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Performance of solar photovoltaic modules under arid climatic conditions: A review

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ABSTRACT

Arid and semi-arid climates are blessed with abundant sunshine, and photovoltaic (PV) modules are now widely used under these climatic conditions. The aim of this paper is to put into perspective the recent uses of solar PV installations under arid climates with the evolution of PV technologies. The novelty of this review is to present up-to-date experimental results under such climates, and to plot results of experiments running for about one year or more. The effect of environmental parameters such as weather or dust are analyzed depending on different locations and technologies. These parameters have a tremendous impact on PV modules performance and degradation, and it is critically important to consider them carefully when implementing a PV installation under such conditions. From this review, general conclusions and guidelines are presented.

1. Introduction

Photovoltaic panels and concentrated solar thermal power are the most well-established technologies used to convert solar energy into electricity. Using photovoltaic (PV) cells to convert light into electricity is a clean and sustainable way of energy production. Nowadays the dominant solar technology uses crystalline silicon (multicrystalline and monocrystalline) as semiconductor material. However, solar technologies using advanced materials such as amorphous silicon (a-Si), copper indium gallium selenide (CIGS), or cadmium telluride (CdTe) are becoming more and more attractive due to higher efficiency in different climatic conditions and lower production costs (Brun et al., 2016).

Adjustment of operational characteristics (such as reliability, availability, maintainability, safety, efficiency and ability to forecast energy production) is the main challenge for maintaining and controlling energy from variable energy sources. In this context, operating conditions (for example, operating temperature) of PV installations are critical in the overall system performance. The electricity production of PV cells is highly dependent on climatic conditions. Moreover, arid conditions, especially at high temperatures, are not optimal for the use of solar PV. However, there is room for development as arid climates are linked with widely available sunshine.

Several environmental parameters can have a huge impact on solar PV performance. In Brazil, meteorological (temperature, humidity, radiation) or mechanical (shocks) parameters prove to affect the PV modules performance and damage the system on a 16 years basis (Afonso and Carvalho, 2015).

The solar PV modules are sensitive to temperature: the efficiency decreases with increasing temperature. The theoretical magnitude of the impact depend on the technology used and can vary for each PV module (Dupré et al., 2016). Skoplaki and Palyvos (2009) insist on the strong correlation between temperature and performance. However, there are many different formulas, and the relevant one should be chosen carefully.

To limit the temperature of the modules, Schiro et al. (2017) tested a water-cooling system for PV panels. They concluded that the system can be a worthy one if the original temperature of the module is high enough and the water sink easily accessible. Du et al. (2016) place emphasis on the influence of the wind to cool down solar PV panels. A regular wind can decrease the temperature of a module and thus increase its efficiency. Thus, including wind in PV modules prevision models can help to increase their accuracy.

Many arid locations are dusty or sandy. This raises the issue of soiling: dust or sand deposition can affect the performance of PV panels: the particles deposited on the surface of the panel obscure the rays of the sun and thus decreases performance. Also, both panel and dust types have an influence on dust deposition (Zaihidee et al., 2016). By preventing soiling, performance of solar PV can be significantly improved: mechanical cleaning, water-based or water-free solutions has been considered; the latest one (electrostatic or electrodynamic) looks

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promising due to its efficiency and low maintenance needs. Deb and Brakmbhatt (2018). Also, wind can help to remove dust and limit the impact of soiling, especially for large particles (Jiang et al., 2018).

Assessment of solar irradiance is complex. The atmosphere contains different substances such as water vapor, clouds, aerosols, or greenhouse gases that differ both temporally and geographically. The atmosphere usually decreases the value of solar irradiance from 35% (clear sky) to 90% (sky with thick clouds) (IPPC, 2011). In hot arid climates, irradiance is important but dust in suspension in the atmosphere can absorb the impending rays and affect the efficiency of solar PV modules (Deb and Brakmbhatt, 2018). Therefore, atmospheric conditions have a significant impact on efficiency even in absence of thick cloud cover in dry areas with little rainfall.

Developing countries with arid environments could benefit from the use of solar PV technologies. Their needs in energy are increasing, and these technologies have tremendous qualities under these climates, but some drawbacks as well. The objective of this paper is to review the variation of performance of PV cells depending on technologies and environmental factors. The novelty is to present up-to-date results under arid climatic conditions, and compare the results of the available experiments running for about one year or more. Technologies, average precipitation and average daily temperature are considered to outline preliminary conclusions from graphical representations. The paper progresses as follows: in Section 2, an overview of the PV technology is given. A review of PV system parameters is described in Section 3. In Section 4, a literature review of PV systems performances in arid and semi-arid locations is presented. Discussion and results of the main performance parameters of several PV power systems with full-scale performance data in different locations are presented in Section 5.

2. Solar PV technology

2.1. Overview

Current solar technologies are the result of decades of performance and cost improvements. Each type of solar energy technology is based on different materials and architecture and has its own merits. Analysis and comparison between different technologies can help to adopt the most efficient and advantageous system respecting certain conditions. Due to various PV applications, different technologies are easily available in the market, with a wide range of efficiencies and costs. A system with a lower efficiency is generally cheaper, but requires a large area for a given energy output, thus increasing costs of land and maintenance (Martín-Chivelet, 2016).

By connecting solar panels in parallel or series, it is possible to get high voltages and currents (reaching up to 1 kV) (Abdelkader and Sharaf, 2010). The conversion of light to energy is due to an electron-hole pair generated from the absorption of light; then, the electron goes to the negative terminal and the hole goes to the positive terminal. This action generates electrical power.

PV technologies involve solar panels made of solar cells, and each cell contains a photovoltaic material. The PV effect is due to the semiconductor material band structure characteristics which emits electrons by absorbing energy from electromagnetic radiation (Nelson, 2003). The main focus of solar technology engineers is to improve efficiency of solar cells to convert as much light as possible into electrical energy. The conversion efficiency is the ratio of energy that a PV cell converts into electricity by the amount of solar energy striking the PV cell (Nelson, 2003).

2.2. Photovoltaic solar panel technologies

There are three generations of PV technologies (Du et al., 2016):

- First generation: Gallium arsenide (GaAs), and crystalline silicon (c-Si) such as multicrystalline (multi-Si) silicon and monocrystalline (mono-Si) silicon;
- Second generation (thin films): amorpheous silicon (a-Si), CdTe, or copper indium gallium (di) selenide (CIS/CIGS);
- Third generation: dye-sensitized, organic and multi-junction.

The first and second generation technologies are already used for very large scale PV power plants (Komoto, 2015):

- In China: c-Si technology for Longyangxia dam (520 $MW_{DC/AC}$ and Germud (500 $MW_{DC/AC}$)
- In USA: CdTe in Agua Caliente (290 MW_{AC}) and in San Luis Obispo (550 MW_{AC})
- In Japan: CIS in Osaka (12 MW)
- In Thailand: thin film in Lobpuri (84 MW_{DC})

The energy pay-back time has been estimated for different technologies in the Gobi desert in China. CIS and multi-Si technologies have the lowest pay-back (below 2.3 years), it is 2.4 years for a-Si technology; the pay-back of thin films is measured at 2.4 and 2.6 years; and 2.4 and 2.8 years for mono-Si (Komoto, 2015).

