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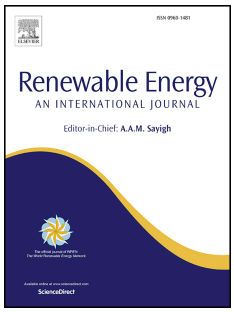

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A real case of thin film PV alternatives to cSi based on a-Si and CdTe. Results after eleven years operating at same conditions

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The new PV technologies need to be analysed in the long term to obtain mature results. Technologies such as tandem amorphous silicon and Cadmium Telluride were installed in the same conditions ten years ago. Now, the results of their operation are presented with the aim to offer real data to the market

KEY WORDS: Cadmium Telluride, Cd-Te, Amorphous Silicon, a-Si, degradation rate, half-lifetime

1. Introduction

1.1.Photovoltaics expansion worldwide

The climate crisis caused by global warming due to the continuous and growing CO_2 emissions since the beginning of the massive consumption of fossil fuels, has led to the general consensus that the solution lies in massive use of energies that do not emit CO_2 and that emit the least possible amount of greenhouse effect gases in their life cycle.

Among the technologies for electrical power generation, one of the most promising is photovoltaics, since it is easy to install, maintain and increasingly efficient. It should be noted in this last point that efficiency is not only relative to the amount of energy converted, but to be able to compare with other energy sources like wind power or fossil fuels, the associated impacts and consequences must be considered. In this sense, photovoltaics is not only efficient but also safe and cost-effective.

The photovoltaic installed capacity in Spain has grown from 4.6 GW and 8.3 GWh in 2013 (start date of this study) to 25.5 GW and 37.3 GWh in 2023 (REE, 2024).

1.2.Mature and emerging photovoltaic technologies

The increase in the use of photovoltaic energy has led to greater investment in research that has led in turn to an improvement in the efficiency of solar panels. In the last 10 years, efficiency has risen from 16% for crystalline silicon panels in commercial use, to the current 22% (Fraunhofer ISE, 2024). These data are surpassed in the laboratory, with an efficiency of 24.7% for the best performing crystalline silicon panels (Fraunhofer ISE, 2024), and foreseeably will be transferred to the public.

All PV technologies have undergone an increase in efficiency supported by research. Almost all of them do not only owe this increase to improvements in manufacturing but

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also to the incorporation of mixed technologies, which make it difficult to classify, for example, amorphous silicon as such, since it usually includes layers of microcrystalline silicon. In any case, other materials such as cadmium telluride have clearly improved in efficiency, going from 9% to nearly 20% in the last 10 years (Fraunhofer ISE, 2024). In contrast, efficiency increase for hydrogenated amorphous silicon a-Si:H has been rather smaller, from 9.5% in 2004 to 10.3% in 2015 (Stuckelberger et al., 2017).

Notwithstanding the large efficiency increase of CdTe, most new commercial PV plants worldwide are equipped with crystalline silicon panels. The main reason is that crystalline silicon average annual degradation rate, measured as percent maximum power loss per year, is lower and more predictable. Piliougine et al. (2022) compiled the degradation rates reported in scientific literature from 2001 to 2021 for thin film PV technologies, and for CdTe, values show a high dispersion, from 0.53% to 10.60%. Contrarily, the certainty on crystalline silicon degradation rate is higher; as a rule of thumb annual degradation rate is below 0.50%. For instance, Pascual et al. (2021) measured an average annual degradation rate of 0.27% for the non-defective panels in a commercial population of 82 MWp panels over 10 years, where the non-defective panels represented about 80% of the total panels population.

2. Objectives of the work

The objective of this work is to present, analyse and discuss the operational evolution of three experimental photovoltaic systems, operating in the same environmental conditions, which were installed for experimentation in 2012 and therefore would have reached half of their theoretical useful life.
The objectives can be summarized as:

- What is the degradation rate for each technology?
- What electrical parameters are more affected by aging?
- What is expected from emerging technologies such as CdTe with the new advances?

This study will help to understand how solar plants in operation with the same technology, installed in the same period, are behaving and whether they may present deficiencies or not, according to what the conclusions of the experiment will provide. Although this is not a large-scale experiment, the results are significant enough considering the controlled conditions and the different technologies working under the same conditions.

3. Materials and Methods.

3.1. The experimental solar plant

The PV plant referred herein is a grid-connected flat-roof PV plant located in one of the buildings of the School of Agricultural Engineers (ETSIAAB) in Madrid, Spain (40.4426 ºN, 3.7295 ºW). The use of photovoltaic installations on roofs of public buildings has an additional educational function, especially when the buildings host universities.
At the installation date (2012) of the plant used in our research, educational photovoltaic installations were hardly common in Spain, limited to research functions.

The plant used fulfils two objectives: on the one hand, it is used to investigate a comparison of different photovoltaic module technologies and on the other hand, it has been carrying out dissemination work on photovoltaic technologies applied to the agricultural field.

Since it is a grid-connected plant, with discharge for sale at a fixed price (Ministerium of Industry of Spain, 2008), the electricity is used both energetically, being used in the buildings themselves as they are the closest consumer, and economically, due to the return for the sale of the energy produced.

According to the legislation in force at the time of installation, the plant, because it has a power of 18.6 kWn and therefore less than 100 kWn, is considered small in size and susceptible to selling energy at a better price. The entire plant is connected to the electrical grid, however, monitoring is closer on the 3.6 kWn experimental part.

The study consists of comparing common multicrystalline silicon photovoltaic generators, amorphous silicon photovoltaics and cadmium telluride photovoltaics. Each technology is connected to an independent inverter although the three inverters are of the same power and model and the input voltage is similar for the three. This allows detailed data for each section to be recorded for later analysis.

The project involves not only professors and researchers from both the UPM and institutions such as CIEMAT, but also students who collaborate in different tasks and whose participation contributes to a better understanding of the technology and its dissemination in an area with many possibilities for photovoltaic applications.

The installation was designed in collaboration with CIEMAT Photovoltaic Solar Unit, with the purpose of measuring the real outdoor performance of relatively new technologies.

The system is divided in two main sections, A and B (Figure 1). Section A is the largest and it is devoted to electricity production, although it is monitored as well, and the data are registered by a computer program. Section A is formed by two sub-sections, A1 and A2, with the following features:

- A1: 45 SUNTECH POWER STP 280 24 Vd panels distributed in three series of 15 panels each, connected to the MPPT1 of an SMA STP15000TL three-phase inverter (Inverter No. 1).
- A2: 18 Polysol 235 DS IBC panels in a single series connected to the MPPT2 of the same inverter as sub-section A1 (Inverter No. 1).

Section A is in total 12600 + 4230 = 16830 Wp, or 15 kWn.

