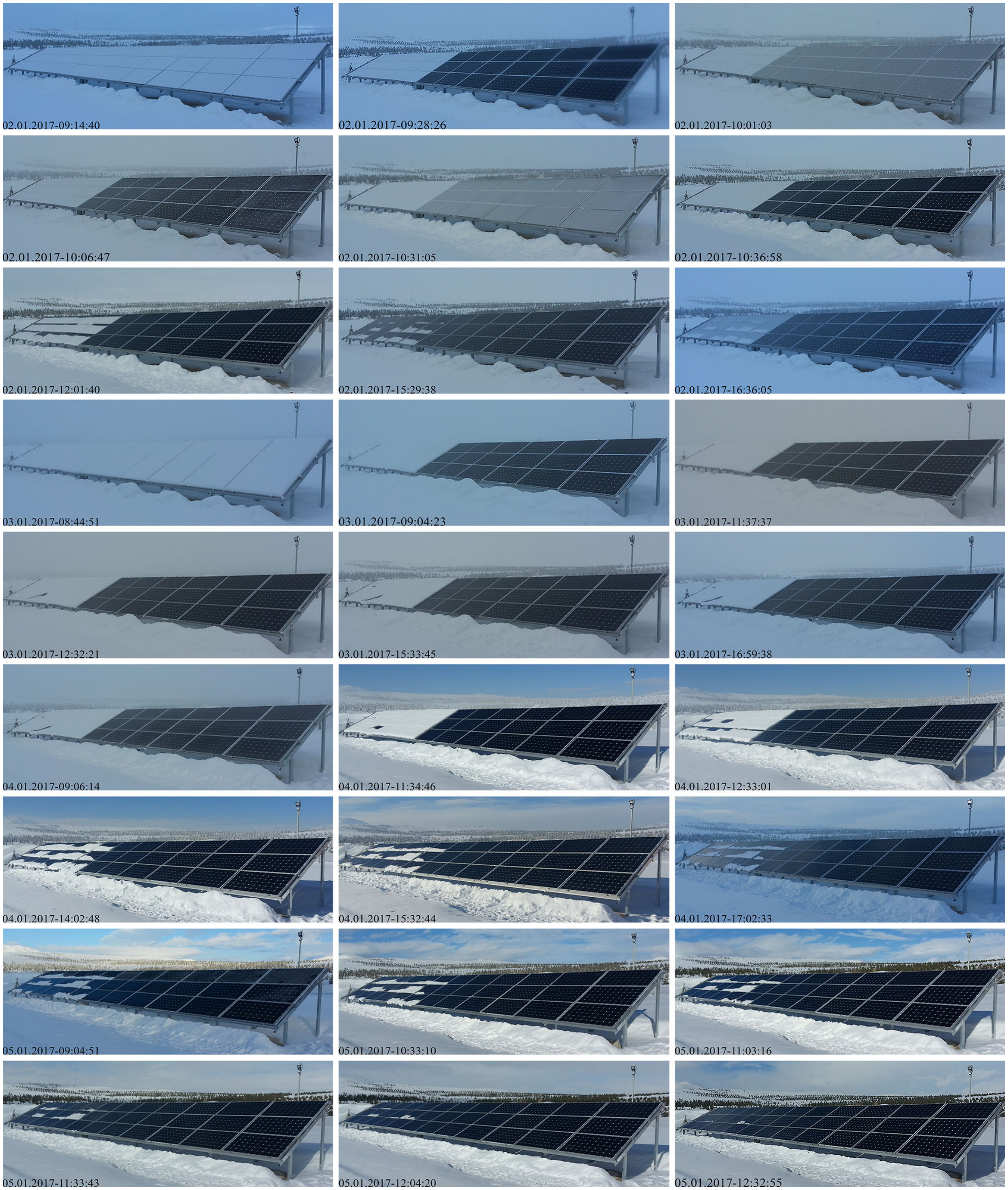

Figure 4. Digital images of snow cover on the PV modules from January 2 to January 5, 2017.