2.2.1. Crystalline silicon (first generation)

Most PV systems (in 2015, 93% of the production) are based on Si-wafer PV (ISE, 2017). To-date, the best efficiency obtained with mono-Si is 26.6% (Green et al., 2017); for multi-Si, the best efficiency reaches about 21%. Multi-Si panels are less expensive than mono-Si panels, but the disordered atomic structure results in lower efficiency. Monocrystalline and multicrystalline silicon modules have almost the same low power degradation (0.5% yearly for both technologies) (Jordan and Kurtz, 2012). Production of multicrystalline silicon is typically done through a screen printing process. In contrast, production of monocrystalline silicon may be achieved in a variety of ways. The commercial manufacturing typically includes a buried contact process.

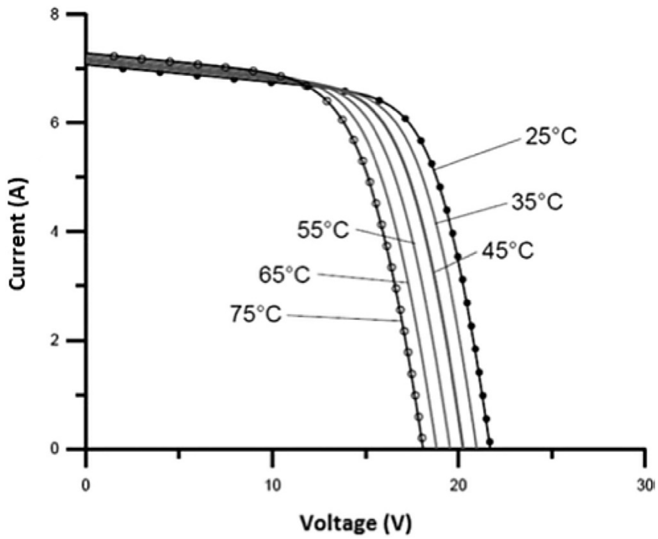
Mono-Si cells have a higher conversion efficiency, but a higher production cost, while multi-Si cells are slightly less efficient but cheaper (Nogueira et al., 2015). The main parameters affecting the performance of these technologies are cell temperature and solar radiation intensity, as shown in Fig. 1a and b.

Crystalline silicon PV modules should remain the dominant PV technology for the foreseeable future due to their reliable and proven technology, abundant primary resources, and long lifetime. The major problem of crystalline silicon technologies is that they require efficiency improvements together with an increase in resource consumption efficiency. These requirements can be achieved through an enhanced approach, manufacturing automation, and reduction of raw-material consumption (IPPC, 2011).

2.2.2. Thin films (second generation)

Thin films have several advantages: (1) low consumption of raw materials, (2) attractive appearance, easy integration into buildings, and (3) high automation and production efficiency (Raugei et al., 2007). Moreover, high efficiency at relatively high temperatures coupled with low sensitivity to overheating creates competitive advantages for this technology, in particular in regions with hot arid climatic conditions.

Cadmium telluride (CdTe) panels hold a market-leading position in thin film technologies (Helbig et al., 2016). However, materials used in their manufacturing processes are less abundant than silicon, and are of a toxic source. At the same time, manufacturing process of CIGS cells is less demanding as it is cost-effective compared to CdTe cells (Raugei et al., 2007). Therefore, all these factors make it difficult to determine which of the thin-film technologies will obtain the highest market share in the long-run (Helbig et al., 2016). Also, it should be emphasized that experimental measurements indicate that CdTe offers the best temperature coefficient which makes this material a good candidate for climatic regions experiencing high temperatures (Dash and Gupta,



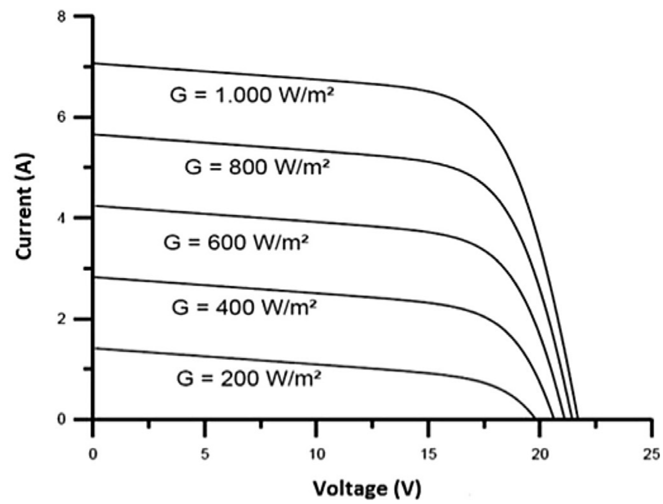


Fig. 1. (a) Influence of temperature on the characteristic curve of a monocrystalline PV system (Nogueira et al., 2015). (b) Influence of solar radiation in the characteristic curve of a monocrystalline PV system (Nogueira et al., 2015).

2015).

2.2.3. Dye-sensitized solar cells (DSSCs) (third generation)

DSSCs are based on the photoelectrochemical process where a semiconductor is formed between an electrolyte and a photosensitized anode (IPPC, 2011). In DSSCs, there is a very high probability of photon absorption; the dyes are effective due to the "depth" of the cell in the nanostructure.

The main losses in this system are optical losses in the front electrode and conduction losses in titanium dioxide (TiO_2) which forms into a porous structure with a high contact area. Only photons absorbed by the dye can generate current and increase the efficiency of this type of cell (IPPC, 2011). In fact dye molecules, unlike silicon, have low absorption at high wavelengths (red and infrared part of the spectrum). This means that less photons in the light can be used for electricity generation. These factors may limit the efficiency of DSSC: for example, silicon-based solar cells offer current up to approximately 35 mA/cm^2, whereas established DSSC systems offer approximately 20 mA/cm^2 (IPPC, 2011). Therefore, photons with related wavelengths are less likely to be absorbed. DSSCs have relatively low efficiency if compared with mature solar cells, approximately 12% (Green et al., 2017).

3. PV system parameters

3.1. Definition of numerical performance parameters

The standard testing conditions (STC) for solar PV modules are: a temperature of 25 °C, and a direct irradiance of 1000 W/m^2. This is also the standard benchmark in industry for solar PV modules. Because STC typically occur indoor, electrical characteristics are not practical to forecast PV behavior under realistic conditions. In this part, we will describe the set of parameters that can be used for comparison: the energy yield (Y_f), the outdoor efficiency (η), the performance ratio (PR), and the capacity factor (CF). Then, we will discuss the effect of environmental parameters.

3.1.1. Energy yield

The energy yield is defined as the energy produced by a PV system during a given period of time (E_{dc}, kWh) divided by the DC power provided by the manufacturer (P, kWp) (Ferrada et al., 2015):

$$Y_f = E_{dc}/P \tag{1}$$

For a given period of test (one month, one year…), Y_f is equivalent to the theoretical number of hours necessary to produce under STC the same amount of energy with the same module.

3.1.2. Efficiency

The outdoor efficiency (η) is non-dimensional and defined as below (Makrides et al., 2012):

$$\eta = \frac{E_{dc}}{A.\ H} \tag{2}$$

where H is the total irradiance reaching the collector (kWh/m^2) and A is the area of the collector (m^2).