Section B, namely the research-focused section, is subdivided in tree sub-sections, B1, B2, and B3, with the following characteristics:

- B1: 7 SUNTECH POWER STP230/20Wd panels in a single series connected to SB1200 inverter (Inverter No. 2): 1610 Wp or 1200 Wn.
- B2: 16 SCHOTT SOLAR ASI 105DG panels forming two series of 8 panels connected to SB1200 inverter (Inverter No. 3): 1680 Wp or 1200 Wn.
- B3: 20 FIRST SOLAR FS 382 panels forming four series of 5 panels connected to SB1200 inverter (Inverter No. 4): 1650 Wp or 1200 Wn.

Figure 1 Google Maps view of the PV plant.

While subsection B1 panels are of multicrystalline silicon, subsection B2 panels are of a-Si and subsection B3 are of CdTe. With regard to B2 panels, they are made of homojunction a-Si:H/a-Si:H tandem cells, with the manufacturer code letters DG standing for double glass i.e. front and back glass (Stuckelberger et al., 2017).

The three sub-sections sum a total of 4.94 kWp or 3.6 kWn.

The tilt-angle of the panels is 30º and their orientation or Azimuth angle is 2º SE. The supporting structure consists of Aluminium profiles, ballasted with concrete slabs. The whole plant reaches 21770 Wp or 18600 Wn. Each section and subsection is monitored using a computer based program connected to the inverters of every section so that a comparative analysis can be performed.

3.2. Analysis methodology

A combination of laboratory tests and actual operation data collection under the same conditions is used for the analysis. In the first case, sampling was carried out measuring four panels of Crystalline Silicon (c-Si) and Amorphous Silicon (a-Si) over 10 years in 2012, 2015 and 2023. Likewise, for the Cadmium Telluride technology (CdTe) tests were conducted in 2012 and 2023, by measuring four panels of this technology.
Of the four panels of each technology tested, three were temporally dismantled off the PV plant (section B) and transferred to CIEMAT for subsequent measuring. For each technology, the fourth panel tested, or reference panel, was not installed at the plant, i.e. the three reference panels were not in operation. Instead, these three panels had been kept in the dark from year 2012, and they were transferred to CIEMAT together with their outdoor

or in-operation counterparts. In this way, it is possible to detect possible fluctuations either in the measuring equipment that, due to the time that has elapsed, has required changes, or in possible variations in the method due to changes in the operators involved. In the case of the CdTe panels, an activation was also carried out due to the accumulation of radiation prior to the measurements.

Indoors measurements were obtained using a flash pulsed class AAA IEC 60904-9[(IEC 2007)] solar simulator (10 ms pulse). An I-V curve measurement was performed according to IEC 60904-1 [(IEC 2008)], which obtained the main parameters, Isc, Voc, Im, Vm Pm and FF at Standard Test Conditions (STC):

- Irradiance: 1000 W/m²
- Cell temperature: 25°C
- Spectral distribution: AM1.5G (according to IEC 60904-3)[(IEC 2008)].
- Normal incidence

Temperature of the modules was obtained using a Fluke® thermometer with dual thermocouple input and sensors connected on representative separated points of the module to obtain the mean value.

Inside the simulator, conditions were very close to STC with little deviation (25 ± 2 ºC and 1000 ± 5 W/m^2). Using module temperature coefficients *(α, β)* and irradiance correction factors, the obtained measurements were extrapolated to STC (see IEC 60891 Standard). Special care was taken in ensuring that PV modules had not received direct solar light before the first round of measurements.

3.3. The stabilization issue for aSi and activation process for CdTe

The measurement of photovoltaic panels of thin film technologies is not a totally obvious matter. For example, the output power of an a-Si panel depends on panel history of sunlight exposure and on recent hours of sun radiation (Mateo et al., 2018). In general, thin film are materials with less maturity than crystalline silicon and often undergo changes not only between manufacturers but within the same producer and even within the same model, depending on the manufacturing batch.

As for amorphous silicon, technology has evolved from single junction panels to other devices in which microcrystalline silicon is stacked into double junction technologies. In our case, the panel technology is a-Si:H/a-Si:H tandem cells. These panels stabilize in the first weeks of life, losing up to 20% of their initial power. After such a process, the power loss is usually less than in crystalline silicon. In addition, it has an "annealing" process during the days with the highest radiation that produces an effect of improving efficiency compared to winter days. In addition, the spectral response must be taken into account, since the simulators are usually calibrated for crystalline silicon cells and panels. Taking all these aspects into account, the measurements can be extrapolated to be compared between years and between technologies.

3.4. Experiments setup and test samples used

The comparison has been made from two points of view. First, real power and energy were compared along the years. Such data are in fact of great interest for owners, worried by their investment and payback time. But must be put besides laboratory data in order to obtain significant conclusions.

In this way, long term continuous data were obtained from the internal dc-ac converters whose data were sent to a logger and compiled periodically for the analysis.

3.5. Visual inspection

Throughout the more than ten years in operation of the plant, no complete failures have been detected in the panels of any of the technologies. However, the gradual drop in power, which may be a normal effect due to degradation within the usual range, may be associated with failures that can be detected with the unaided eye. For this reason, a visual inspection is also carried out to detect defects such as delamination, yellowing or breaks in both the frame and the glass.

The process for the visual inspection, follow IEC recommendations (61215, 61646), and should be performed under the following conditions:

- 1000 lux
- Unaided eye

It must be documented by taking photographs and it is valid for the detection of:

- Bubbles, delamination, yellowing, browning
- Broken or split cells, discoloration
- Burnt or oxidized metallization
- Peeling, misaligned, scratched or broken frame
- Delamination or bubbles on the back side
- Peeling oxidation or corrosion of the connection box
- Wiring problems: disconnection, loose parts

4. Results and discussion

Three different photovoltaic technologies working in the same real conditions were analysed along ten years of operation. Throughout these years, the insulation of the roof had to be changed during the spring of 2019, something that was barely noticed in production during the month of March 2019. In addition, it suffered the heaviest snowfall in Madrid in more than a century during the winter of 2020 (Muñoz-García et al., 2021) and once again the plant withstood this event well.

