Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 77 (2015) 386 – 396
Energy Procedia

5th International Conference on Silicon Photovoltaics, SiliconPV 2015

Performance improvement techniques for photovoltaic systems in Qatar: Results of first year of outdoor exposure

Diego Martinez-Plaza[a]*, Amir Abdallah[a], Benjamin W. Figgis[a], Talha Mirza[b]

[a] *Qatar Environment and Energy Research Institute, P.O. Box 5825, Doha, Qatar*
[b] *GreenGulf Inc, P.O. Box 210290, Doha, Qatar*

Abstract

The state of Qatar has established firm renewable energy deployment targets for the next decade, using primarily solar photovoltaic technologies.
Qatar, in the Arabian Peninsula, is in the MENA Region, where the solar resource is fairly abundant, but local environmental conditions are challenging, particularly, high ambient temperatures all-year round, a dusty atmosphere due to high aerosol content, and water scarcity, which impact negatively on PV system performance and reliability.
The Solar Test Facility (STF) at the Qatar Science & Technology Park (QSTP) was founded in 2012 for the main purpose of contributing to the achievement of Qatar's sustainable energy technology deployment targets. STF provides scientific and technical capabilities for testing and evaluation of solar technologies under the specific local climate conditions.
This paper presents the results of outdoor exposure of a specific model of multicrystalline silicon (mc-Si) photovoltaic (PV) modules after their first complete year of operation at STF. The impact of module cleaning frequency, use of commercial anti-soiling coatings and module mounting on either fixed, one-axis-tracking or two-axis-tracking systems was studied.
These results give some indication of the next steps to be taken and the solutions that would eventually work for the improvement of both the energy yield and the durability of PV systems deployed in this region.

Peer review by the scientific conference committee of SiliconPV 2015 under responsibility of PSE AG

Keywords: solar energy; poly-silicon; dust soiling; sun-tracking systems

* Corresponding author. Tel.: +974-44543088; fax: +974-44541528.
E-mail address: dmartinez@qf.org.qa

Peer review by the scientific conference committee of SiliconPV 2015 under responsibility of PSE AG
doi:10.1016/j.egypro.2015.07.054

1. Introduction

Qatar is a peninsula located between 24° and 26° latitude north. The peninsula is only 160 km north-to-south, with an area of 11.586 km^2. Much of the country consists of sand dunes and salt flats across a low, barren plain.

Qatar has a dry, subtropical desert climate, with low annual rainfall (~ 80 mm) and intensely hot summers. Temperatures are warm but not hot in spring and autumn, and the evenings use to be pleasantly cool. Temperatures in June to September are very high, with means of the daily maximum values around 42 °C for June, July and August, but it is not unusual for the mercury to rise as high as 50 °C. In the winter months, temperatures are cooler but still warm, with means around 23 °C from December to February [1].

The region is rich in the solar resource with a reported value of 2.113 kWh/m^2 for the global horizontal irradiance (GHI), as the average of measurements taken at ten existing radiometric stations spread all over the country in the period ranging from 2009 to 2012 [2].

It is well known that performance of photovoltaic modules is affected by environmental variables, beginning logically with the solar radiation available, but also by others such as the ambient temperature and presence of dust in the air causing soiling [3, 4, 5]. This paper presents for the first time a study on the effect of those environmental factors on the performance of certain model of mc-Si PV modules in Qatar after their first year of operation. The results have been obtained at the Solar Test Facility (STF), an experimental facility developed by Qatar Science and Technology Park (QSTP) which is located at the Qatar Foundation's Education City premises.

2. Test set-up

2.1. The Solar Test Facility at QSTP

The Solar Test Facility (STF) at the Qatar Science and Technology Park (QSTP) contributes to the adoption of sustainable energy in Qatar by evaluating solar technologies under local climate conditions. It has been developed and is operated in partnership by QSTP, the local company *GreenGulf Inc*. and the Qatar Environment and Energy Research Institute (QEERI). Testing campaigns on around 30 photovoltaic and solar thermal technologies from manufacturers around the world are currently on their way.