The sunrise and the sunset happen between 08:00 and 18:00 during winter months in Konya (Turkey time, GMT + 3) where especially snowing and icing make transportation difficult in early hours. Therefore, snow clearing operation on some days started with 1 hour delay in the morning. During this time, the modules were covered with snow or ice. Since the available irradiance in the early hours is quite low, this time loss does not make a considerable difference between the powers derived from the arrays.

5.1.1. Case I: snowy day

On January 2, 2017, the snowfall occurred during the night and continued as short-duration snowfalls during the day. The large and deep fluctuations observed in the instantaneous power production of the arrays and the global radiation during snowfall are seen in Figures 3a and 3b. In the morning, the snow thickness on the modules was measured as 2 cm. Due to the slight snowfalls which occurred during the day, one of the arrays was cleared every half hour and tried to be kept clear throughout the day. The first clearing activity was carried out at approximately 09:15. The clearing of the 18 modules by only one person took about 14 min. Average clearing time during the day measured as 5 min. Therefore, clearing of modules in large PV production plants with this method will require a considerable amount of time and labor.

The power production of the cleared array increased rapidly depending on the rise in irradiance, whereas the power production of the other array remained very low because of the snow cover. Although the air temperature was below –5 °C during the day, the snow layer decreased as a result of irradiance which increased during the day because the upper part of the snow layer is exposed to low ambient temperature, while the lower part is at zero degrees. Solar radiation reaching up to PV cells heats the module glass under the snow layer. The glass melts the snow layer from the bottom and the snow-water slips the snow layer downward from the inclined module surface. Module frames prevented the snow layers from falling off the module surface. The last melting snow is that deposited on the lower edge of the modules at the same row. At the end of the day, a slight snowfall occurred again and covered the modules with snow. When the power production of the arrays is taken into consideration, intermittent snowfalls during the day and the very thin layer of snow on the array caused a 72% loss in production per day.

5.1.2. Case II: full shading

On January 3, 2017, heavy snowfall covered all of the arrays in the plant with snow during the night. In the morning, the snow thickness on the modules was measured as 8.5 cm. The snow cover removed from the array by the cleaning activity starting at 08:50. It took about 15 min to clean the array. While the snow cover on one of the arrays was removed by clearing operation, the other array was covered with snow all day. A very little snowfall occurred in the middle of the day. This snowfall did not change the amount of snow on the array. The instantaneous power production of the arrays with atmospheric variables is shown in Figures 3c and 3d, respectively. The air temperature which decreased to –15 °C during the night increased to –5 °C again during the day as it happened the previous day. There was not a major change in the snow layer due to low irradiance and ambient temperature. When the clear and snow-covered arrays are compared, it is seen that there is a big difference between the production values. Cleared array reached the same production value as in the previous day, whereas the array covered with snow during the day could generate very little. Snow layer caused a 93% of loss in production per day.

5.1.3. Case III: icing

On January 4, 2017, one of the arrays started the day with the snow cover belonging to the previous day. It did not snow during the day, so no clearing operation was carried out. The changes of the atmospheric variables and the instantaneous power production of the arrays are given in Figures 3e and Figure 3f, respectively. An ice layer was observed on the clear array because of the temperature reaching –15 °C in the morning. It was not possible to clear the ice layer. Low air temperature continued throughout the day as it was on other days. The ice layer and the snow cover on the arrays began to melt because the irradiance value during the day increased. The melting of the ice layer continued until 10:00. The snow cover, which began to disappear from the top edge of the modules, slipped down the array at 14:00. However, the heaps of snow accumulated on the ground and frames of the module prevented the fall of the snow layer from the array. Therefore, it is necessary to install the PV modules at a certain height from the ground depending on the amount of snowfall of the region to facilitate the fall of snow accumulated on the surface of the modules. As the snow layer decreased by the melting, the power production of the snow-covered array gradually increased during the day. While the amount of irradiation increased by 30% in comparison with the previous two days, the energy generated by the clear array increased by 110% with fluctuations depending on the cloud movement. The daily energy loss was calculated as approximately 88%.