4.1.Actual production results and plant performance

Despite the degradation of the panels expected over the years, the plant has been producing electricity above expectations, possibly due to a good Performance Ratio (PR) given the special care taken in its design. Even so, the gradual drop in production can be seen in Figure 2,Figure 3 and Figure 4 being within the expected margins. This graph represents the total production of the plant, which is mainly due to crystalline silicon panels (subsections A1, 12600 Wp, A2, 4230 Wp, and B1, 1610 Wp, or 18440 Wp out of the plant total 21770 Wp)

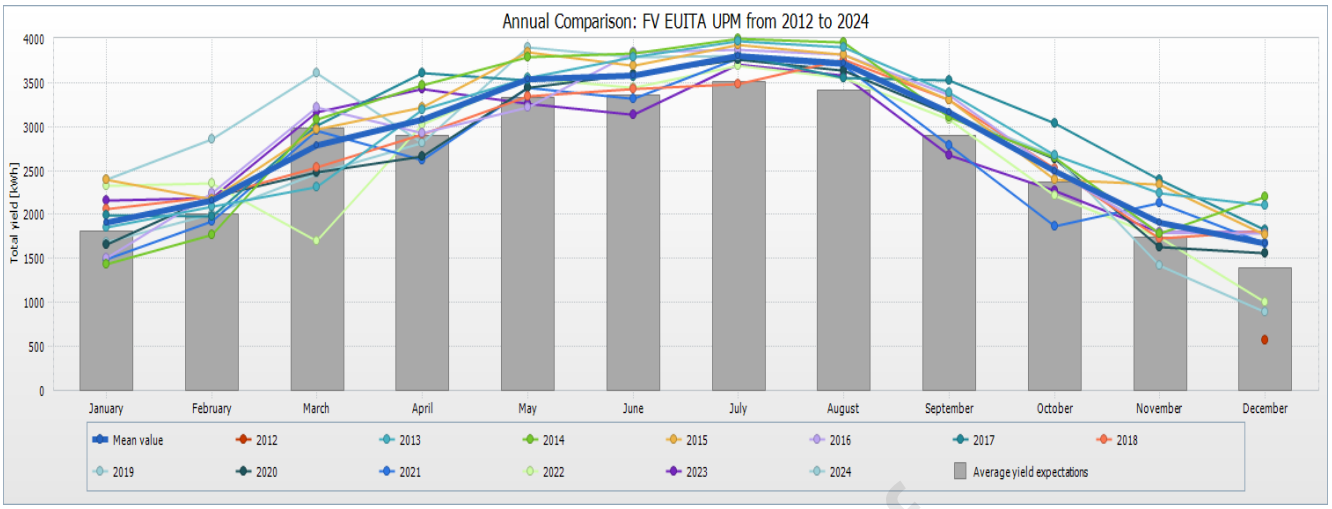

Figure 2.- Monthly comparison of the real and predicted production for the whole plant (PSH expected: 1600).

When we analyse the different areas of the solar plant, using the real data, we obtain interesting results. In general, production decreases with the course of time, but according to the expected due to the degradation effect. We must consider also the specificities of each year. In 2023 the CdTe area had less modules due to maintenance reasons, so it should be excluded from the comparison. Nevertheless, that year was also hotter than usual what could affect to a better performance of the aSi modules, due to thermal annealing (Hamelmann et al., 2016; Wang et al., 2017).

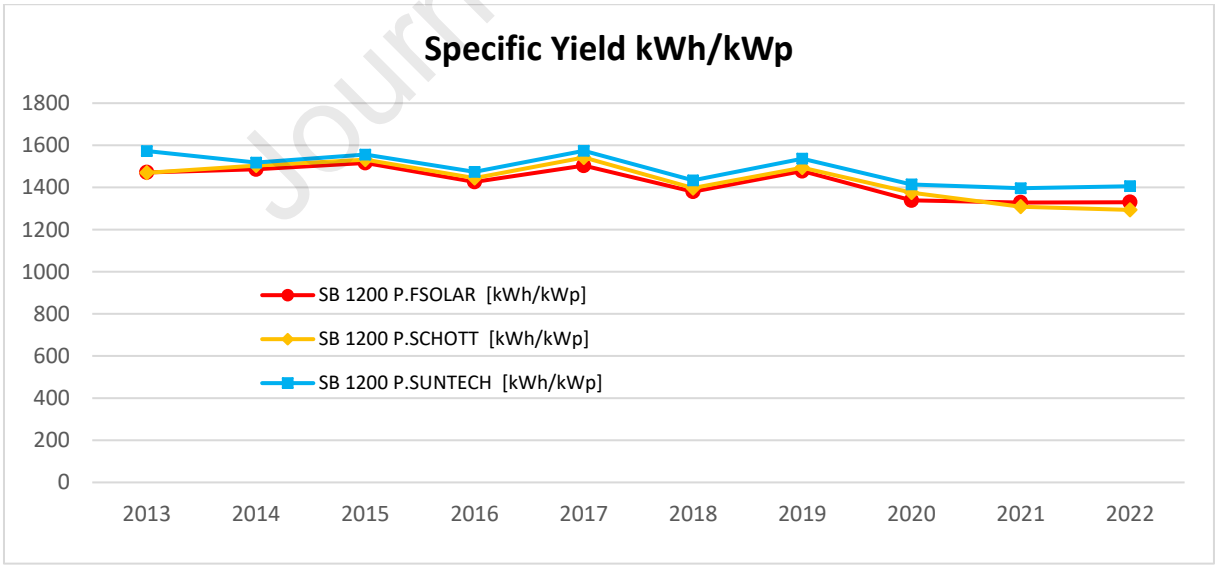

Figure 3.- Specific yield for each technology along the analysed period.

The PR calculated and shown in Figure 4 carried out considering the yield of generated energy, the peak power of each section and the peak solar hours. No correction is made for temperature, so that the variability of the different technologies can be appreciated in their real form.