The STF is a 35.000 m^2 (7 acre) open-field, grid-connected test site, located at Education City, about 10 km from the Doha coast (Fig. 1). It was inaugurated on December 2012 and testing activities began in March 2013. They are planned to continue for several years carrying out long-term studies like:

- Evaluation of single PV modules
- Evaluation of small PV arrays and inverter assessment
- Evaluation of PV arrays in specific mounting configurations
- Evaluation of concentrated PV (CPV) generators

2.2. The PV array and multi-crystalline silicon module test benches

A certain type of multicrystalline silicon modules has been used for this study. These modules were installed in strings of eight, with total nominal power ranging between 1.700-1.800 W_p (see Fig. 2). Up to 10 strings have been used, so the effects of a variety of factors in their electricity yield could be studied.

The data acquisition system measures current, voltage, yield power and yield energy for each module or array installed at the STF at 'maximum power point' (MPP) conditions, which are secured through the inverter's electronics.

Fig. 1. The 'Solar Test Facility' at Qatar Science and Technology Park, in Doha

Table 1 below shows the main features of each string used in this study. String #8 was early shut down because of technical problems.

Table 1. List of strings and their relevant features

String #	Mounting system	Washing cycle	Coating
1	Fixed	Low	No coating
2	Fixed	Low	A
3	Fixed	Low	B
4	Fixed	Medium	No coating
5	Fixed	Medium	A
6	Fixed	Medium	B
7	Fixed	High	No coating
9	Fixed	Medium	C
10	1-axis, North-South	Medium	No coating
11	2-axis	Medium	No coating

3. Methodology

The facility has already been in operation for almost two years, so it is possible to study various points of interest to photovoltaic module performance throughout a complete meteorological cycle. Clearly, it would be best to have several complete years of data available for more solid results, but one year can already provide some indications.

The period from April 1, 2013 to March 31, 2014 was studied. It is important to point out that some of the graphics in this article show data in order from January to December, even though they are not in chronological order. The purpose of this modification is to emphasize seasonal differences in the variable under consideration.

Fig. 2. Several 'poly-Si' strings at the Solar Test Facility

A larger number of individual models based on different technologies and by different manufacturers are being tested, however, only a specific module made with poly-silicon technology was used in this preliminary study.

Specifically, the influences of the following factors on power yield have been studied:

- Application of different cleaning frequencies.
- Use of different experimental anti-soiling coatings.
- Effect of using sun-tracking systems.

4. Test results and discussion

4.1. Cleaning frequency study

The purpose of this experiment is to estimate what the optimum washing frequency would be for ambient conditions typical of this region. Different cleaning frequencies have been set up for the modules: weekly (*high*), bimonthly (*medium*) and biannual (*low*).

As the systems to be compared are identical and located in the same place, it is rather simple to make the comparison just by using the daily performance ratio parameter 'PR' for each, following the recommendations of standard IEC-61724 [6]. Some necessary definitions are the following:

The reference yield, Y_r, is based on the in-plane irradiation, H_A (kWh/m^2) and the solar irradiance of reference, G_S (1 kW/m^2), thus representing the number of hours G_S is collected per day.

$$Y_r = H_A/G_S \tag{1}$$

The array yield, Y_A, is the daily array energy output, $E_{A,d}$, (kWh) and represents the number of hours per day that the array would need to operate at its rated output power, P_{max}, (kW$_p$) to contribute the same daily array energy to the system as it was monitored.

$$Y_A = E_{A;d}/P_{max} \tag{2}$$

Finally, the array performance ratio, *PR*, is the ratio of actual array output energy to the energy available theoretically. Thus defined, *PR* is independent of location and array size, and indicates the overall losses on the array's rated output due to module temperature and incomplete utilization of irradiation.

$$PR = Y_A/Y_r \tag{3}$$

The Table 2 below summarizes the rainy days and days with scheduled cleaning within the studied period.

Table 2. List of days with programmed cleaning or rain events

Date	Event	Category
2-Apr-13	Rain	Light
17-Apr-13	Rain	Medium
19-Apr-13	Rain	Light
27-Apr-13	Rain	Light
30-Apr-13	Rain	Light
1-May-13	Cleaning	Medium
4-May-13	Rain	Heavy
8-May-13	Rain	Light
2-Jul-13	Cleaning	Low - Medium
3-Sep-13	Cleaning	Medium
7-Nov-13	Cleaning	Medium
17-Nov-13	Rain	Moderate
20-Nov-13	Rain	Heavy
2-Jan-14	Rain	Moderate. Low' and 'Medium' washes cancelled.
5-Jan-14	Rain	Moderate
6-Jan-14	Rain	Moderate
11-Jan-14	Rain	Heavy
18-Jan-14	Rain	Light
2-Feb-14	Rain	Moderate
9-Feb-14	Rain	Moderate
6-Mar-14	Cleaning	Medium

Five periods long enough (a minimum of 30 days has been established by the authors of this study) to be able to extract information on the soiling rate from the decrease in the PR index were found.