3.1.3. Performance ratio

The performance ratio (PR) is the ratio of the actual E_{dc} and the theoretical energy output under standard conditions E_{STC} (both in kWh) (Edalati et al., 2015):

$$PR = E_{dc}/E_{STC} \tag{3}$$

3.1.4. Capacity factor

The capacity factor (CF) is the ratio of the actual E_{dc} and the theoretical energy output $P.\ t$ if the installation was producing continuously at its maximum power output (Edalati et al., 2015), and is defined as:

$$CF = \frac{E_{dc}}{P.\ t} \tag{4}$$

where P is defined above and t is the time.

3.2. Influence of environmental parameters

3.2.1. Solar irradiance effects

In general, the global solar radiation for a given surface is much higher under arid or semi-arid climates compared to other zones (IEA, 2011). One of the reasons for this difference is the much less dense cloud cover in arid climates; in addition, the variability of solar radiation is much lower and the power output is easily predictable. If the solar radiation is high, more energy can be converted by the solar PV module. Thus, high radiation mechanically increases the potential for electricity production.

3.2.2. Spectral effects

Spectral distribution can vary depending on the composition of the atmosphere. Different gases, humidity, particles or atmospheric pressure can have an influence on the spectrum of light reaching the ground. This is especially true for water vapor molecules, which are absorbing sunlight at several wavelengths (Fernández et al., 2014). Low humidity in the atmosphere then has a positive impact on the solar irradiance and so on the output of PV cells (Komoto, 2015). Clouds can, of course, impact spectral distribution. Under arid conditions, clouds are not an issue, but particles such as sand can be more problematic (Makrides et al., 2012). For example, c-Si PV cells typically have a wide spectrum of absorbance; thus, variation in the spectrum can have an influence on the output of the cell (Makrides et al., 2012). Polo et al. (2017) and Dirnberger et al. (2018) plotted the spectral responses of seven PV technologies: huge differences can be noticed on the optimal wavelength: from 500–600 nm for a-Si to 1000–1100 nm for CIS/CIGS. Both studies reach similar conclusions: variations in spectral irradiance can then impact the competitiveness of different technologies. Also, the spectral factor can vary up to 10% during the same year due to phenomena such as thick atmosphere during winter; this is especially true for thin-film technologies. The sensitivity of PV technologies, especially thin films, is significant and can play a significant role in the optimization process of PV technologies under arid conditions.

3.2.3. Effect of dust

The effect of dust on PV performance is commonly referred to as soiling losses. The dust affects the efficiency and deteriorates the performance of the system by obstruction of solar light. Sarver et al. (2013) investigated the different solutions to deal with dust issues. The performance reduction because of dust can reach 15 to 30% in dusty and dry areas. They concluded that several approaches may be considered depending on localization: treatment of the surface to make it dust-repellant and/or hydrophilic/hydrophobic; or regular cleaning with water jets, air or other mechanical cleaning.

Measurements show that soiling influences the energy output of PV installations on a long-term perspective (Saidan et al., 2016; Khonkar et al., 2014). All these studies have shown a significant effect from soiling on the performances of different PV modules in different arid places such as Baghdad (Iraq) (Saidan et al., 2016), Abu Dhabi (UAE) (El-Nashar, 2003), Thar Desert (India) (Nahar and Gupta, 1990), Oman (Charabi and Gastli, 2013), and Algerian desert (Semaoui et al., 2015). Khonkar et al. (2014) explained that precipitations are not regular in dryer climates. Moreover, a reduced amount of rain can stick dust and other particles to the panels. Cleaning may then become necessary after such light rains. The multi-Si PV panels efficiency reduction during the dry period of the study described by Kalogirou et al. (2013) in Cyprus is between 10% and 15% for 4 to 12 weeks of outdoor exposure, respectively. If this parameter is neglected, the difference between actual and estimated energy yield can be significant.

Al Shehri et al. (2016) measured the transmittance of samples exposed to the dust of Arabian Desert in Saudi Arabia. The transmittance is reduced from approximately 92% to 84% after 7 days of exposure due to the accumulation of dust. They demonstrated that washing and wiping can restore the original transmittance, while brushing does not totally remove all the dust. In Qatar, Touati et al. (2016) measured the influence of dust, the advantage from cleaning and the impact of rain on dust cleaning. They concluded that the power output can be reduced by 30% because of dust. However cleaning or rain improve immediately and significantly the efficiency because of dust removal. Figgis et al. (2017) discussed the mechanisms of particle deposition. Medium-size particles are more likely to stick to panels. Indeed, the deposition of small particles is low while large particles are more likely going to rebound (unless high moisture rate). Also, air flow increases the resuspension of particles. In Iran, Pulipaka and Kumar (2018) investigated the influence of the composition of the soil on irradiance losses of a PV panel. By spreading artificial soil on the panels, they noticed that soil made of larger particles (up to 300 µm) are more likely going to affect the efficiency of the panel. Also, the angle of inclination of the panel has an impact, especially for soils charged with large particles. The more horizontal the panel, the higher the negative impact. For soils with smaller particles, the impact of the angle is not significant. Wiesinger et al. (2018) discussed the issue of sandstorms in Morocco and Kuwait: huge differences are noted between the different locations. The losses due to specular reflectance reach 53.5% (in Kuwait, after 9 months), 5.9% and 0.8% (in Morroco, after 25 months). In Qatar, Javed et al. (2017) noticed that the dust accumulated on solar PV varies in composition with the duration of exposure: the longer the exposure, the smaller the particles; and is dependant on the time of the year. Also, sandstorms bring larger particles than normal weather conditions. Olivares et al. (2017) studied soiling in the Atacama desert. Four months of exposure reduced transmittance by 55%. Boddupalli et al. (2017) showed that the typical size of particles deposited on a roof-top PV panel is between 20 and 80 µm in the Thar desert, India. Also, the wake region behind a given panel may increase the impact of soiling by disturbing the flow of air charged with dust. Fountoukis et al. (2018) demonstrated that the ambient concentration of particles alone is not reliable to predict the energy yield of a PV installation in Qatar; they recommend floating solar panels on the sea to limit the effect of soiling. Following numerical simulations, Lu and Zhao (2018) showed that particles around 150 µm are more likely to affect solar PV panels by deposition. The tilt angle has a major influence: with a more horizontal panel, or a panel facing the wind, the deposition rate is higher (up to 14%). In Iran, Gholami et al. calculated a loss of 21.47% for solar monocrystalline PV panels due to dust accumulation after 70 days without rain and cleaning. Gholami et al. (2017) showed that a high-tilted angle helps to reduce particle deposition as they simply fall by gravity. Also, if the panel is facing the wind, deposition can be neutralized by air flow. The reduction in the transmission after 70 days of exposure varies from 15 to 24.83% for the two extreme situations. Neher et al. (2017) modeled the influence of aerosols using climatic data from Niamey, Niger. The range varies from 2 to 48% during 69 days, with a mean of 14%. Daher et al. (2018) characterized the impact of the Djibouti climate on the performance of a PV power plant. Soiling impact is almost null after rain and can reach 14.23% under dry and dusty conditions. A cleaning every second week is recommended to limit losses due to soiling below 5%. Hammad et al. (2018) studied and modeled the impact of environmental factors on solar PV performance in Jordan. Temperature and dust accumulation are the main parameters impacting performance. However wind, humidity and visibility may have an influence too. The average daily efficiency reduction is between 0.61 and 0.77% depending on the model. The recommended cleaning period is from 12 to 15 days. Also, dust may cost about $1 per m^2 of solar panel per day, because of the decrease of electricity production. Javed et al. (2017) modeled the impact of environmental factors on soiling effect in Qatar. High wind speed and high humidity rate appears to be influence positively the performance of the PV module. Said et al. (2018) reviewed the effect of environment and dust deposition on performance of PV modules. They noticed that the location plays a critical role in the optimization of the dust cleaning process.