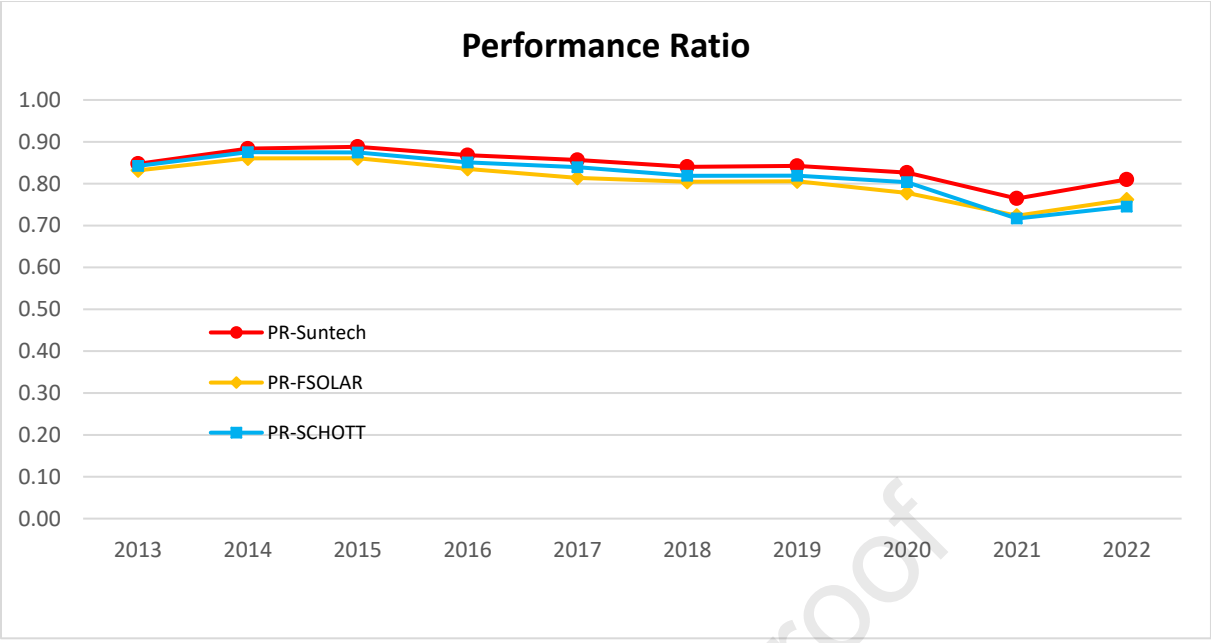

Figure 4.- Performance Ratio (PR) calculated for each technology section.

4.2.Indoor flash solar simulator for I-V measurement of I-V characteristic curve.

The I-V curve of a PV module is the standard measurement to evaluate its performance in all its operation range at certain irradiance, temperature and spectrum conditions. Measured at Standard Test conditions (irradiance of 1000 W/m², 25°C of module temperature and reference spectrum AM 1.5G), it permits to make comparisons among different module types, or to evaluate the long-term evolution of the same module trough periodical measurements. The current voltage characteristic of a PV module can be described by Equation 1, (Wolf and Rauschenbach, 1963), which corresponds to the electrical circuit of Figure 5 .

$$I = I_L - I_0\left[\exp\left(\frac{V+IR_s}{mV_t}\right)-1\right]-\frac{V+IR_s}{R_{sh}}$$

Equation 1 .- Electrical model for a PV cell

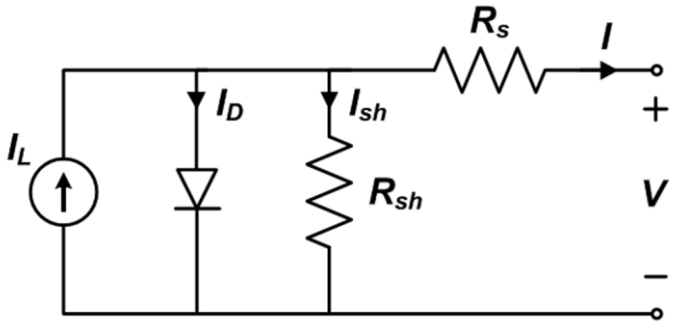

Figure 5.- Electrical circuit corresponding to equation 1. I_D is the current trough diode due to recombination, developed in equation 1 according to Wolf and Rauscehnbach 1963.

In Figure 5 the I_D is the current trough diode due to recombination, developed in Equation 1 according to Wolf and Rauschenbach 1963. Both Equation 1 and Figure 5, include the following parameters: I_L as the photogenerated current, Io the diode saturation current, m de diode ideality factor, Vt the thermal voltage (kT/e), Rs the series resistance and Rsh the shunt

resistance. Variation in circuit parameters, such as Rs and Rsh, due to aging, can be reflected in I-V curve characteristic parameters as short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum power current (P_{max}) and fill factor (FF= P_{max}/I_{sc} x V_{oc}).

Despite the degradation of the panels expected over the years, the plant has been working according to expected. This section presents the results of the performance of crystalline c-Si, amorphous a-Si and cadmium telluride CdTe PV modules compared over the years 2012, 2015 and 2023. In the following figures, the parameters maximum power, open circuit voltage, short circuit current and fill factor are shown. These measurements were taken under STC following IEC 61215 standards.(International Electrotechnical Commission, 2005)