Chemical solvents can be preferred as a short-term solution because they are relatively inexpensive and easy to use in cleaning a small amount of snow and ice. However, this application which has an abrasive feature may cause the deterioration of the module structure, corroding of screws in the supporting system, and reducing light transmission of glass because of residues remaining on the module surface. Furthermore, due to melting snow and ice, these solvents which can be hazardous for nature can contaminate the soil and ground water sources. Another difficulty of this application is the carrying chemical solvents to the site area by means of a vehicle in winter season. In addition, the amount of chemical solvent, the required workforce and cleaning frequency will get increase the cost of the activity.

5.1.4. Case IV: partial shading

January 5, 2017, was a sunny and partly cloudy day on which the effect of the fragmented snow belonging to the previous day on power production of the plant was obviously demonstrated. The records obtained from the meteorological station with partial data loss are shown in Figure 3h. The air temperature which decreased to –17 °C in the morning linearly increased to 5 °C during the day. In the morning, the surface of the modules was covered with ice layer as it was on the previous day. Increasing irradiance and air temperature throughout the day eliminated both ice and snow cover on the arrays, as well as the production difference between arrays. Although the irradiation value increased by 40% in comparison with the previous day, the power production of the arrays could not rise to the desired level because of the intensive cloud movement (Figure 3g). The loss of production caused by working with fragmented snow cover was determined as 16%. Many array inverter groups or microinverters that produce at module level can be preferred instead of a single central inverter system in PV installations in order to reduce the effects of shading.

5.2. Monthly energy production losses

Figures 5 and 6 show the daily energy production results obtained during the winter season (November–March) from the plant in the last two years. It is possible to distinguish between the clear and snow-covered arrays from graphics. The snow clearing activities increased the power output of the cleared array. However, the power production in the fragmented or completely snow-covered array considerably reduced. Snow cover and icing staying on the array over a long period of time increased the production difference and losses between the arrays. Besides, it is seen that there is a continuous ongoing production difference between the two arrays. One of the arrays produces more energy than the other. This production difference between the two arrays continues throughout the year. This difference decreases on rainy and cloudy days, whereas it increases on sunny and clear days when the sky is cloudless. In order to determine the difference between the two arrays, the daily production values of the arrays over months were examined.