These experiments show that dust is generally a major concern and cannot be neglected in arid climates; however, there are large disparities depending on the environmental conditions of a given region or area. A careful monitoring of the local situation is necessary to assess the best methods to limit the impact of dust deposition. However, for most of these experiments, regular cleaning is necessary under arid climates.

3.2.4. PV degradation

The other major aspect in the performance of a PV module is its long-term reliability. As mentioned before, the performance of PV technologies can be affected by several parameters: climatic conditions, humidity, temperature and ultraviolet spectrum. As a consequence, this degradation affects the performance of the solar PV modules on a long-term basis. Therefore, detailed relativity assessment on module degradation, stability issues and external factors is required. Several tests have been conducted at the National Renewable Energy Laboratory (NREL) which show the important impact of time on the performance of PV panels (Tamizh-Mani and Kuitche, 2013). Tahri et al. (2017) measured the degradation rate of two thin film PV technologies. The CIS module suffers a degradation of −2.34% per year, and −1.73% per year for the micromorph (a-Si:H/c-Si:H) module. High performance ratios (over 90%) can be reached for both technologies over 3 years of exposure. Wiesinger et al. (2018) assessed the erosion risk under desert climatic conditions in Morocco and Kuwait. The influence of the environmental parameter is extensively discussed. Concerning the soil: large particles (or mix of particles of different sizes), low moisture and high quartz concentration can significantly increase the risk of erosion. Exposure to wind due to climate or local geography also influences the erosion risk. Experiments in desert areas of China show a degradation rate from 3.8 to 7.2 % over 2 years for c-Si technology and more than 20% over 3 years for thin film (Komoto, 2015). Silvestre et al. (2018) monitored the performance and degradation of 3 types of PV cells: monocrystalline, multicrystalline and HiT (heterojunction with intrinsic thin layer). The multicrystalline are slightly more resistant than the monocrystalline over time (about −0.7 and −0.8%/year respectively); the HiT modules have the highest degradation rate, with around −1.7%/year. However, the highest values of PR and efficiencies are reached by HiT modules, and the lowest by multicrystalline ones. Despite more competitive performance parameters, the presence of the intrisic thin layer seems to harm the performance of HiT modules on a long term basis. In Algeria, (Bouraiou et al., 2018) conducted an extensive investigation of defects of crystalline PV panels exposed to desert climate. The results show that the EVA (ethylene vinyl acetate) discoloration is the predominant consequence; traditional defects such as cracks or general deterioration of the panels are also observed. In the experiments from Daher et al. (2018) the reduction of the performance of PV modules can be observed over 4 years: the desert maritime climate of Djibouti proved to be relatively less harmful compared to other difficult climatic conditions. Gagliardi and Paggi (2018) simulate the EVA degradation under different climates: the arid and semi-arid climates are shown to be among the worst climates for EVA degradation, preceded only by humid tropical climates.

Degradation is significant under arid climate; a careful study of the environment and the sensitivity of PV technologies can help to limit the consequences of degradation; however arid climates can be considered as detrimental to the performance of PV panels in the long term.

4. Literature review

Numerous studies have reviewed the performance of PV systems. Singh (2013) states that electric power generation from PV systems is related to their orientation, type, and geographical location. Through simulation and modeling of solar PV modules under various irradiance conditions, Nguyen and Lehman (2006) has shown that the theoretical or simulation models can help to determine the power losses in the case of solar cells.

4.1. Review of PV systems under different arid locations

Extensive research either with simulation and modeling or experimental testing have been carried out on PV systems. Several of them are conducted under arid or semi-arid climatic conditions. A literature review of these experiments is presented here.

Many projects related to these studies and situated in various locations around the world have similar purposes: to reduce environmental impact by using solar power and increasing its exploitation. All these studies are focused on analysis, assessment and evaluation of the PV modules performance operated under arid or semi-arid environment.

Most arid climate conditions are found near the tropics and the poles including most of Australia,the Middle East, the Arctic and Antarctica; and parts of Africa, South America, North America, South and Central Asia.

4.1.1. Middle East

In 1998, experimental studies on PV systems under arid climatic conditions of Saudi Arabia concluded that the high operating temperature during the day resulted into as reduction of more than 30% in power generation (Al Harbi et al., 1998). This demonstrates how much high temperatures can impact the output of PV panels in the region.

Aldossary et al. (2014) discussed the lack of sustainable interventions in the Saudi domestic sector and aimed to clarify the extent of the problem including the installation of on-site energy generation PV systems. The results from this study examined energy consumption in residential properties in Saudi Arabia and showed how PV technologies could reduce reliance on the grid, and thus reduce the CO_2 emissions.

Halász and Malachi (2014) studied and analyzed the performance of many PV fleet combinations over different periods in the Negev Desert (Israel). They compared different PV development scenarios depending on power fluctuations. They concluded that scattering the different production areas decreases the risk of power output fluctuations, even under desert conditions.

In Yemen, Hadwan and Alkholidi (2016) studied the impact of solar energy technologies for desert communities. They investigated the cost-effectiveness as well as the design of such technologies by using different cases related to the rural communities of the country. PV systems proved to be economically competitive for communities living in the desert.

Griffiths and Mills (2016) investigated a rooftop PV panels in the United Arab Emirates. The results showed that a rooftop solar PV is competitive and viable in the region (Middle-East and North Africa). Besarati et al. (2013) simulated the performance of a 5 MW PV power plant in different cities of Iran. According to their simulations, the CF can reach 24% in several cities in the arid and semi-arid regions of the country, much better than other regions. However the impact of the temperature on the performance of PV modules is not considered. Edalati et al. (2015) compared mono and multicrystalline PV modules. By looking at the PR and CF, the multicrystalline modules shown are more performant than the monocrystalline throughout the year. Both systems are more effective during the winter time, when temperatures are more moderate. Mirzaei and Mohiabadi (2017) tested monocrystalline and multicrystalline PV modules under semi-arid climatic conditions. The monocrystalline module proved to be clearly more efficient during the winter months. During the summer months, both modules show a similar level of performance. In terms of efficiency and power output, the monocrystalline module is then more performant all year long, however the multicrystalline one is less sensitive to changes in temperatures. Indeed, its efficiency tends to slightly increase in summer in this experiment, and the monthly yield is slightly higher than the monocrystalline module during the most sunny months.

Charabi and Gastli (2013) studied the influence of temperature and dust on PV modules performance in Oman. By including these two parameters in the simulation, the area of this country considered suitable for solar PV is reduced by 81% compared to previous simulations which did not consider dust and high temperature. Only 9% of the area of the country is then considered highly suitable for the solar PV technology. Kazem et al. (2014) showed that the CF in Oman can reach 21% for a rooftop system.