It is known that PR undergoes seasonal variation due to variation in the cosine factor among others [7], however, it was not considered in this study as the periods under study were relatively short.

Fig. 3 below shows degradation of this parameter over time due to accumulation of dust on the modules.

Evolution of PR is shown for a module with low washing frequency (#1, dashed line) and for another one with medium frequency (#4, solid line). The high-frequency washing module (#7) showed a rather constant value of ‘PR’ all year long, so it is assumed that this is the maximum cleaning frequency.

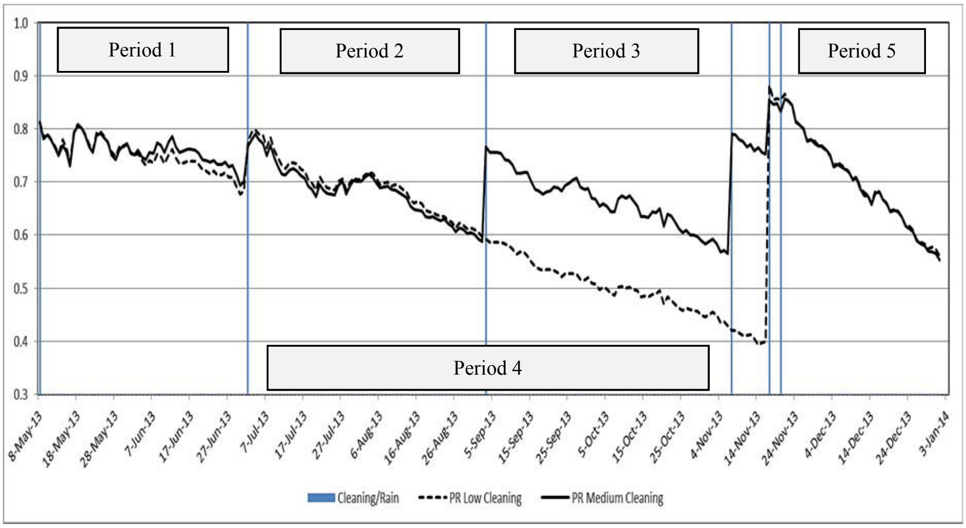


Fig. 3. Evolution of ‘PR’ over time

The vertical lines in the graphic show both, washing or rainy days, as specified in Table 2.

Table 3 below shows the results of a linear regression study of the relationship between intervals between washings (days) and deterioration in the mean 'PR'.

Table 3. Results of linear regression studies

Period	Module	Cleaning rate	Start date	End date	Total days	Linear coefficient	R^2
1	#1 - #4	Low - Medium	8 May	1 July	55	-0.0016	0.6707
2	#4	Low - Medium	2 July	2 September	62	-0.0026	0.8660
3	#4	Medium	3 September	6 November	64	-0.0027	0.9293
4	#1	Low	2 July	6 November	126	-0.0028	0.9820
5	#1 - #4	Low - Medium	20 November	1 January	42	-0.0069	0.9848

Daily fall in 'PR' (linear coefficient) can be summarized as 0.26% to 0.69% for the period and location under study. The figure 0.16% shows higher data dispersion and has been discarded.

Apart from this, 'PR' remains rather constant for the module which is washed weekly (#7).

The experiment continues active and in upcoming publications it will be possible to report on this phenomenon backed by more data.

4.2. Use of anti-soiling coatings

Another facet of this project is the study of solutions 'anti-soiling coatings'. During this first period, three commercial anti-soiling coatings were tested in the field to study their performance, applied as shown in Table 4 below.

Table 4. Application of commercial anti-soiling coatings used for this study

Module #	Code	Coating type
4	No coating	-
5	A	Hydrophilic
6	B	Resin
9	C	Anti-static

Fig. 4 below compares PR for modules to which each of the three coatings has been applied, all of them subject to "medium" washing frequency (bimonthly) and compared to the module with no special coating.