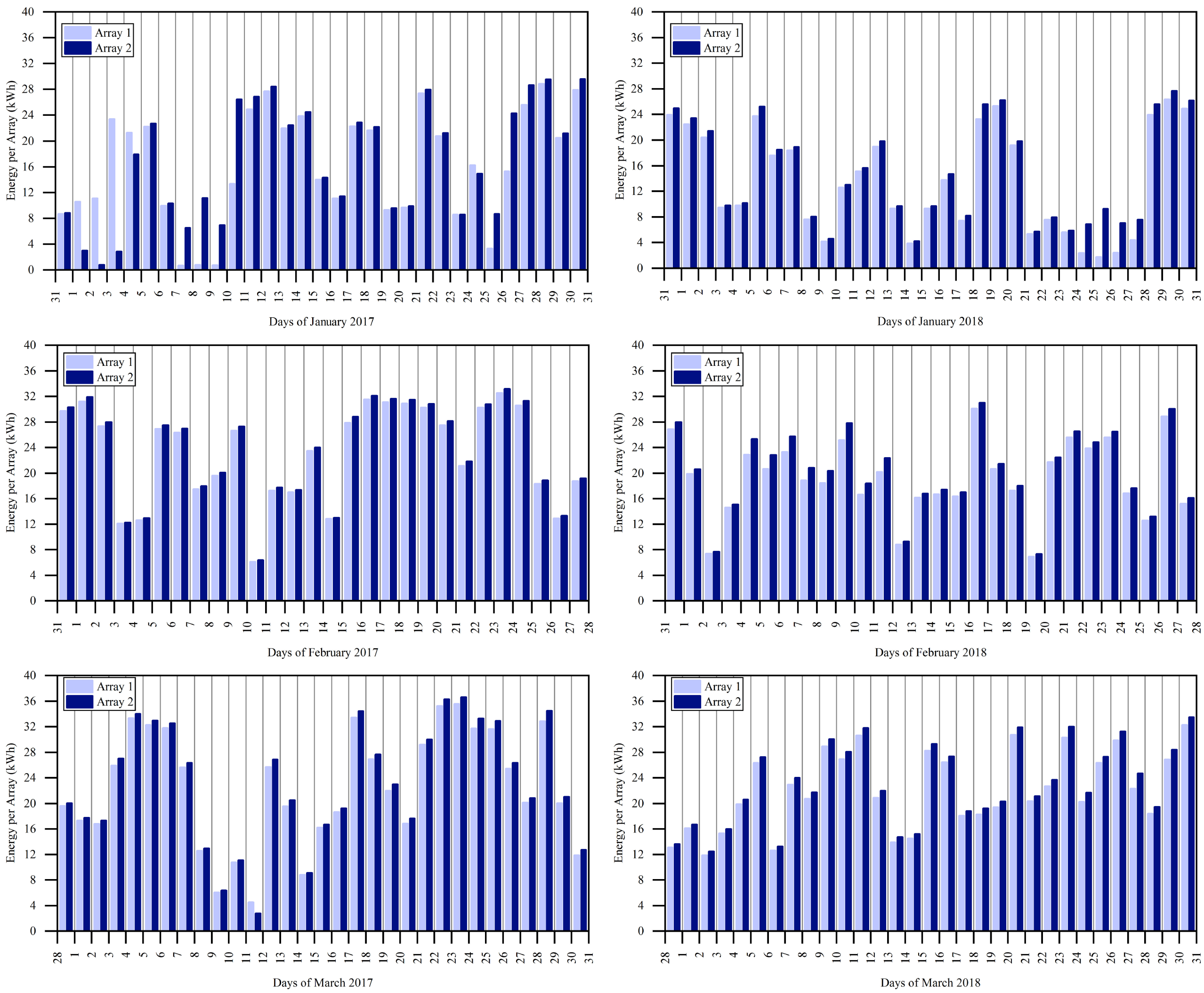

Figure 5. PV system energy production in winter season (January–March) in the last two years.

Figure 7 shows the power production of two different days belonging to summer and winter when the power production of the arrays shows a uniform distribution. One of the reasons is that the arrays are shaded by the existing school building beginning from the sunrise. This effect makes a difference between arrays in both summer and winter. By season, it takes approximately 1 to 2 h for the arrays to get rid of this effect in the morning. In the meantime, one of the arrays is shaded more than the other, and the production in this array