Dabaieh et al. (2016) studied the impact of implementing solar PV systems in remote and off-grid areas of the Egyptian Desert. The study demonstrated a high level of acceptability among the local populations, who consider the technology economically competitive, easy to handle, and convenient in general. The integrity of local architecture is respected, and the technology participates in the development of renewable energies in the country. However, the current lack of incentive policies may slow further developments.

In Jordan, Abdelkader and Sharaf (2010) tested mono and multicrystalline technologies. The performances are similar for both technologies, the monocrystalline technology is slightly more performant than the multicrystalline one. Hammad et al. (2017) compared the performance of fixed and tracking PV panels. The tracking system is obviously producing more electricity (approximately 30% extra). However the efficiencies of both systems (fixed and tracking PV panel systems) over one year are equal. The temperature of the modules is higher for the tracking system but the dust accumulation is less of an issue compare to the non-tracking system: these two issues balance each other out. Throughout the year, the conversion rate is more constant for the tracking system: although it suffers from higher temperatures during the summer, while the dust significantly affects the efficiency of the fixed system throughout this period.

In Kuwait, Ali et al. (2017) simulated the behavior of four different types of cells: monocrystalline, multicrystalline, thin-film CdTe and Cds/CdTe. The monocrystalline cells were by far the most efficient. The performances of multicrystalline and thin-film CdTe cells were similar, with the second one being slightly more effective (approximately −6 and −11% compared to monocrystalline cells). The thin-film Cds/CdTe was by far the least efficient (−23% below monocrystalline cells). Al-Otaibi et al. (2015) tested two PV installations on the rooftop of schools. For all the experiments, the PR was kept above 0.7. Both systems are cleaned weekly.

In the Emirates, Said and Mehmood (2017) ran simulations with fixed, one and two-axis systems for PV panels. They concluded that one-axis systems are more financially competitive and the best compromise between cost, power output, space occupied, and complexity. Emziane and Al Ali (2015) tested multicrystalline and monocrystalline PV panels during one year. The monocrystalline panels proved to have a significantly higher CF throughout the year.

4.1.2. North America

Raghuraman et al. (2007) carried out evaluation of performance of 44 modules of three different technologies from different manufacturers in Arizona, USA (under arid climate) for 2.4 to 6.7 years. The a-Si modules exhibited relatively higher power degradation (1.16% per year) while c-Si modules degraded two times slower than the a-Si ones (approximately 0.5% per year).

Another life cycle assessment study investigated the economic and environmental performance of 8 PV systems from 3 kW to 1.14 MW that were deployed on buildings in Reno and Las Vegas (Nevada) (Liu et al., 2015). For these systems, results showed that 75% of the energy use is for the manufacturing process (on a lifetime basis). Installation and mounting of the PV systems takes a considerable part of the energy needed (21%). By dismantling, recycling, or disposing the systems, a significant amount of energy savings can be expected together with optimized lifetime energy use.

4.1.3. Australia

There are several papers that have investigated financial and environmental aspects of solar PV panels in Australia. Nicholls et al. (2015) performed a life cycle analysis of the rooftop PV panels, and estimated different costs and energy payback time depending on the regions. Due to the different climates, the performance parameters can vary depending on the territory. In the study conducted by Ma et al. (2016), authors aimed to forecast the performance of PV roof systems for 2030, 2050, and 2070 by considering climate changes (increase in both radiation and temperature). They show that as a general rule, the optimal situation for PV output will be reached around 2030 before slightly decreasing until 2070, however the differences are small. The role of Australian residential or rooftop solar PV panels in providing renewable energy was analyzed by Chapman et al. (2016). As the number of PV panels increased in Australia, the authors studied the economic impact of the activity. The cost in manufacturing, maintenance, and workforce per MWh decreased substantially with an increase of the market size.

Another study has stated that solar energy commercial-scale projects can be competitive, but energy storage and transfer must support the development of solar energy (Bahadori and Nwaoha, 2013). Nevertheless, through life cycle sustainability assessment, Yu and Halog (2015) validated the study by demonstrating that solar PV can be sustainable in Australia. Hua et al. (2016) compared potential, current policies, and the status of China and Australia in terms of the development of solar PV energy technologies. This paper emphasized the importance of considering each site specifically before implementation. Quantitative technical standards as well as legislation have an influence on the sustainability of rooftop PV systems.

In Western Australia, Jamal et al. (2017) described the issues faced by developing solar PV systems in arid remote areas. The harsh weather conditions (dust, occasional cyclones) impact the durability of the panels. Most of the remote areas are mining stations powered by fossil fuels. A high penetration of solar PV may lead to the instability of a given remote electricity network. However, future technologies should be able to overcome these issues.

4.1.4. Africa

In a survey conducted by Adaramola (2014), the feasibility of a PV grid-connected system in a dry region of Nigeria was assessed. The economic viability of the system was proved. A similar study was dedicated to the assessment of a hybrid energy system including PV to provide electricity in a northern city of Tunisia which also had a number of positive impacts for the environment of the region and economics of the project (Maatallah et al., 2016). Bouraiou et al. (2015) investigated the impact of environment on the performance of PV panels to the south of Algeria. They show that the impact of harsh conditions (sand storm, high temperatures) on PV panels is tremendous, between 1% and 3% of maximum power output reduction per year.

Opiyo (2016) projected the development of electrification in a rural region of Kenya under semi-arid conditions. According to his simulations, the electrification of the community will most probably go through a PV system at an individual or community level. Indeed, even without any public subsidies, PV systems are generally more competitive. Furthermore, social aspects such as defiance towards institutions will support the local initiative against connection to the national grid.

Tebibel and Labed (2013) investigated the yearly performance of a remote PV installation in the Algerian Sahara. According to their results, the performance during summer suffers from high temperatures (approximately −10%). To implement more systems in the future, the temperature must be considered to dimension the system properly. Daher et al. (2018) ran 4 years of measurements in Djibouti with multi-Si PV modules: a PR of 84% is reached and the temperature gradient proves to be −0.7%/°C.

4.1.5. Asia

Nicholls et al. (2015) reviewed the potential of solar PV technologies in desert areas (Sindh, Balochistan, Cholistan) in Pakistan. The technology is promising and competitive, thanks to the energy tension in the country and the availability of solar energy.

Ito et al. (2003) ran a pre-feasibility study of a solar PV power station in the Gobi Desert. The simulation showed a great potential at that time for energy savings, financial competitiveness, and greenhouse gas reduction.

4.1.6. South America

In Chile, Ferrada et al. (2015) analyzed the performance of multi-Si and thin-film technologies in a desert climate area. The multi-Si modules achieved a slightly higher energy yield compared to thin-film modules. However, thin film modules are more performant under high temperatures than multi-Si modules, especially when the modules are clean. When the temperature decreases, the performance of the multi-Si drops to approximately −1.4% per month (dust accumulation balanced by temperature drops). The performance drop for the thin film is more than two times higher than that for mc-Si, as they are less sensitive to temperature decrease but more sensitive to dust. When the temperature increases throughout the year, the performance of mc-Si decreases strongly (−4 to −5% per month, due to a combination of the increasing temperature and dust accumulation). The decrease in performance for thin films is comparable: they are still more sensitive to dust but less to higher temperatures (or to temperature changes in general).