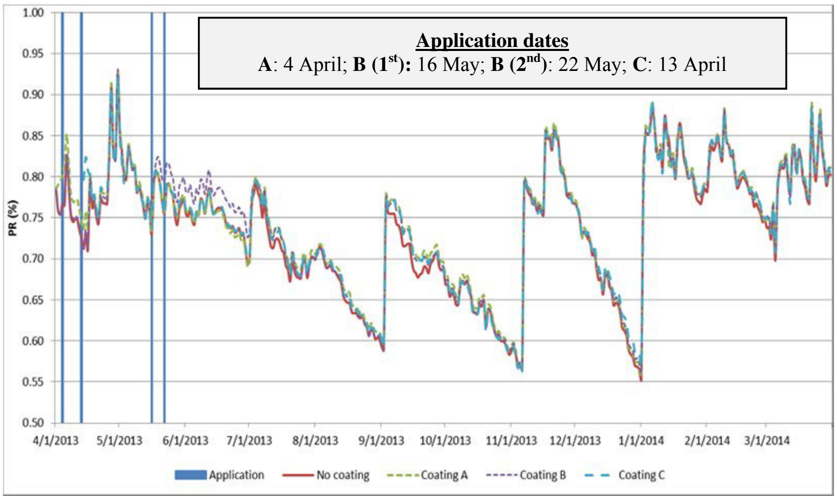


Fig. 4. Evolution of 'PR' for modules with anti-soiling coatings

It may be seen that there is no noticeable difference in the value of ‘PR’ for modules with different coatings. Coating ‘B’ seems to work well from time of application, but this is really because the module has to be cleaned before application.

It should also be mentioned that all three products claim to make module cleaning easier, but avoiding accumulation is different, and this could have caused the performance observed. The use of coatings does not decrease accumulation of dust, but does facilitate its elimination as soon as there is a minimum of rain.

Nevertheless, it is possible that the ‘dirty’ periods have not been long enough to allow the coatings to work properly, so further studies are still necessary before more solid conclusions can be drawn.

4.3. Effect of using one or two-axis solar tracking systems

It was also desired to study the operation and possible interest of the use of tracking systems. To do this, modules were mounted on one-axis (north-south aligned with azimuth tracking) and two-axis tracking systems.

In the first place, incident global irradiance was studied on the horizontal plane (GHI), stationary module plane (GPOA_F), plane of the modules in the one-axis tracking system (GPOA_1A) and plane of modules in the two-axis tracking system (GPOA_2A). The comparative results are shown in Table 5 below.

The way of reading this table and Table 6 as well is ‘Row value vs. Column value’. For example, ‘Fixed Plane at 22º collects 2.8% energy more than 1-axis tracking plane (azimuth)’.

This being said and in view of the table, it can be stated that the two-axis tracking plane collected more energy than the others in any month of the year, more so in winter.

On the other hand, the horizontal plane collected the least energy after one year than any other of the options studied.

The system tilted a fixed 22º collected 8.6% more energy after one year than the horizontal plane, although in the summer months it performed comparatively worse. The determination of the optimal angle of inclination for stationary systems for conditions in this region would be the subject of a later study.

Table 5. Comparison of incident global irradiance measured on plane of arrays

	Horizontal plane	Fixed plane at 22º	1-axis tracking plane (azimuth)	2-axis tracking plane
Horizontal plane	-	-8.6%	-5.5%	-39.1%
Fixed plane at 22º	+8.6%	-	+2.8%	-28.1%
1 axis tracking plane (azimuth)	+5.5%	-2.8%	-	-31.8%
2 axis tracking plane	+39.1%	+28.1	+31.8%	-

On the plane of the azimuth tracking system, more energy is collected than on the horizontal plane, but not more than the fixed system. This system collects 2.8% less energy than the fixed system after one year. This effect is stronger in winter, its use only being advantageous in the summer months. The explanation for this phenomenon is that the one-axis tracking system is oriented North-South located on the horizontal plane with no tilt angle, tracking the Sun just on azimuth angle but not in elevation angle, so its cosine factor is worse than the fixed system, which is tilted 22º from the horizontal. This effect is stronger in the months of the year when the elevation of the sun is lower in the sky, that is, in winter.

The Fig. 5 below shows the monthly data measured.