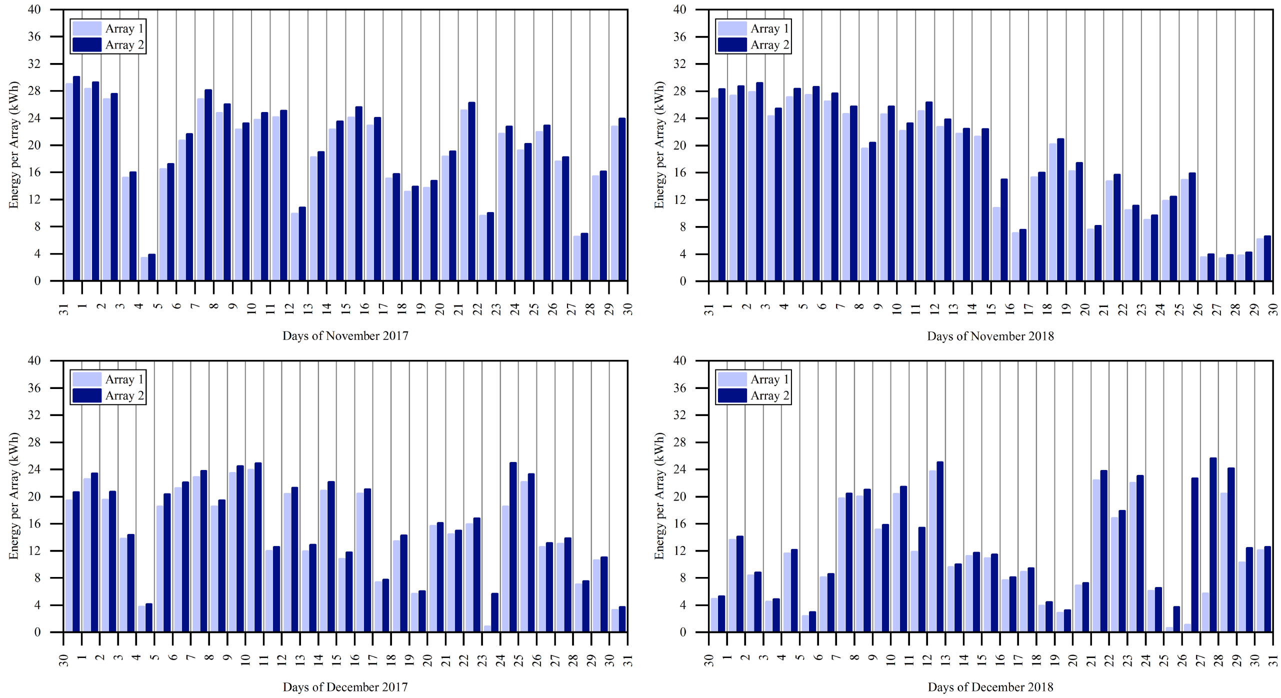

Figure 6. PV system energy production in winter season (November–December) in the last two years.

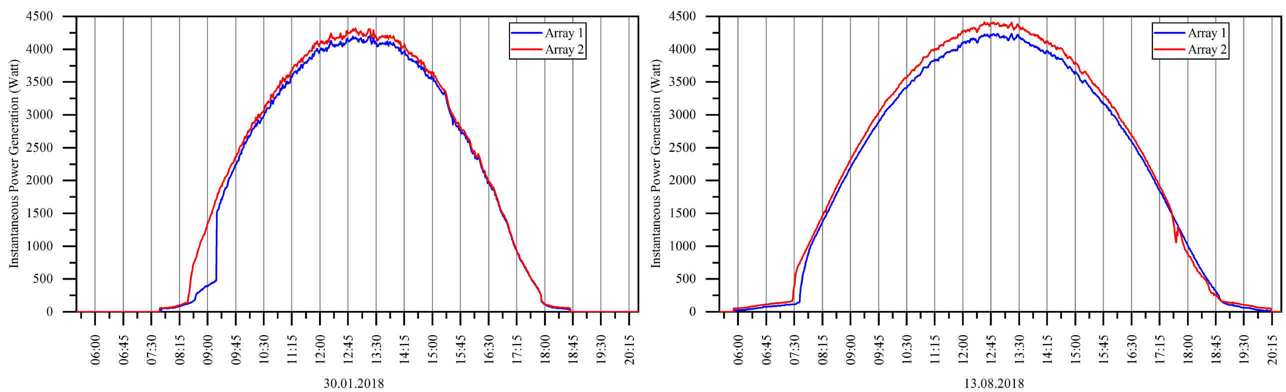

Figure 7. Comparison of the power generation of arrays in two different seasons.

which is shaded for a long time is slightly lower than the other. Furthermore, the energy production difference between the arrays also increases on days when the air temperature drops to –15 °C below zero because icing occurs on the surface of the modules early in the morning in cold winter months. This ice layer melts later than the other on the array which is under the effect of shading and the production in this array is slightly lower than the other.