Ferrada et al. (2017) investigated the influence of the glass-encapsulant-glass layer protecting the PV cell. For the solar spectrum of the Atacama Desert, Chile, the transmittance of the different structures tested varies from 84.5% to 90.7%. Choosing the right combination glass-encapsulant-glass depending on the spectrum and the cell is demonstrated to have a significant influence.

4.1.7. Europe

In Cyprus, Makrides et al. (2012) tested a range of different commercially available solar PV panels during several years. Significant performance differences could be detected depending on the samples. Thin film technologies proved to be much more resilient when the temperature increases.

4.1.8. Antarctica and Arctic

In Antarctica and Arctic, the main consumers of energy are research stations that mainly depend on imported fuel oil to maintain operations and to provide a safe working environment. Therefore, modern PV technologies could be useful and provide cost-competitive supplements to the existing diesel generation plant in such sensitive regions. These regions have an interesting potential because of their low temperature and high irradiation (Mason, 2007; Mason, 2007; Wolf, 2015). Power requirements of scientific bases are relatively limited compared to more traditional settlements. Case studies prepared by Tin et al. (2010) have proved the feasibility of using solar panels in the remote areas of Antarctica.

Safety and environmental risks in terms of using PV system in remote Arctic locations were assessed in a paper prepared by Blair (1994). The results show that releases of heavy metals from batteries is the main potential problem, due to their toxicity and potential hazard for the environment.

A mathematical model conducted by Pablo Vega Arroyo (2016) was used to calculate the power production by real data from a PV system located in Greenland. The results showed that Arctic climatic conditions with relatively high irradiance and low temperatures make Greenland a good candidate for PV systems. Therefore, the Arctic and Antarctica should be considered as relatively high potential locations for solar technologies but not for large-scale applications.

4.2. Enhancing a PV system

Many research papers suggest various practical methods for estimating and enhancing the use of the established PV systems in regions under arid climatic conditions. The results are as follows: Sabziparvar and Shetaee (2007) proposed a predictive model based on cloud fractions. Estimating the solar radiation by using this parameter proved to be effective in arid and semi-arid regions. By combining direct and diffuse solar radiation, the mean percentage error of the prediction is less than 3%.

To manage the problem of dust and weather conditions in Qatar properly, Touati et al. (2016) presented a monitoring system. By combining temperature, humidity, and dust data, it is possible to have a better overview of the influence of these parameters and, in the future, make appropriate improvements such as regular cleaning. Two investigations on support vector machine (SVM) models have been carried out recently. Belaid and Mellit (2016) designed a model able to accurately predict solar radiation on a daily or monthly basis, mainly based on a set of temperatures. The system proves to be reliable under arid climates. In Saudi Arabia, Ramli et al. (2015) confirmed that to predict solar irradiance, SVM is more reliable than artificial neural networks.

By using a cooling system with thermoelectric modules, Benghanem et al. (2016) could significantly improve the efficiency of a solar PV module, at a rate of approximately 0.5% per degree. Another study investigated the PV module performance when the module is coupled with automatic cooling and surface cleaning. The experiment is compared to another one without cooling and cleaning. It is demonstrated that the efficiency of such modules reaches 11.7%, as compared with 9% for the standard module (Elnozahy et al., 2015). Schiro et al. (2017) tested a water-based cooling system and proved that achieving a positive energy balance is realistic, providing that the access to water is not an issue.

The research conducted by Koussa et al. (2012) looked at the influence of sun-tracking systems on performance considering different seasonal sky cover conditions. On a clear day, the highest performance is reached when using a two-axis sun tracking system. The length of the day affects the performance as well. As expected, the two-axis system increases the energy collected by the PV panel during the morning and the afternoon compared to a fixed PV panel oriented optimally.

PV technology has been used to develop other applications under arid climates: in Saudi Arabia, for sea water desalination in remote areas (Chafidz et al., 2014); or for powering a direct current compressor for refrigeration in Egypt (El-Bahloul et al., 2015); or photovoltaic solar refrigerated containers in Algeria (Laidi et al., 2012).

Yu et al. (2011) discussed the implementation of the PV pumping irrigation system in arid regions, and demonstrated that approximately a quarter of the arable land in Qinghai Province (North-West China) is economically and environmentally suitable for such systems. Similarly to the previous study, Boutelhig et al. (2012) analyzed performances of different DC pumps powered with PV under the desert climate in Algeria and concluded that optimization makes the system competitive.

Piliougine et al. (2013) tested an anti-soiling coating on PV modules. The coating proves to reduce soiling losses from 3.3% to 2.5% as a yearly average.

In Egypt, Yousef et al. (2016) tested four configurations of PV panels (with and without cooling and concentration). The low concentration brings approximately 30% extra output to the system. The cooling has a better impact on the CPV system due to the original higher temperature of the module (more than 20 °C higher than without concentration). The benefit of the cooling is evaluated at approximately +20% of power output at noon, but is insignificant early in the morning or later in the evening.

Said et al. (2018) investigated the solutions available at the research stage to limit dust deposition. Textured surfaces with lubricant and electrostatic fields show interesting outputs and promises. Goossens (2018) tested a PV treated with anti-soiling coating in a wind tunnel. The coating does not make a huge difference at low wind speed; however, once the wind speed increases, the dust is removed at a lower wind speed when the surface is coated. Also, the coating improved the transmittance.

5. Discussion and results

5.1. Comparative study

Reliable and accurate evaluation is obviously important to predict the performance of a PV system and design it properly. As previously stated in part 3.1, the major outdoor performance parameters are the PR and the CF. In this context, to assess system performance parameters, the PR and CF values describe how effectively the following power plant examples operate under different climatic conditions. Table 1 summarizes some of the outputs measured in the experiments described in this paper.

Table 1
Performance parameters of PV systems in arid and semi-arid locations.