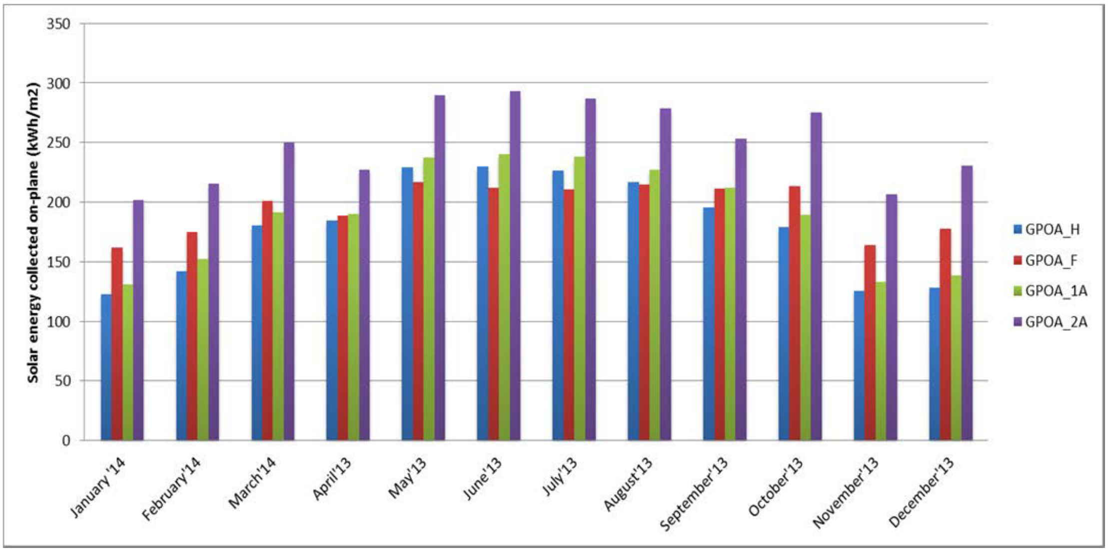


Fig. 5. Monthly comparison of radiation collected by tracking systems vs fixed tilt angle system

Further on, the global solar radiation collected is converted into electricity produced as shown in Fig. 6 below, and measured by the data acquisition system described in [8].

To make the comparison uniform, the unit used is kWh/W_p for each system, which is equivalent to hours/month at full capacity system operation. The Table 6 shows the comparison of results for the different systems.

The trends that could already be observed for the GPOA are confirmed in view of the table above and figures below. However, it should be underlined that the percentage differences are greater for electricity yield than for GPOA. Even in the case of '*Fixed plane at 22º vs 1-axis tracking*', the latter yields more power though the global irradiance collected is lower than by the first. The reason for all these phenomena is that not all the global radiation collected on the surface of the module behaves the same in its conversion to electricity [9]. It is known that global radiation is composed of direct irradiance (DNI) and diffuse irradiance (DHI). The tracking systems make better use of the DNI, which is usually the main component of global irradiance in several months of the year of study and, therefore, justifies this increase.

Table 6. Comparison of annual electricity yield for the three mounting systems

	Fixed plane at 22º	1-axis (azimuth) tracking	2-axis tracking
Fixed plane at 22º	-	-10.4%	-51.4%
1-axis (azimuth) tracking plane	+10.4%	-	-37.2%
2-axis tracking plane	+51.4	+37.2%	-

At this point it should be mentioned that the one-axis tracking system production data for the months of September and October are lower than they should be, which distorts the comparison a little, although it continues to be basically realistic. The reason is that the three systems should follow the same washing schedule, but due to an error, the one-axis tracking system was not washed in September, while the fixed and two-axis systems were. This was not corrected until November when all three systems were washed again following the '*medium*' schedule (every two months).