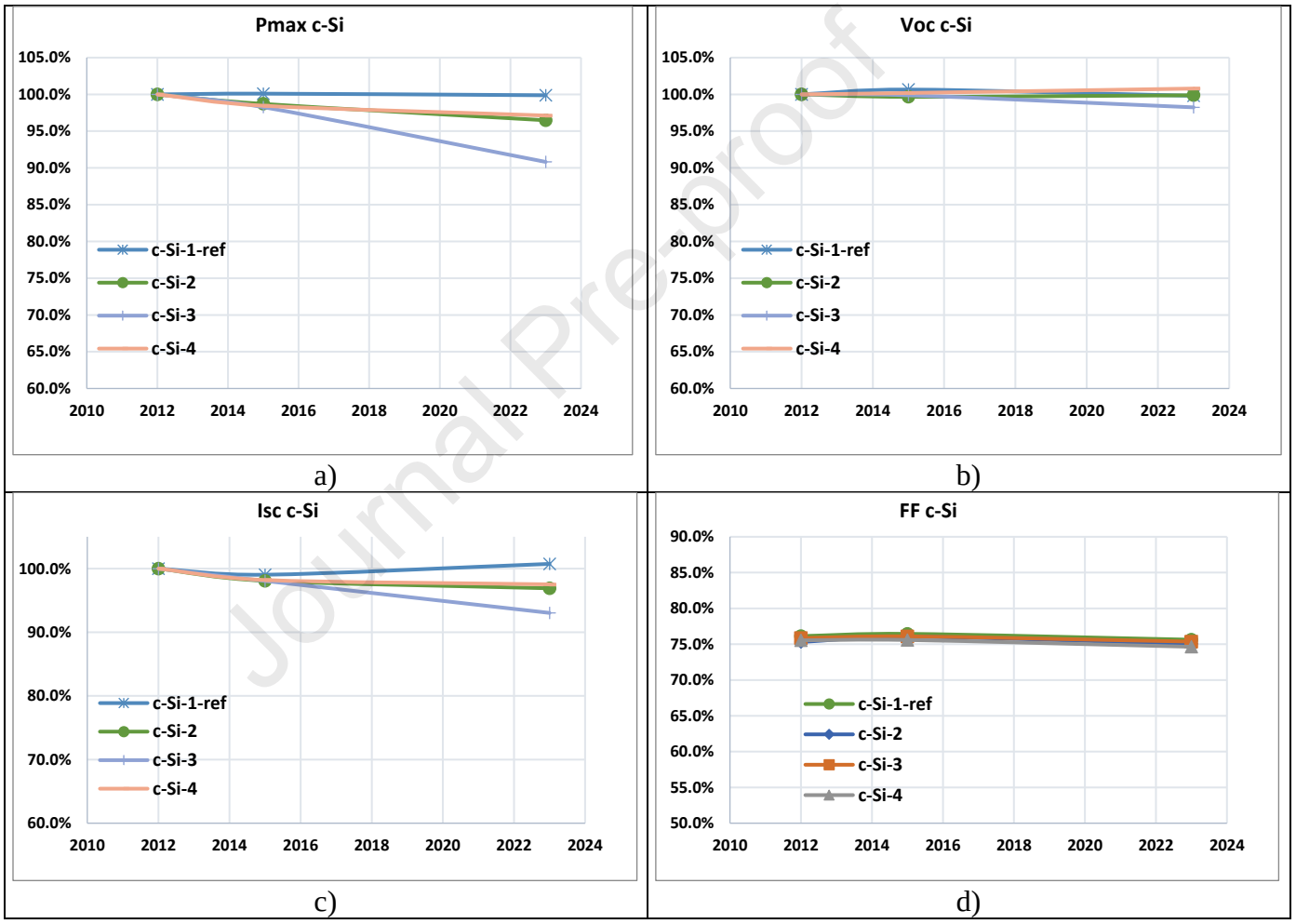

Figure 6.- Parameters evolution along ten years for cSi, including reference module and three in-operation modules. a) maximum power, b) voltage in open circuit, c) short-circuit current and d) fill factor.

These group of modules demonstrated a stable performance over the period of study with a slight decline in Pmax and FF. The values for Pmax declined from 3% (modules 2 and 4) to 10% (module 3), while the reference module remained stable without losses.

The open circuit voltage presented a lower descent (1-2%) compared to the short-circuit current (3-7%), thus indicating the robustness of this technology under sustained operational conditions.

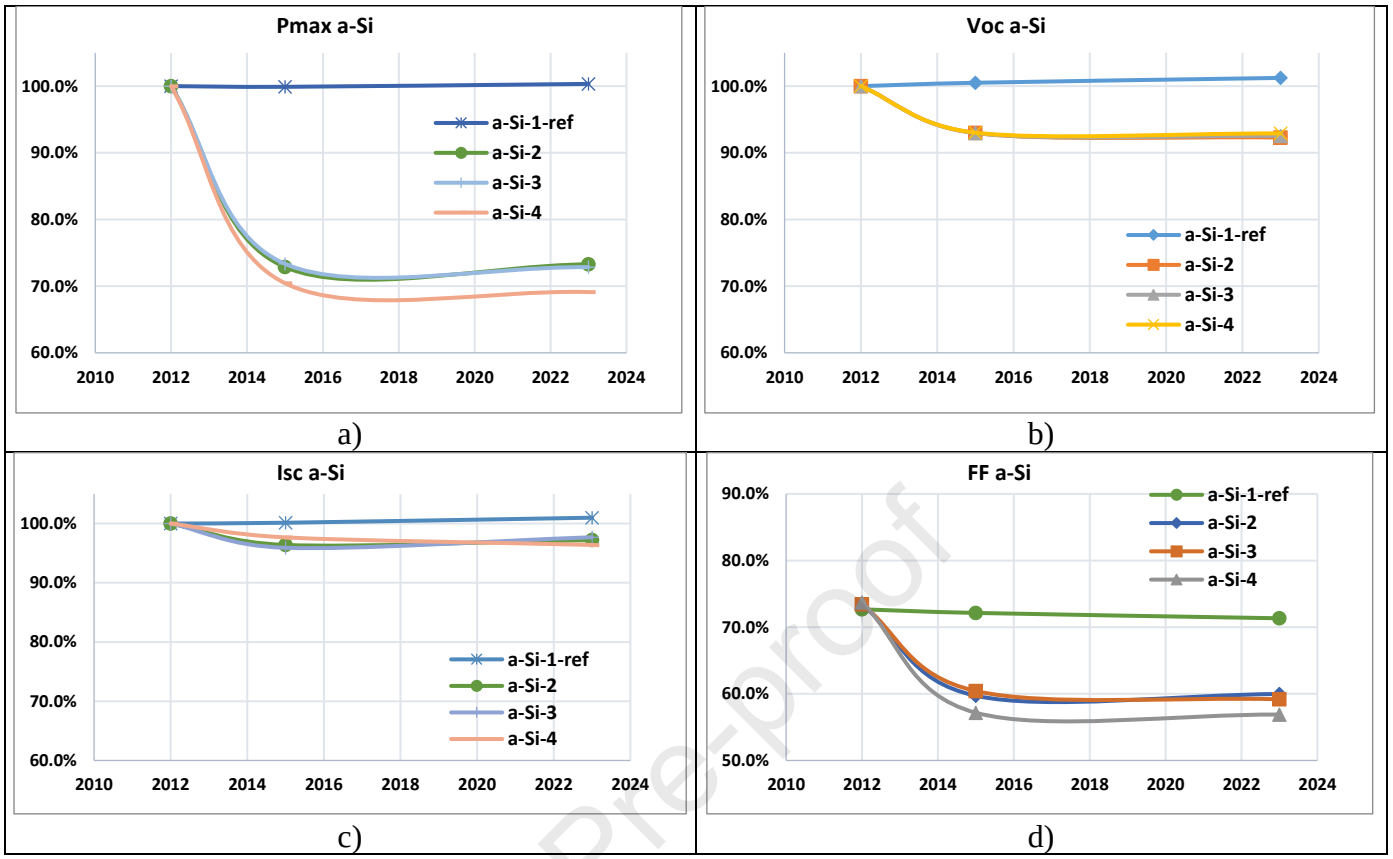

Figure 7.- Parameters evolution along ten years for aSi, including reference module and three in-operation modules. a) maximum power, b) voltage in open circuit, c) short-circuit current, and d) fill factor.

The analysis of the a-Si modules is of great interest. Unlike crystalline silicon, in which initial power stabilization ends after the first few days of panel outdoor exposure (Munoz et al., 2011), a-Si takes longer to stabilize, typically they do after 1000 hours of light exposure (Berov et al., 2014). Amorphous silicon technologies suffer from an initial light induced degradation known as Staebler–Wronski effect (Staebler and Wronski CR, 1977). The stabilization period depends on the type of module and the environmental conditions, with documented periods of stabilization from 6 weeks to one or more years (Piliougine et al, 2022 b). In our case, this stabilization seems to be achieved after one year and half, and it is observed in all module parameters, Isc, Voc, Pmax and FF.