Technology	Reference	Location	Precipitations per year (mm)	Experiment duration – ? if uncertainty (years)	PR (%)	Efficiency (STC)	Outdoor effic.[1] (%)	Temp.[2] (°C)	GTI[3] (kWh/m^2)
mono-Si	Silvestre et al. (2018)	Saida, Algeria	336	2014–2016	88*	15.4	13.6	20.9	2095
	Tebibel and Labed (2013)[b]	Tamanrasset, Algeria	43	2011?	70	12.9	9.0	28.6	2306
	Ferrada et al. (2015)	Antofagasta, Chile	3	2013	78**	14.6	11.5	19.6	2217
	Makrides et al. (2012)[a]	Nicosia, Cyprus	329	2006–10	90*	16.1	14.5	25.5	1921
	Edalati et al. (2015)	Kerman, Iran	224	2013–14	80.81	14.3	11.6	24.4	2144
	Mirzaei and Mohiabadi (2017)	Rafsanjan, Iran	136	2014	90	15.5	14.0	25.7	2144
	Emziane and Al Ali (2015)	Abu Dhabi, UAE	75	2010-?	70	18.4	12.9	32.9	2335
HiT	Silvestre et al. (2018)	Saida, Algeria	336	2014–2016	90*	18.6	16.7	20.9	2095
multi-Si (coated)	Piliougine et al. (2013)	Malaga, Spain	520	2010–11	94.1	13.4	12.6	22.6	2106
multi-Si	Silvestre et al. (2018)	Saida, Algeria	336	2014–2016	85*	12.2	11	20.9	2095
	Makrides et al. (2012)	Nicosia, Cyprus	329	2006–2010	87*	13	11.3	25.5	1921
	Daher et al. (2018)	Djibouti, Djibouti	164	2012–2015	84	14.4	11.9	33.6	2194
	Edalati et al. (2015)	Kerman, Iran	224	2013–14	82.92	14.3	11.9	24.4	2144
	Mirzaei and Mohiabadi (2017)[a]	Rafsanjan, Iran	136	2014	92.4	13.24	12.2	25.7	2144
	Hammad et al. (2017)	Zarqa, Jordan	182	2014–15	94.1	14.7	13.8	24.2	2134
	Kazem et al. (2014)	Sohar, Oman	77	2012–13	84.6	13.9	11.8	31.9	2366
	Emziane and Al Ali (2015)	Abu Dhabi, UAE	75	2010-?	80	14.2	11.4	32.9	2335
CIGS thin film	Tahri et al. (2017)	Saida, Algeria	336	2014–2016	90.5*	12.2	11	20.9	2095
	Makrides et al. (2012)	Nicosia, Cyprus	329	2006–2010	88*	10.3	9.1	25.5	1921
	Al-Otaibi et al. (2015)	Azda, Kuwait	103	2014	78.4	14	11.0	31.1	2280
	Al-Otaibi et al. (2015)	Azda, Kuwait	103	2014	76.5	14	10.7	31.1	2280
a-Si/μ-Si	Tahri et al. (2017)	Saida, Algeria	336	2014–2016	93.1*	9	8.4	20.9	2095
	Ferrada et al. (2015)	Antofagasta, Chile	3	2013	79**	8.9	7.0	19.6	2217
CdTe	Makrides et al. (2012)	Nicosia, Cyprus	329	2006–2010	83*	18.6	16.7	25.5	1921

[a] Best model.
[b] 9 months.
[1] Outdoor efficiency.
[2] Average Temperature (1 year).
[3] Global Tilted Iraddiance (1 year).
* Approximate values estimated from graphical representations.
** Approximate values calculated from experimental data.

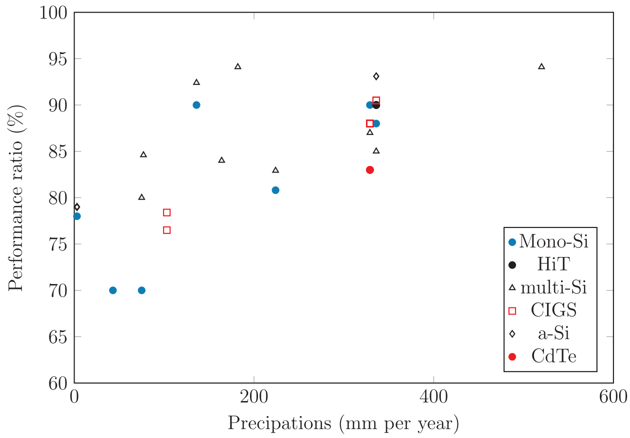


Fig. 2. PR vs. annual precipitation for the selected experiments.

The CF was not always available: thus the PR, the efficiency STC, and the outdoor efficiency are considered. To quantify the level of aridity, the annual precipitation and the yearly average maximum temperature are displayed in Table 1. The data are taken from the website https://en.climate-data.org. Also, the Global Tilted Irradiance (GTI) is displayed, extracted from globalsolaratlas.info. All the experiments but one ran on at least one year. When the exact period of the experiment is not given, it is estimated from the date of the submission and a question mark is displayed.

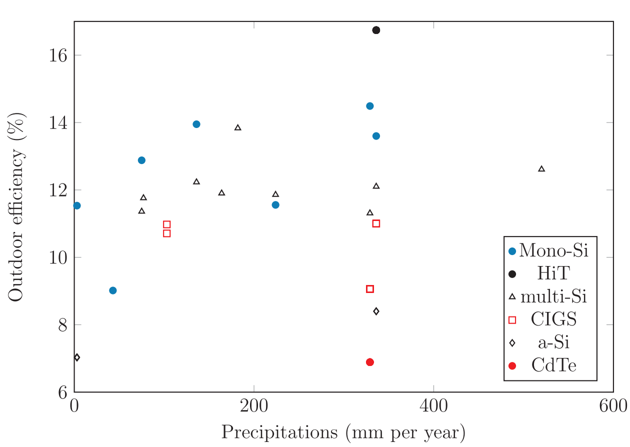


Fig. 3. Outdoor efficiency vs. annual precipitation for the selected experiments.

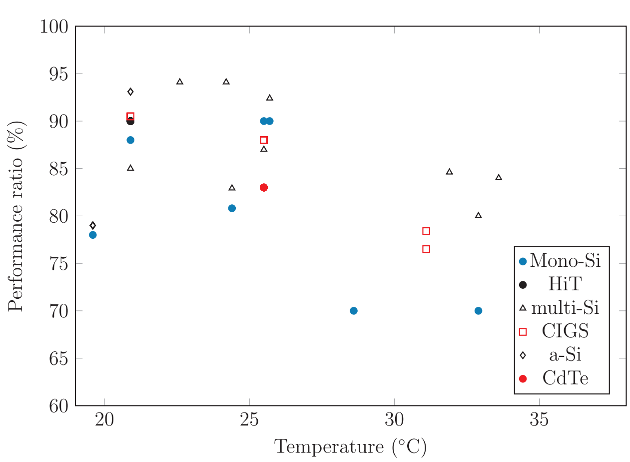


Fig. 4. Performance ratio vs. average temperature for the selected experiments.

5.2. Results and interpretations

Figs. 2–7 show the graphical distribution of the PR and outdoor efficiency versus precipitations, temperature, and Global Tilted Irradiance, respectively. The points are differentiated depending on the PV technology of the related experiment.

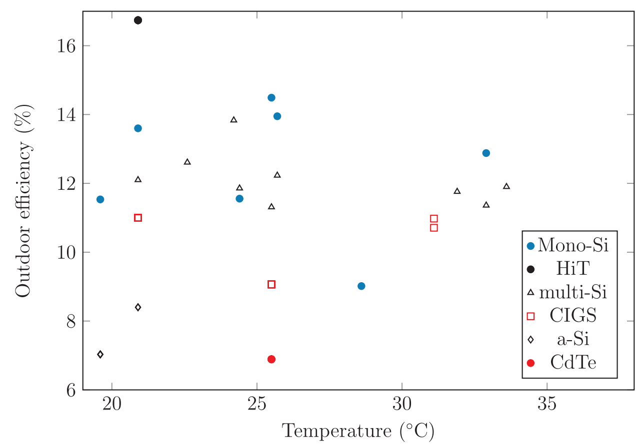


Fig. 5. Outdoor efficiency vs. average temperature for the selected experiments.