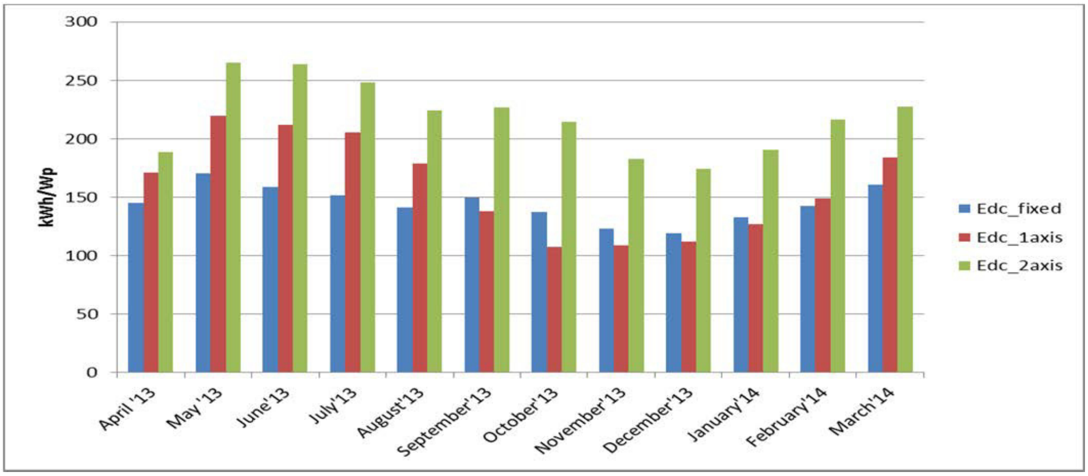
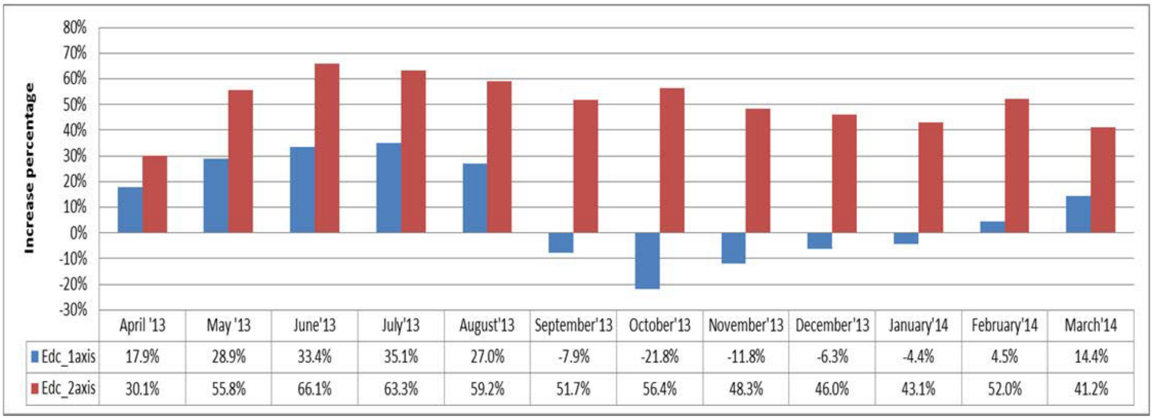


Fig. 6. Specific monthly energy yield for the three mounting systems

The main conclusions arrived at from this section for this geographic location and multicrystalline silicon modules are illustrated in Fig. 7 and Fig. 8 and can be summarized as follows:

- Two-axis tracking system can generate up to 50% more electricity than a stationary system in one year. In principle, this type of system would be more recommendable, although there are two more factors that should be considered in the analysis, amortization of the extra investment cost and the added cost of more maintenance than for a stationary system.
- Azimuth tracking hardly generates more energy than the stationary system (10%), so the extra costs are apparently not worthwhile.
- The stationary system may be an option of interest, still pending study of the optimal angle of inclination for Doha climate conditions.



	April '13	May '13	June'13	July'13	August'13	September'13	October'13	November'13	December'13	January'14	February'14	March'14
Edc_1axis	17.9%	28.9%	33.4%	35.1%	27.0%	-7.9%	-21.8%	-11.8%	-6.3%	-4.4%	4.5%	14.4%
Edc_2axis	30.1%	55.8%	66.1%	63.3%	59.2%	51.7%	56.4%	48.3%	46.0%	43.1%	52.0%	41.2%

Fig. 7. Comparison monthly energy yield of tracking systems vs fixed tilted system