Thereby, an aspect of utmost importance regarding improvement of a-Si application is stabilized conversion efficiency (Ichikawa et al., 1990). In our case, it can be seen how after the initial stabilization, where the panels lose more than 27% (an effect that is known and does not imply irreversible degradation but, as mentioned, stabilization), the electrical parameters remain stable over time with a non-significant degradation of Pmax, Isc and Voc. Even the fill factor remains stable from the second measurement (2015) to the last one (2023). Piliougine et al. (2022b) found that while in the first two years of operation the degradation of a-Si panels is mainly due to a decrease of the current, the long-term degradation is dominated by the reduction in voltage. Nakamura et al. (2023) reported an annual degradation rate of 3.776% for the first two years of operation of their a-Si panels followed by 0.31% per year in the eight next years.

Among the reasons to explain degradation and failure modes in amorphous silicon, they are mentioned at the cell level the diffusion of dopants and impurities causing loss in FF, Isc and Voc, other element diffusion or corrosion causing changes in parasitic resistances (both, Rs and Rsh, abovementioned on *Equation 1)*, or lamination stresses (the separation of the encapsulating

layer, which can modify the optical conditions) causing Isc decrease (McMahon 2004, Radue 2010). At the module level it is observed interconnect or busbar degradation causing changes in electrical resistances, solder joint degradataion or encapsulation failures, provoking loss in fill factor and Isc. (McMahon 2004, Radue 2010).

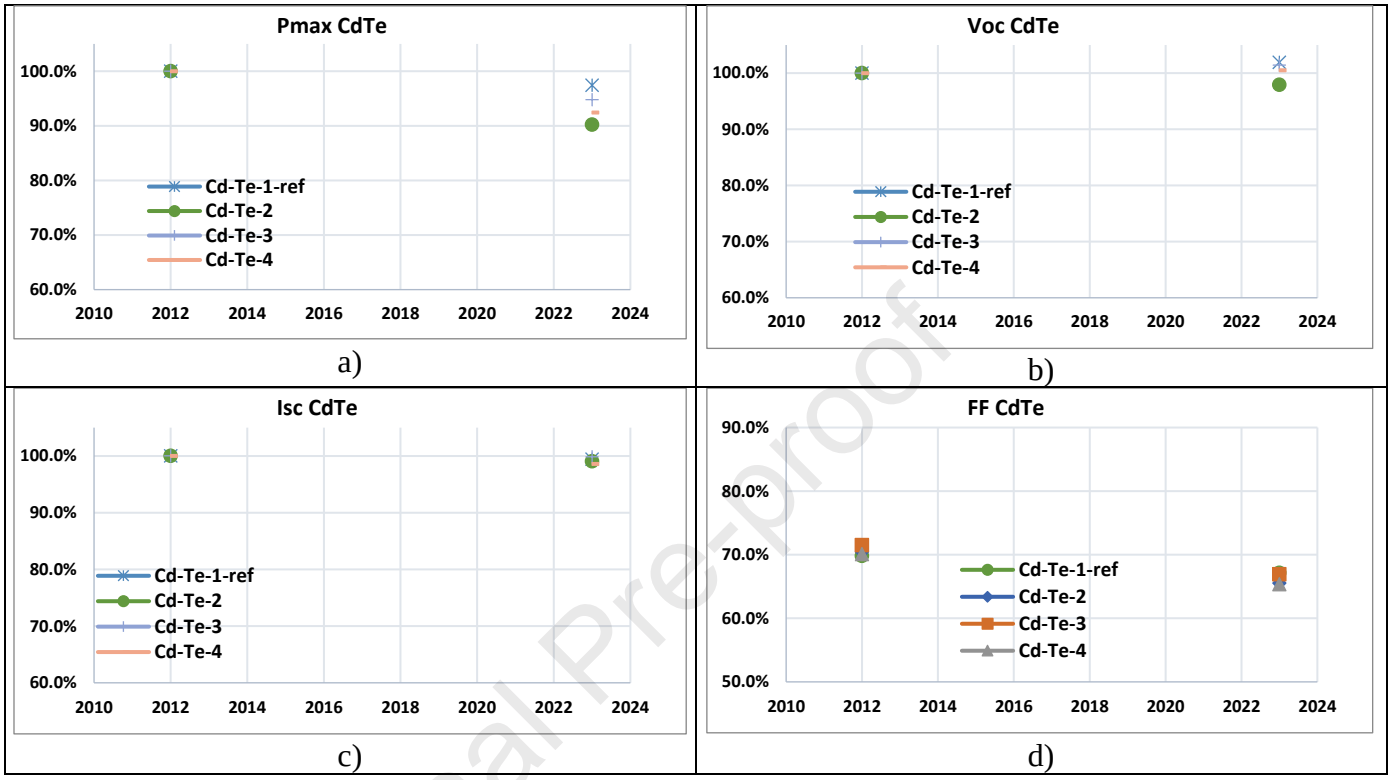

Figure 8.- Parameters evolution along ten years for CdTe, including reference module and three in-operation modules. a) maximum power, b) voltage in open circuit, c) short circuit current and d) fill factor.

Regarding CdTe modules, they showed a different degradation pattern compared to the two groups of panels analysed above. Although Pmax output values decreased a 9,8 %, open circuit voltage and short-circuit current remain reasonably stable. Thus, the degradation came from the descent in the fill factor, which points at the degradation of internal parallel and series resistances. Nevertheless, the degradation rate remained within the expected values.

4.2.1. Comparison of power drop between technologies

We have a very significant image of this analysis in the comparison of the power variation of the different technologies. We can see in Figure 9 that, as above-mentioned, the test found that none of the modules tested had a power drop greater than expected. Likewise, the reference panel (which in all cases presented stable behaviour) has been excluded from the graph, and an average of the annual power drop has been obtained for each of the technologies.

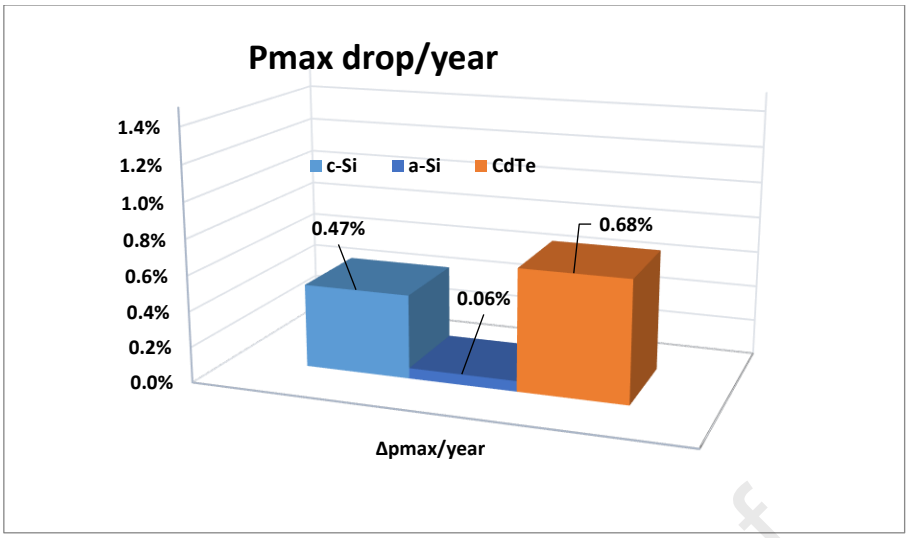

Figure 9.- Comparison of the annual power drop for the three technologies.