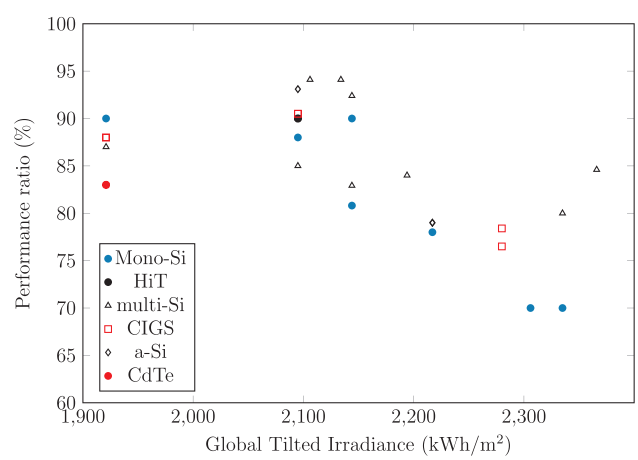


Fig. 6. Performance ratio vs. Global Tilted Irradiance for the selected experiments.

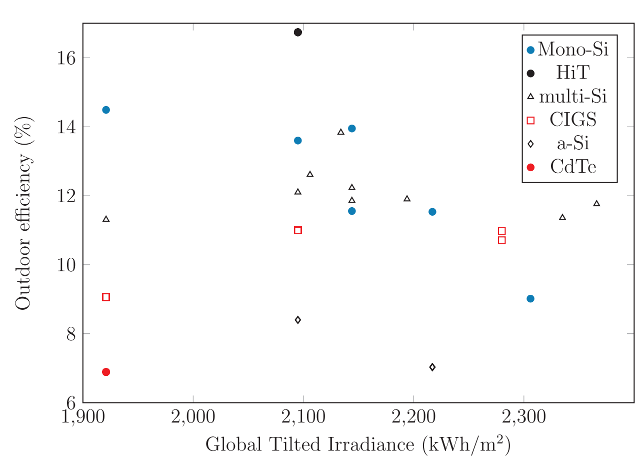


Fig. 7. Outdoor efficiency vs. Global Tilted Irradiance for the selected experiments.

5.2.1. Outdoor efficiency

It is difficult to draw any conclusion about outdoor efficiencies as cells with different STC efficiency are used. However, Figs. 3, 5 and 7 give a graphical overview of the global performance of the different devices. We can also observe the expected levels of performance for the different technologies.

- The efficiency of experiments based on second generation technologies is lower than first generation;
- The efficiency of mono-Si experiments seems slightly higher than the other technologies, apart from HiT;
- The efficiency of the HiT experiment is by far the highest.

5.2.2. Performance ratio

Unlike outdoor efficiency, tendencies seem to emerge for the performance ratio. Note that it is difficult here to extrapolate definitive conclusions as the amount of data available is limited. However, several trends can be noticed from this limited set of experiments:

General trends:

- The PR is slightly higher for multi-Si technologies compared to mono-Si, especially when aridity is important;
- The PR of mono-Si and second-generation technologies are on the same range;
- Although there is not much feedback about thin films (a-Si, CdTe and CIGS), the PR of these technologies under arid conditions looks promising.

PR and precipitations:

- The PR has a slight tendency to increase with an increase in precipitations. This may be explained by the reduction in temperature and cleaning effect of the rain; however, more experiments and data are necessary before stating a definitive conclusion.

PR and temperature:

- As expected, the PR seems to decrease with increasing temperature. All the technologies seem to suffer from the temperature, however the multi-Si technology seems slightly less sensitive.

PR and Global Tilted Irradiance.

- Apart from Cyprus, the GTI of the experiments are between 2095 and 2335 kWh/m^2. The PR has a tendency to decrease with increasing GTI. The R^2 coefficient is 0.565 on these 20 points (excluding the four points from the Nicosie experiments). Again, more long-term experiments may be necessary, however a high GTI could be detrimental to the PR. Assuming a similar number of sunshine hours, it could be explained by the overheating of the module because of high irradiation.

5.3. Preliminary conclusions

Concerning the efficiency: under arid climatic conditions, these experiments show that mono-Si and multi-Si modules have generally a better efficiency than thin films. The experiment run with HiT technology reached the highest outdoor efficiency. This is in line with what is observed under STC; however notice that the outdoor efficiency is just one parameter among many others, and other issues such as degradation rate or performance ratio need to be considered.

The performance ratio has a tendency to be slightly higher for experiments located where precipitations are higher; also, it is globally lower when the average daily temperature is high. Finally, at locations where GTI is high, the PR is generally lower. Under arid climates, precipitations seem to give a slight advantage to PV modules. while high atmospheric temperature and high GTI, on the other hand, may deteriorate the global performance of PV modules. The high atmospheric temperature increases the temperature of the module (or limits the cooling) by convection; high GTI may be the consequence of high irradiation, such phenomena may lead as well to the increase of the temperature of the module because of absorption of sun rays.

The limited number of experiments prevents any further and definitive conclusion; however these trends, if confirmed, may raise interesting points. While clouds are obviously detrimental to performance of PV panels, occasional precipitations may, on the other hand, be beneficial. Also, as expected and observed in former studies, high temperatures seem harmful to performance under such climates. Finally, if the GTI trend is confirmed, it means that high GTI may not necessarily be fully beneficial to PV module performance.

6. Conclusion

Solar PV technology under arid conditions has huge potential due to the large solar radiation. However, environmental parameters such as high temperatures, high irradiation and dust, common in arid areas, can drastically affect the performance of solar modules. The impact of dust deposition can be massive: frequent dust storms, size of particles around 100 µm, and rare and low-intensity precipitations can have a very negative impact by increasing the dust deposition. Similarly, wind can be an ally when it does not carry particles, as it can clean the modules from deposited particles.

Under arid and semi-arid climates, high temperatures tend to decrease the performance ratio; however, different PV technologies seem to respond slightly differently to exposure to high temperature.

Also, high GTI seem to affect the performance ratio even more significantly than atmospheric temperature. The increase of temperature of the module itself could be an explanation.

Precipitations have potentially a positive impact probably due to the cleaning effect, however humidity in the atmosphere is detrimental due to absorption of the rays by molecules of water vapor. A climate with brief and intense rainfalls followed by long and stable periods of dry sunshine may be close to the optimal situation.

Monocrystalline PV modules are more efficient under standard conditions; however, for the experiment analyzed here, multicrystalline modules have generally a slightly higher PR for the models tested compared to monocrystalline modules. Thus there is no evidence of the superiority of monocrystalline over multicrystalline technologies under arid climates.

Under specific temperature conditions, a careful assessment may be necessary as multi-Si modules may be more interesting than expected. Furthermore, thin-film technologies have low efficiencies but are less temperature sensitive. They may become extremely competitive in the near future under arid climates if significant progress is made. HiT seems to be the most promising technology: high efficiency, competitive thermal coefficient and high performance ratio.

Finally, degradation is an important issue: the accumulation of aggressive environmental parameters makes arid climates among the most difficult conditions for solar PV panels. The crystalline technologies seems much more resistant, with a slight advantage to multi-Si compared to mono-Si. The thin film technologies are heavily impacted by degradation in this climate. Although only one experiment was considered on HiT in this study, degradation seems to be a major challenge for this technology under arid conditions.

Arid and semi-arid climates offer tremendous amounts of sunshine; however a very careful assessment of the environmental parameters and the objectives of a given project is necessary before selecting an appropriate technology. More long-term experiments, especially for second and third generation technologies, are necessary to ameliorate the knowledge on their competitiveness under arid and semi-arid climatic conditions.

Conflict of Interest

The authors declared that there is no conflict of interest.

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