One of the major reasons for the difference between arrays is that the modules used in both arrays do not produce equal amounts of power. The reason of this is that 8 modules used in one of the arrays have a label value of 270 W. It is stated on the module label of the manufacturers that there may be a difference of $0-3\%$ between the power generation of the modules coming out of the same production line in the factory. This situation causes a small difference between the arrays being compared. This difference becomes more apparent during the day only at noon. Daily energy production difference between arrays varies between 2% and 5% by season. This difference and also the snowy days are known. Therefore, while comparing the daily energy production of the arrays, the array making overproduction can be likened to a watch. The watch measures time but shows an acceptable extra amount. This difference remains stable on nonsnowy days. The actual value is obtained by subtracting this excess from the measured value. Consequently, there is no loss of energy production difference between the arrays on days when it does not snow and icing conditions are not observed. On snowy days, the energy generation of the array which is used as a reference and produces more is reduced at the rate of the monthly average difference obtained during the nonsnowy days. The loss of production caused by shading was neglected because the share of shading in total daily energy production of arrays is quite low.

In the first year of the study (2017), the maximum snowfall occurred in January with 13 days. As a result of snowfall which started at the end of December 2016 and continued in January 2017, the maximum snow height on the ground reached 51 cm. The disappearance of snow on the ground continued until the end of the February (53 days). It did not snow in February and November, while snowfall in March and December was limited to only a few days. In 2017, the number of days on which the temperature decreased below –15 °C and the icing was effective, was 4 days and 3 days in January and February, respectively. Snowfall and icing events in January, March, and December resulted in production losses of 18%, 0.25%, and 2.6%, respectively.

In the second year of the study (2018), the number of snowy days was 4 days in January and December, and only 2 days in November. The height of the snow on the ground was 10 cm and 12 cm in January and December, respectively. These values are quite low compared to the previous year. Snowfall and icing were most effective at the end of December. The snowfall and icing events in January, November, and December caused 5%, 1%, and 13% loss of production, respectively.

5.3. Annual energy production losses

Figure 8 shows the monthly production values of PV arrays for 2017 and 2018. System outputs vary from month to month due to the weather conditions such as icing, fog, rain, and cloudiness rate that affect the production in the year with snowfall. May is one of the months in which the number of rainy and cloudy days is the highest. Cloudiness rate, snowfall, and icing are the most effective in January and December. The most significant difference among the production data belonging to the last two years occurs in the months in which snowfall is effective. In January and February 2018, the number of snowy or rainy days is low and production loss is also quite low. However, energy production is lower than the same period of the previous year. It is thought that the sun rays reflected from the snow cover on the ground during January and February 2017 caused this situation. Total energy production of the plant for 2017 and 2018 was 17,500 kWh and 16,900 kWh, respectively. Annual production loss caused by snowfall and icing for 2017 and 2018 was calculated as 1.3% and 1%, respectively.

