Cleaning is the key!

Energy yield | As early as 2010, Phoenix Solar along with Saudi Aramco installed the first of three PV test facilities in Dhahran, Saudi Arabia, putting four different module technologies (monocrystalline, amorphous-microcrystalline, CdTe and CIS) to the test in extreme climatic conditions. Klaus Friedl of Phoenix Solar LLC shares some hints and lessons learned from the tests

Before the initial results from the tests carried out at the Phoenix Solar PV test field were evaluated, little had been known about actual module behaviour when confronted with the extreme climatic and technical challenges of the Near and Middle East deserts. The main objective of the tests was to investigate a number of parameters which were deemed critical for the purpose of building the first megawatt-scale PV power plant in Saudi Arabia. Saudi Aramco, a highly demanding customer of Phoenix Solar, was keen on determining the best possible technical solutions for this prestigious project.

The first phase of the research project, which began in July 2010, lasted approximately six months. The results did indeed serve as a reliable platform in the course of engineering and building a 3.5MWp ground-mounted PV power plant, which has been operational since 2013, on the premises of the King Abdullah Petroleum Studies and Research Center (KAPSARC) in Riyadh.

The aim of this pioneering project was to expand Phoenix Solar's knowledge base regarding the performance of different PV modules subjected to the climatic conditions of Saudi Arabia. Since the temperature of a PV module has quite a big influence on the efficiency of the modules as well as of the inverters, the overall PV system efficiency might be significantly affected by the climatic conditions.

The climate

One set of basic data which had to be gathered beforehand related to the actual climate. The following climatic factors, assumed to exert an influence on the potential energy harvest, were investigated in three different locations:

- **Irradiation:** clearly of paramount importance and key to the common assumption that the Gulf countries are likely to enjoy extremely high solar energy yields.
- **Ambient temperature:** heat is well known for causing stress in all electrical and electronic devices.
- **Wind:** this has an impact on the effect of ambient temperature on module temperature.
- **Pollution:** sand and other pollutant particles may obscure the modules and hence reduce their efficiency.
- **Humidity:** the widespread ground fogs as well as the climate of the Saudi Arabian coastal areas have been found to have some link with output performance.

Table 1 roughly outlines the findings for the three locations for comparison purposes; the subsequent detailed discussion will focus on the Dhahran test field location.

Dhahran test field

The test field for which the results will be presented in this article took three months to construct on the premises of Phoenix Solar's customer Saudi Aramco in Dhahran, with the actual test programme beginning in September 2010. The installation consisted of three to four modules of each technology, namely monocrystalline, amorphous-microcrystalline, CdTe and CIS. The test system was equipped with a pyranometer for irradiation measurements (full spectrum), an ambient temperature sensor, an anemometer for wind speed measurements, and a humidity sensor.

In order to observe the performance of individual modules, each one was connected to its own DC/DC converter (Solar Magic by National Semiconductor); this took over the MPP (maximum power point) tracking for each individual module and converted the output voltage to a level that allowed the module to be connected to the inverter. The inverter, a product of SMA Technology AG (SB4000TL-20), had two independent inputs with MPP trackers. It converted the total DC energy from all DC/DC converters to AC, which is necessary for the connection of the installation directly to the AC grid.

In addition, the individual modules were each connected to an Omega Pt1000 module temperature sensor, a DC voltage measurement sensor on the PV module output, and a DC current measurement sensor on the PV module output (shunt). These sensors were connected to a Campbell Scientific CR3000 data acquisition system, and all data were stored by the data logger.

The temperature

A very important factor is the module temperature. All specification sheets for PV modules provide a temperature coefficient; however, no public data exist for the real behaviour of modules in hot climatic conditions, such as those found in Saudi Arabia, where maximum temperatures exceed 58°C. Table 2 shows the characteristics of the types of module that were put to the test at the Phoenix Solar test field.

The different temperature coefficients, acquired from the published product specifications, indicated already that the

Table 1. Basic climatic data of the three test fields.