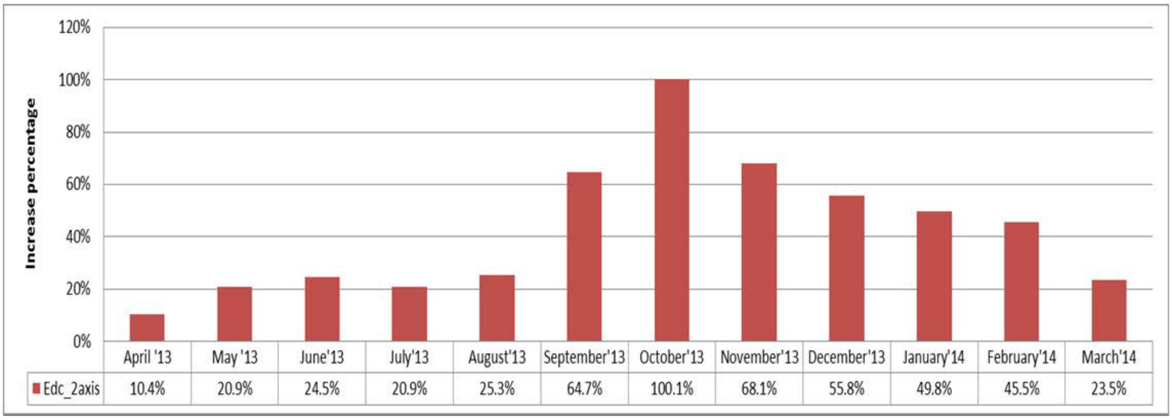


Fig. 8. Comparison monthly energy yield of 2-axis tracking systems vs one-axis tracking system

5. Conclusions

The new Solar Test Facility at the QF's QSTP has proven to be a very versatile test bench for carrying out studies which will pave the way for achievement of Qatar's targets for deployment of renewable energy technologies.

Of the several test campaigns which have been carried out during the STF's first year of operation, this paper reports on the results of specific studies done on a single type of poly-Si PV module. Preliminary tests have identified PV system cleaning requirements, decrease in their performance parameters and the usefulness of anti-soiling solutions under local dusty conditions.

Cleaning rate tests have shown that weekly cleaning is more than enough to keep modules at constant yield levels. Performance decreased over 1%/day when modules were not cleaned or it did not rain for more than 30 days.

Some commercial anti-soiling coatings were applied and compared for the decrease in 'PR'. No significant improvements were found over a standard, uncoated module.

Several different mounting systems were used and the energy yield compared. The fixed-tilt system was the simplest with the lowest investment, and results were promising. The one-axis tracking system barely improved results over the fixed-tilt, with just 10% additional electrical power production. As expected, the two-axis tracking system performed very well, (50% more than the fixed-tilt system and 37% more than the one-axis system), but its economic feasibility is still pending study, which is out of the scope of this paper.

Future work will be deployment of small-scale facilities over the country, development and testing of new anti-soiling coatings, and studies on an optimized tilt angle for a fixed system.

Acknowledgements

The authors would like to acknowledge the support given by both, the Qatar Science and Technology Park (QSTP) and the company *GreenGulf Inc*, which have made this scientific paper possible.

References

[1] Qatar Weather Monthly Averages (http://www.worldweatheronline.com/Doha-weather-averages/Ad-Dawhah/QA.aspx). Last accessed 27th January, 2015.

[2] Bachour D, Perez-Astudillo D. Ground-measurement GHI map for Qatar. Energy Procedia 49: 2297-2302, 2014

[3] Sarver T, Al-Qaraghuli A, Kazmerski L. A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature and mitigation approaches. Renewable and Sustainable Energy Reviews 2013; 22:698-733.

[4] Mejia FA, Kleissl J. Soiling losses for solar photovoltaic systems in California. Solar Energy 2013; 95:357-63.

[5] Mani M, Pillai R. Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations. Renewable and Sustainable Energy Reviews 2010; 14:3124-31.

[6] International Electrotechnical Commission (IEC). International standard IEC-61724: Photovoltaic system performance monitoring – Guidelines for measurement, data exchange and analysis. 1998.
[7] Jordan DC, Kurtz SR. Analytical improvements in PV degradation rate determination. 2010:2688-93.
[8] Martinez, D; Figgis, B; Abdallah, A. A new PV module reliability laboratory in Qatar. First results of outdoor exposure. Proceedings of the 6th International Renewable Energy Congress (IREC'2015). In press.
[9] International Electrotechnical Commission (IEC). Photovoltaic (PV) module performance testing and energy rating-Part 2: Spectral response, incidence angle and module operating temperature measurements (IEC 61853-2, Draft). 2012.