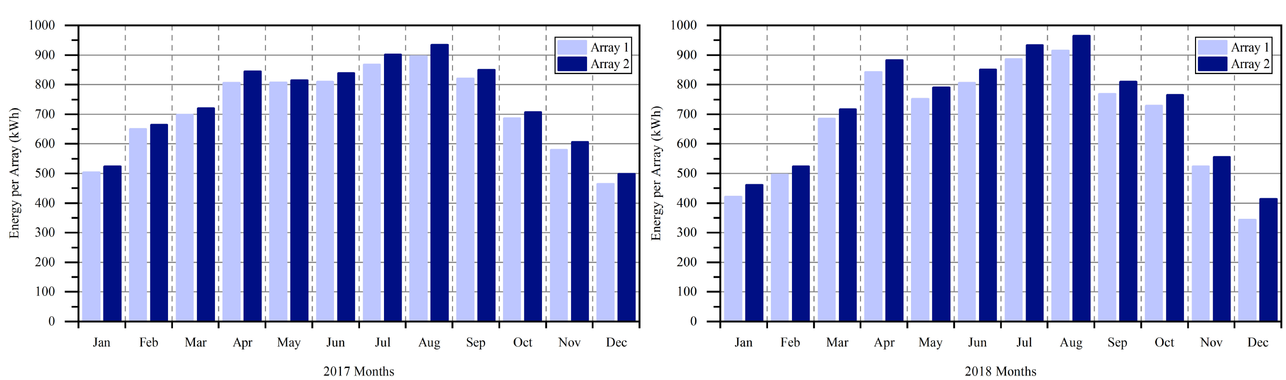

Figure 8. Comparison of monthly change of energy from the PV arrays in the last two years.

6. Conclusion

There is a need for the evaluation of economic losses and for the determination of the performance losses caused by the snowfall for energy generating facilities based on PV technology in Turkey where the PV plant investments have been rapidly increasing in recent years. In order to get meaningful results, loss estimation should be carried out in a location where PV plant installations are intense rather than in an ordinary area. The purpose is not to achieve large loss values. Regional results are very valuable for the plant operators and investors. In this study, the effect of snowfall and icing on energy production was examined in a snowy region (Konya, Turkey) where PV plant installations in MW size have been performed.

There is not a known practical method that can prevent the accumulation of ice or snow on the PV system without damaging its structure and without degrading its performance. For this reason, the mechanical scraping method was preferred in this study as it is more environmentally friendly and cost-efficient when it is compared with other conventional methods. This study was carried out on a grid connected PV system and the actual operating values were used. The daily, monthly, and annual production data of the cleaned and snow covered arrays were examined in detail to determine loss values and presented comparatively.

In a PV system, inverters which have MPPT feature or additional MPPT devices are used to obtain maximum power output from the modules. The load determines the current drawn from the PV system which does not include MPPT devices. In this case, variable loads must be used to determine module performance and to operate the PV system at the maximum power point. Furthermore, it is necessary to record the current and voltage values of the system continuously. Simultaneous measurement of several quantities requires a data logger. In addition, the employed measuring devices must be compatible with the data logger. Besides the data logger must have large data storage memory for long-term measurement duration and high data resolution. In this study, the quantities required to evaluate the performance of PV arrays were obtained from the inverter. Accordingly, there is no need for variable loads and expensive measuring devices that measure each quantity separately.

The results of the study showed that the daily production losses in a completely snow covered array could reach very high values as 93%. Module frames that prevent the slip of snow layers, and snow heaps on the ground were influential in the occurrence of high losses. However, the annual evaluation results for 2017 and 2018 were quite low for the existing plant location. Monthly production losses due to snowfall and icing are 18% at most and annual losses vary between 1% and 2%. The results are completely regional and only limited to the Konya region where the plant area is located. Of course, different results will be obtained in different regions of Turkey with different climatic and precipitation characteristics. The results are based on measurements performed under real atmospheric conditions. Although different amount of snowfall and loss values were obtained during the research period, regional annual loss rate did not vary much. In this respect, the results of the research are valuable in providing regional estimation. Including the losses caused by snowfall in the estimates of production and gain will increase the reliability of the analyses.

In large PV power plants, the cleaning of modules by conventional methods requires considerable time and labor. Therefore, the gain obtained by cleaning the modules may not compensate the snow cleaning cost. To maintain production in winter and to facilitate the removal of snow mass from PV modules, using frameless PV modules, increasing the mounting height of the lowest edge of the modules with the ground depending on the amount of snowfall in the location, installing the PV modules horizontally to the supporting system, using string inverter or microinverter systems instead of central inverter system may help solve this problem at a certain level.

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