It can be seen how the one that presents the best performance is the a-Si, although its efficiency is the lowest, so the use of space must be considered. But even so, its performance has been very good with a non-significant power drop (less than 0.1%). It should be noted that the effect of annealing may have an influence on these measurements, but even so, the behaviour is proven to be very good.

On the other hand, we have classic silicon, whose behaviour is also stable, and the power drop is less than 0.5% per year, within expectations.

Finally, CdTe technology remains promising. Since we must consider that the modules analysed were manufactured more than eleven years ago and during this time improvements have continued to be produced. In the case of CdTe, the power drop is less than 1% per year, being fundamentally due to the worsening of the fill-factor.

4.3. Visual defects detected

After more than ten years in operation, none of the solar panels seems to suffer important damages. Although degradation of parts such as glass can be detected in certain areas, in one case it can lead to a possible failure over time. The panel with said possible failure is not one of those included in the indoor analysis. Nor is a significant drop in power or voltage detected in the string in which said panel is connected.

On the other hand, cSi panels present generalized yellowing. Once again, this is a visual defect that, in view of the results of the energy generated as well as the data obtained in the solar simulator, does not seriously affect operation.

The Figure 10 shows a general view of the cSi experimental area. A yellowing effect is clearly observed in the image. This effect is not present in the panels that are part of the non-experimental area. The difference between one area and another is the aspect orientation of the panels, since they are the same brand and model. This could lead to thinking about an effect of greater heat accumulation in panels that are placed vertically (portrait aspect) as a possible cause of the difference, since the ambient temperature and radiation is the same in both cases.

As mentioned above, the performance of the PV plant in general and the crystalline silicon panels in particular was within or even surpassed expectations during the first eleven years.

Nevertheless, these expectations are based on uncooled PV panels. Undoubtedly, cooling crystalline silicon panels would enhance their electrical conversion efficiency, since cooling counteracts the temperature coefficient issue of silicon crystalline technology, generally quantified as a 0.45% decrease in efficiency for every 1 ºC rise of solar cell temperature above 25 ºC (Cavadini & Cook, 2021). A variety of PV panel cooling systems have been tested in the last decades. (Dida et al. 2021) attached a wet burlap cloth to the rear surface of an 80 Wp multicrystalline silicon panel. The evaporative cooling of the water absorbed by the cloth led to a temperature decrease of 17 ºC compared to the reference PV panel. This translated into an electrical efficiency increase that ranged between 9% and 14.8% throughout the day. The average water consumption of their 80 Wp panel was 0.39 $L \cdot h^{-1}$. Another possibility to cool PV panels is trickling water on the front surface of the panel. This method has the merit that the trickled water not only cools the PV panel, but also washes it. A synergistic PV panel cooling approach is the so-called hybrid PV-thermal design, which enables producing both electrical energy and domestic hot water. Unarguably, PV panel cooling is beneficial both to its efficiency and lifespan (Sharma et al., 2018); however, a cooling system adds maintenance costs (Sato & Yamada, 2019), entails non-negligible water consumption or, in case that forced air cooling is implemented, subtracts output yield to the PV plant. Finally, the co-location of PV plants with green roofs can also aid cooling the PV panels (Jahanfar et al., 2020). For example, Cavadini and Cook (2021) found that the annual energy yield of PV panels on a green roof in Zurich, Switzerland, would be 1.8% higher than the same PV panels on a gravel roof.

Figure 10.- Perspective image of the experimental and commercial areas with c-Si panels of the same model.

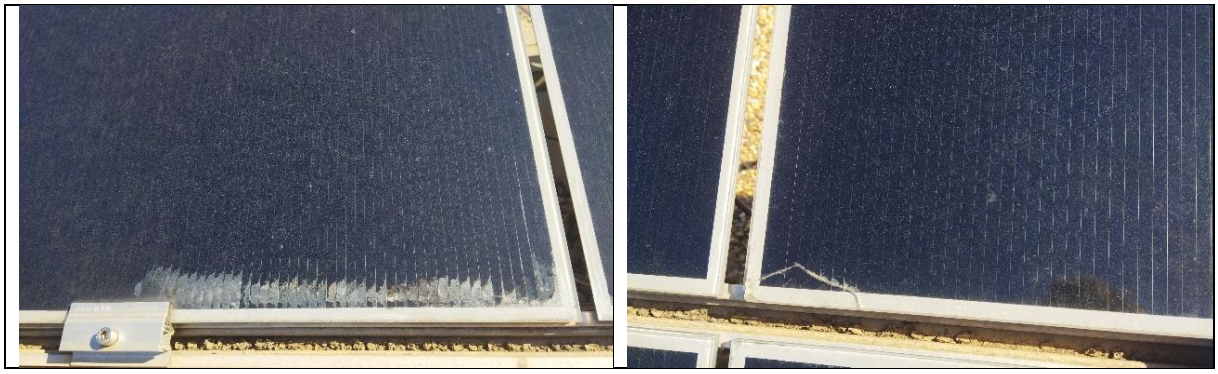

Figure 11.- Close-up image of two of the CdTe PV modules with visual defects.

The following figures show the current state after more than 10 years of operation, of the modules involved in the study as well as a view of the corresponding experimental part.