	Dhahran (on the Gulf coast, a Saudi Aramco location)	Jeddah (on the Red Sea coast)	Riyadh (location of KAPSARC)
Temperature (°C)	-1 / +50	+11 / +49	-2 / +48
Humidity	54.7%, frequent ground fogs	62.8%, frequent ground fogs	26.0%, rare ground fogs
Air quality	Salty	Salty	Dry

high-temperature behaviours would differ to some extent. Actual findings, however, exceeded the expected range of differences in performance. Table 3 gives an overview of the climatic and module performance data over the first five months of data collection.

Technology	Module efficiency	Pmpp (temperature coefficient in %/°K)
Monocrystalline	14.5%	–0.48
Amorphous-microcrystalline	9.5%	–0.24
CdTe	11.1%	–0.25
CIS	9.8%	–0.45

▲Table 2. Module data extracted from manufacturers' datasheets, as of September 2010.

Discussion of findings

September

The best energy yield related to the rated power was achieved by the microcrystalline modules, followed by the monocrystalline modules; CdTe and CIS modules achieved approximately the same level of energy yield.

The first cleaning of the test field took place at the end of September, which means that, from 7 July until 30 September, the system had not been cleaned since its installation.

October

It was significant that the amorphous microcrystalline curve was above that for monocrystalline, CdTe and CIS modules. The temperatures in October were already lower than in September.

Amorphous-microcrystalline: 1st in performance ratio; huge break-in (reduction in energy yield) at low light; best temperature behaviour.

Monocrystalline: 2nd in performance ratio; best low-light behaviour; biggest break-in at noon (worst temperature behaviour).

CdTe: 3rd in performance ratio; good low-light behaviour; break-in at noon.

CIS: 4th in performance ratio; huge break-in at low light; break-in at noon.

November

It was again significant that the amorphous microcrystalline curve was above that for monocrystalline, CdTe and CIS modules. There were colder temperatures in November compared with October.

Amorphous-microcrystalline: 1st in performance ratio; huge break-in at low light; best temperature behaviour.

Monocrystalline: 2nd in performance ratio; best low-light behaviour; biggest break-in at noon (worst temperature behaviour).

CdTe: 3rd in performance ratio; good low-light behaviour; break-in at noon.

CIS: 4th in performance ratio; huge break-in at low light; break-in in the afternoon.

December

Likewise in December it was significant that the amorphous microcrystalline curve was above that for monocrystalline, CdTe and CIS modules. The temperatures in December were lower than in November.

Monocrystalline: 1st in performance ratio; best low-light behaviour; biggest break-in at noon (worst temperature behaviour).

Amorphous-microcrystalline: 2nd in performance ratio; huge break-in at low light; best temperature behaviour.

CdTe: 3rd in performance ratio; good low-light behaviour; break-in at noon.

CIS: 4th in performance ratio; huge break-in at low light; break-in in the afternoon.

January

It was found that the CIS panel performed much better in the cooler January climate than in the previous months.

Monocrystalline: 1st in performance ratio; best low-light behaviour; biggest break-in at noon (worst temperature behaviour).

CIS: 2nd in performance ratio; huge break-in at low light; break-in in the afternoon.

Amorphous-microcrystalline: 3rd in performance ratio; huge break-in at low light; best temperature behaviour.

CdTe: 4th in performance ratio; good low-light behaviour; break-in at noon.

When the basic technologies at stake were compared it became clear that under the specific climatic conditions of the region, crystalline technology took the lead over the thin-film technologies, while there were only minor performance differences within each of the four technology groups. The crystalline modules turned out to be less heat sensitive and performed decisively better than their thin-film counterparts, particularly in the summer months. This is most strikingly evident from the graph in Fig. 1, which highlights the performance advantage of a monocrystalline over a CdTe module on 22 July 2010.

"The crystalline modules turned out to be less heat sensitive and performed decisively better than their thin-film counterparts, particularly in the summer months"

In direct comparison the performance of the modules was assessed as follows:

- *Monocrystalline:* Above expectations (despite the high temperature coefficient, but good low-light behaviour).
- *Amorphous-microcrystalline:* Good, as expected (because of the good

▼Table 3. Results from September 2010 to January 2011 (only for modules which were cleaned every month).

Module comparison (average and cumulative yields)*	Sep 2010	Oct 2010	Nov 2010	Dec 2010	Jan 2011
Ambient temperature [°C]	34.8	30.6	23.5	18.6	16.6
Module temperature [°C]	39.2	35.3	26.6	21.7	19.9
Wind speed [mph]	5.0	4.7	4.5	5.0	5.3
Humidity [%]	46.8	49.2	49.0	53.4	69.4
Panels and pyranometer	**Cumulative yields [W/m²]**				
Irradiation	183.06	174.23	138.63	125.74	128.10
Monocrystalline (2nd place)	119.60	148.90	132.11	118.50	133.86
Amorphous-microcrystalline (1st place)	123.75	156.25	131.96	115.96	127.66
CdTe	106.86	137.56	118.10	106.38	114.69
CIS	81.90	130.82	121.14	96.34	124.14

* 'Average' refers only to the irradiation, and 'cumulated' refers to the module yields. All data are summed for each technology for the period of one month.

temperature coefficient).

- *CdTe:* Below expectations (despite the good temperature coefficient and constantly good low-light behaviour).
- *CIS:* Below expectations (because of the high temperature coefficient and weak low-light behaviour). CIS was able to improve somewhat in the lower-temperature winter months, but this was not enough to make up for the shortcomings throughout the rest of the year.

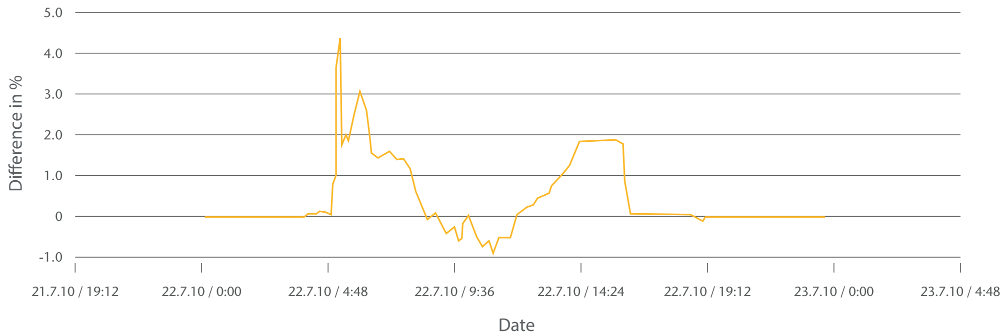
From an overall perspective, therefore, it was concluded that in terms of temperature dependency, the best average performance is to be expected from amorphous-microcrystalline modules, which performed best under high-temperature conditions. It had to be accepted, however, that those particular modules had significant drawbacks as regards low-light behaviour, but these did not outweigh the performance advantages at times of high irradiation.

The pollution

Besides the effects of temperature, it was considered important to find out how strong the impact of dust pollution on the energy yield would be and how much the yield could be improved by cleaning; moreover, at what intervals and how should the cleaning be carried out? To this end, the following aspects were monitored:

- Characteristics and intensity of the pollution.
- Cleaning methods, with special attention being paid to water consumption.
- Specific module behaviour.
- Respective power losses.

Performance was measured before and after cleaning. The impact of pollution was then determined from the differences in output between the cleaned modules on the day after cleaning and the ones left dirty. In order to correct differences between panels of the same brand, a correction factor was calculated and used after the first cleaning of all modules in the field.



▲Figure 1. Difference in percentage yield between monocrystalline (yellow line) and CdTe (zero line) modules.

After one month of constant pollution, the reduction in energy yield was already considerable – around 15% (Table 4).

"After one month of constant pollution, the reduction in energy yield was already considerable"

Technology	Yield losses after consecutive months of constant pollution [%]		
	1 month	2 months	3 months
Monocrystalline	15.42	28.98	36.03
Amorphous-microcrystalline	15.14	30.90	31.97
CdTe	16.49	17.39[1]	28.12
CIS	14.18	29.75	26.31[2]

[1] The low value for CdTe could not be precisely traced, and may be due to a failing of the cleaning team.
[2] Wind may be responsible for this abnormal deviation.

◀Table 4. Results for October, November and December 2010 for modules exposed to pollution, without any cleaning at all.

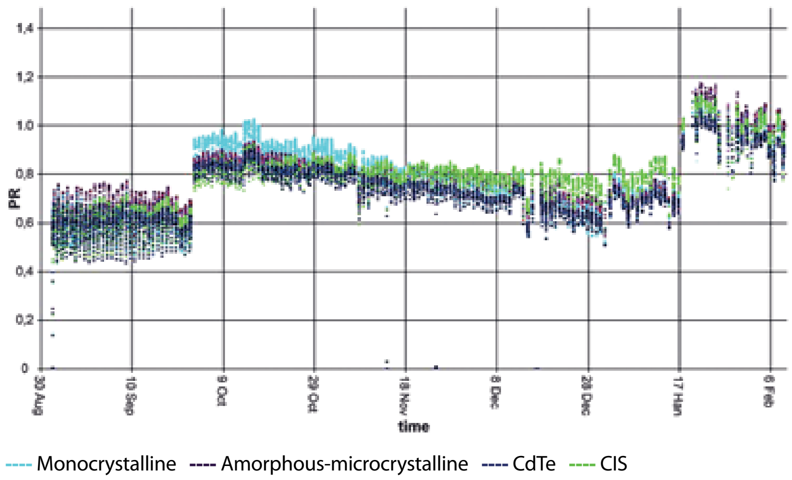
◀Figure 2. Test field in Dhahran, Saudi Arabia (photo taken on 1 November 2010 after partial cleaning).

◀Figure 3. Zoom-in on the polluted modules of the test field.

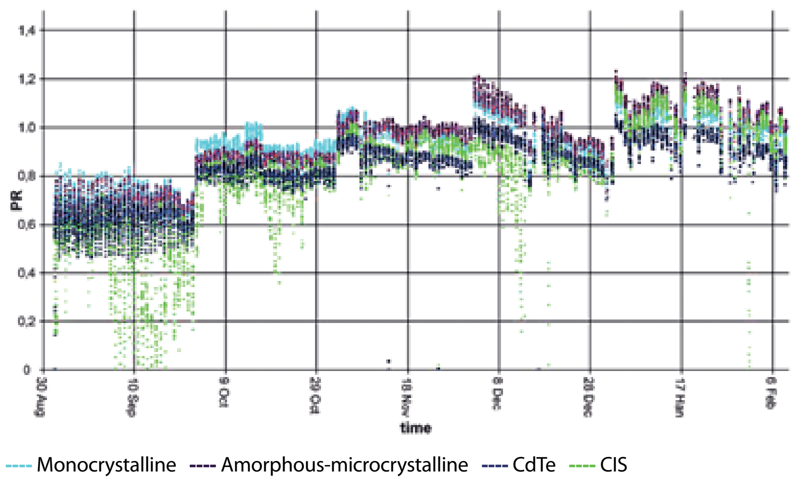
Over the next four weeks, the effect of the aggravating soiling increased at the same rate as in the first month, leading to a cumulative reduction in yield of around 30% after two months. However, performance differences between the technologies occurred which could not be explained in the course of the evaluation. The impact on yield losses after three months of pollution was still around 30%. The values were spread out much more among the modules than in the previous two months. As the losses did not increase at the same rate as before, it seemed as if the pollution had already reached a certain kind of peak or final stage at some point after two months of pollution.

There was no denying the fact that pollution began to have a significant negative impact after only a fairly short period of time. Another line of investigation, therefore, was to determine the best intervals and techniques of cleaning. In Spain and other European countries, Phoenix Solar has already experimented with various cleaning methods, devices and technologies – experience which could be built upon in the Saudi Arabian environment, but which also had to be adapted to suit the specific conditions of the region.

The actual level of pollution and its subsequent effects all exceeded expectations. It was even discovered that irradiation



◄ **Figure 4. Module performance ratios for the period September 2010 to February 2011, with two cleaning sessions over a three-month period.**



◄ **Figure 5. Module performance ratios for the period September 2010 to February 2011, with frequent cleaning (monthly).**

is often lower than anticipated as a result of the high amount of sand and dust in the air. This also seems to be a likely explanation for the high day-to-day volatility of the irradiation, even under clear skies and in bright sunshine.

Figs. 2 and 3 give an excellent idea of the heavy soiling on the module surface formed after only four weeks by the coagulation of sand, dust and salt because of the surprisingly high humidity in the coastal area. The test field had turned grey after just one month; for contrast, the blue modules had been cleaned immediately before the picture was taken. The character of the coating can be clearly observed on the zoom-in image in Fig. 3.

The actual extent to which cleaning affects module performance independently of the different technologies can be seen in the graphs of Figs. 4 and 5. One has to keep in mind that the temperature was decreasing steadily over the five months of observation and that there was some rain in December and January. In addition, groups were formed by picking modules of each technology; these groups were then cleaned in different cleaning intervals.

Fig. 4 shows how much the performance of the modules was reduced over time between the two cleaning sessions carried out on this group of modules over the three-month period. Note the jumps in performance ratio right after the cleaning sessions.

More frequent cleaning not only improved the performance because of a smaller reduction in energy yield but also resulted in a sustained higher average yield, as shown in Fig. 5. Again, from the graph it is evident that after each cleaning session, the module performance improved significantly, which reinforced the increase in energy yield resulting from the lower temperatures in winter.

Summary and conclusion

As a rule of thumb one may assume that the agglutination of sand, dust and salt takes effect after around one week. The option to wipe the modules dry with soft brushes either by hand or using appropriate machinery will not be possible after approximately ten days: the coating becomes too sticky and the risk of damaging the modules increases rapidly. After two weeks, wet cleaning is the only reasonable option.

Experience gained from the test fields as well as from operating the KAPSARC power plant in Riyadh leads to a recommendation of a wet cleaning every three to four months, complemented by regular intervals of dry cleaning; the actual frequency of the latter will undoubtedly depend on the exact location and the size of the PV power plant. Moreover, it has to be noted that, for various reasons, the cleaning task is far from easy in these areas with extreme climates. For example, it always needs to be borne in mind that water is a highly critical resource in desert regions and cannot be used as lavishly as may be necessary to get the best results. Obviously, regular dry wiping with soft brushes might be an option.

In terms of cost effectiveness, one factor to take into account is the low cost of labour in the region, keeping in mind, however, that a local workforce would have to be advised to work carefully in order to avoid scratches and other damages. The use of cleaning machines will be cost effective in plants of more than 50MWp, but different plant construction types will require different machinery for the purpose. In order to save water and cost, Phoenix Solar recommends a system that is efficient but not too sophisticated: small amounts of air-pressurized water are conveyed over the field through a system of pipes and spray valves, rinsing the modules as required.

To summarise:

- High temperatures as well as high intra-day temperature spreads affect module efficiency.
- Wind mitigates the influence of heat.
- Wind, however, carries sand and dust, which obscure the modules.
- Rain helps to clean the modules to some extent.
- Humidity, e.g. in a coastal environment, on the other hand, will promote the agglutination of sand, dust and salt on the module surface and form an opaque coating.

Cleaning, therefore, is the key to maintaining high energy yields under desert and desert/coast conditions, and clearly requires thorough attention and care. ■

Author

Klaus Friedl has a degree in mechanical engineering and is the managing director of Phoenix Solar LLC in Muscat, Oman. He has been with Phoenix since 2009, and realized the first megawatt-scale PV power plant in Saudi Arabia (5.2MWp) in 2012 as the senior vice president of project development in EMEA at Phoenix Solar AG.