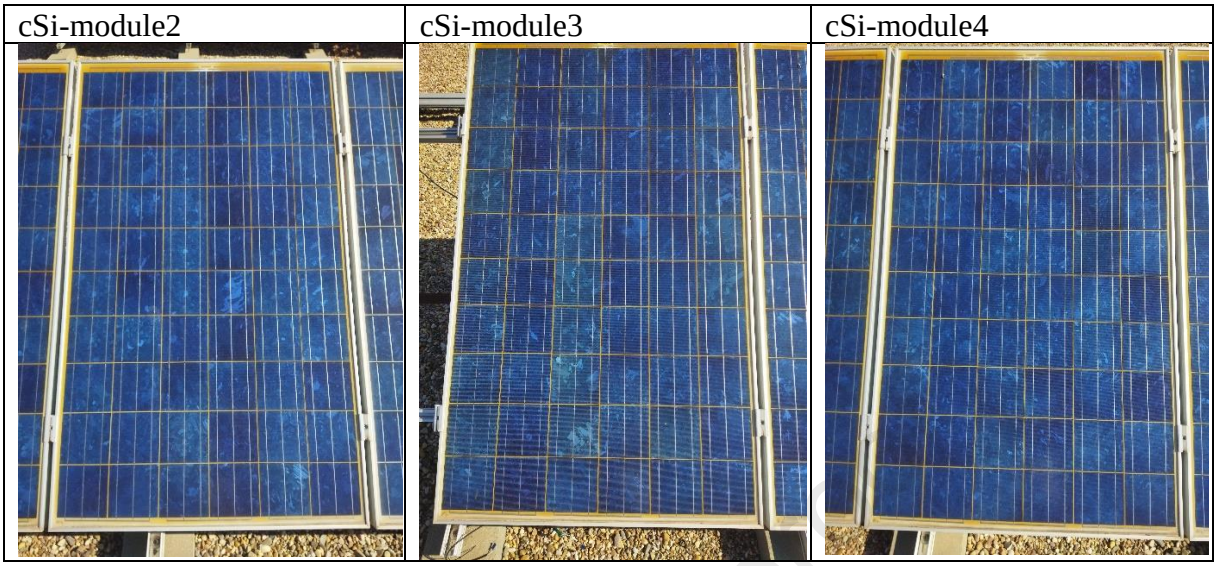

Figure 12.- View of the three installed and working cSi modules used in for the analysis.

Figure 13.- View of the three installed and working aSi modules used in for the analysis.

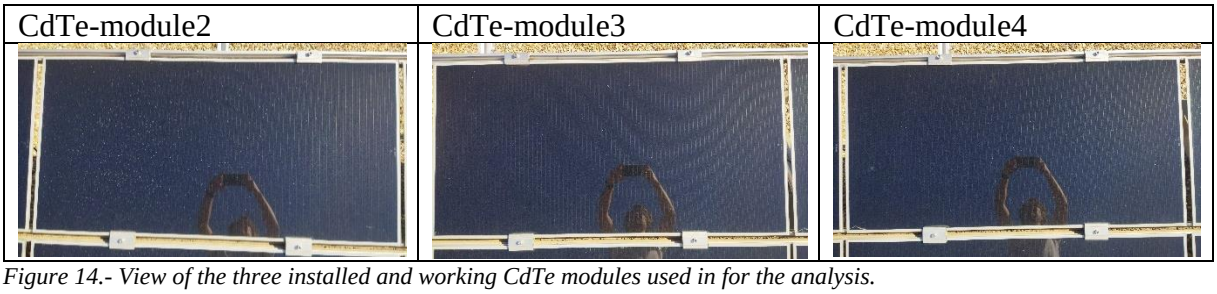

Figure 14.- View of the three installed and working CdTe modules used in for the analysis.

Kettle et al. (2022) summarized the specific degradation mechanisms of different PV technologies. For CdTe, they divided degradation mechanisms in two groups: Those related to the electrodes, and those related to the absorber. For the front electrode, they highlighted

potential induced degradation (PID), while for the rear electrode they mentioned copper diffusion to front junction and molybdenum back contact oxidation. With regard to the absorber, they pointed to migration of sodium from the panel soda-lime glass to the absorber or CdTe-based cell. From the electrical point of view, ultimately copper diffusion provokes a decrease in V_{oc}. Barbato et al. 2021, present a comprehensive review of the history, operation and reliability of CdTe solar cells. Among the recent cases studies, they present the stress at high temperature as one of the conditions that involve degradation, accounting for Cu and its migration in crystal lattice as one of the relevant degradation processes.

In our case, PID should not be considered a plausible cause of degradation rate in the CdTe panels, since these are frameless. Sodium migration from the panel glass cover should not be an issue either, since our panels belong to a commercial generation that includes a barrier below the glass. Contrarily, copper diffusion could play a role in the degradation rate observed, since the Cdte technology of the panels installed, namely the Series 3 by the manufacturer First Solar, did not yet include the countermeasures against copper diffusion of their recent siblings (Series 4 onwards by the same manufacturer). One of these countermeasures is a ZnTe back contact (Scarpulla et al., 2023). This insight aligns with the broader findings on protective coatings presented by Nakamura et al. (2023), and Kettle et al., who emphasized the versatility of coatings in countering a range of degradation mechanisms. For instance, anti-reflective coatings reduce surface reflectivity, improving light capture as noted by Scarpulla et al (2023). Meanwhile, Nakamura et al. discussed hydrophobic coatings, which prevent moisture ingress, a major factor in delamination and encapsulant degradation in humid environments. UV-resistant layers further extents PV lifespans by protecting sensitive interfaces from photodegradation. Scarpulla et al. described coatings that use chlorine or selenium to improve passivation at grain boundaries in CdTe PV modules. The evidence is clear: protective coatings significantly reduce degradation rates over time. Kettle et al reported annual degradation rates ranging from 0.2% to 4% in CdTe and m-Si PV modules, highlighting the potential of coating to stabilize performance.

5. Conclusions and future works

Experiments were carried out to analyse the effect of the course of time at plant half-lifetime on the performance of three different PV technologies. The sample included 12 PV modules, including emerging technologies like a-Si and CdTe.

The performance of three PV technologies under identical conditions over eleven years shows some differences in their long-term stability and efficiency. All the modules analysed present, an operation within the tolerances given by the manufacturer, and none of them show a power drop of more than 1% per year.

- Crystalline silicon modules exhibit the lesser degradation, confirming their technological maturity. These are monofacial and single junction multicrystalline panels.
- The amorphous silicon modules, in tandem or double junction a-Si:H-a-Si:H configuration, after the initial drop in power due to stabilization, warned by the manufacturer, present stability with an average power drop of 0.2%/year. Furthermore, under high temperature conditions, its relative performance increases due to regeneration or thermal annealing.
- The case of cadmium telluride modules demonstrates a moderate degradation rate, being a technology that, due to its efficiency and with the improvement in characteristics in the latter years, would be one of the most promising technologies.

This real-world, comprehensive performance, degradation, and annealing analysis provides valuable insights into the long-term performance and reliability of different PV technologies under real-world operating conditions.

To continue obtaining valid data for the underlying of the degradation process, electroluminescence images would be a valuable tool for the analysis of the cracks and broken cells that is supposed that would appear with the pass of the years. Also thermographies would help to detect the presence or absence of hot spots, that could be even related to the electroluminescence analysis.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: