STUDY OF THE USE OF ORGANIC PHOTOVOLTAICS IN THE TUBELIKE BUS STATIONS OF CURITIBA

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INTRODUCTION

In 2004, each of the 6.35 billion Earth's inhabitants consumed an average of 1.77 tons of oil; this is approximately one million times over the amount consumed by primitive men [1]. Over the years, common energy sources (such as petroleum) are becoming increasingly scarce, which might lead to an eventual resource impoverishment as shown in the graph in Figure 1. It is estimated that the planet originally had approximately two trillion petroleum barrels; in 2006, 45% to 70% of those were already explored [2].

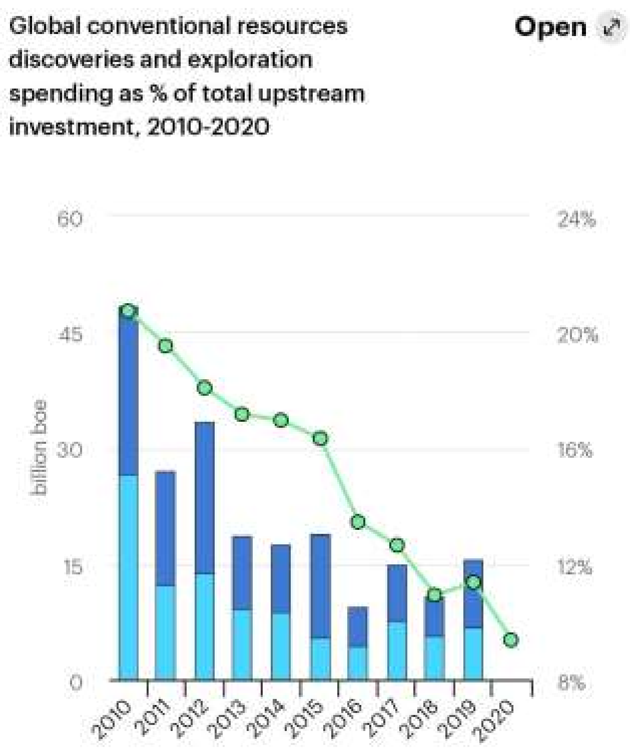

Figure 1: Global conventional energy resources discovered from 2010 to 2020 [3].

With the fast advance of the energy demand and the decrease in the use of fossil energy sources, the search for renewable energy has been a focus in many sectors [3]. Currently, production is at an all-time high and it is estimated that there will be grand developments in renewable energies, with a 49% growth by 2030, according to the graph in Figure 2. Among the many renewable energy sources, solar energy can be emphasized. The radiant energy emitted by the sun has a power of the order of $174 \times 10^{15} W$ and, of all the incident energy over living matter on Earth, only $40 \times 10^{12} W$ is fixated by photosynthesis [4], which is equivalent to approximately 0,0023%. The growth in solar energy production was 32.7% per year between 1990 and 2020 in the OECD countries, and, in 2020, it was the third biggest renewable energy source, being applied in 13.2% of the technologies using renewable energy sources and representing 3,4% of all energy forms (Figure 3) [3]. The comparison of the increase in solar energy use with other energy production methods is represented in Figure 4.

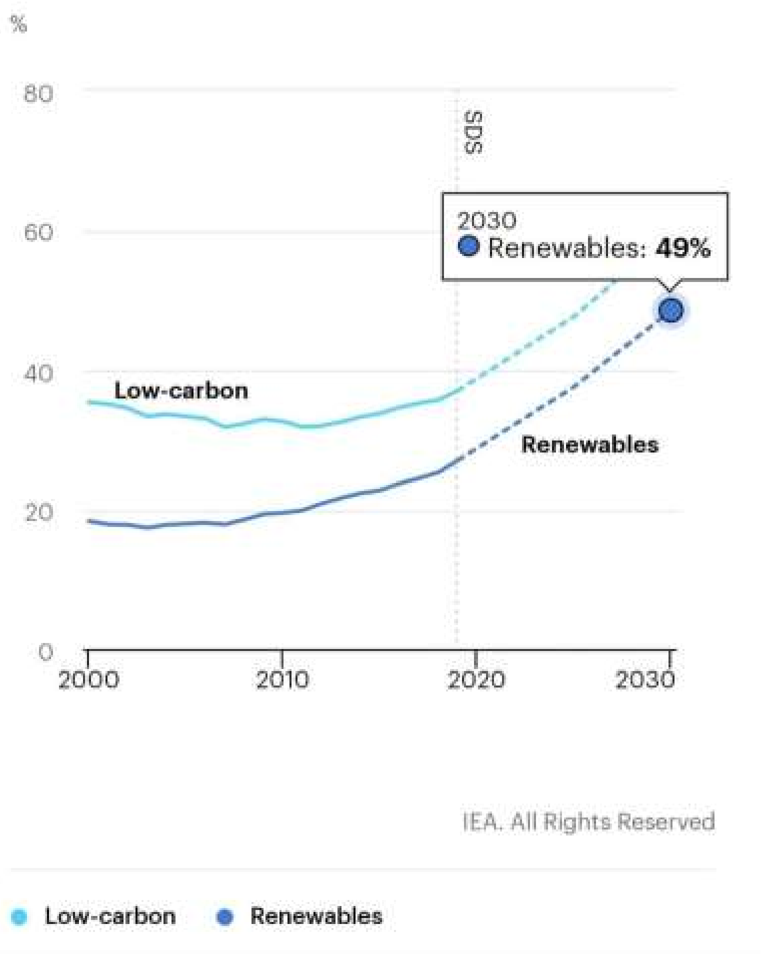

Figure 2: "Global share of renewable power generation in the sustainable development scenario 2000-2030"[3]

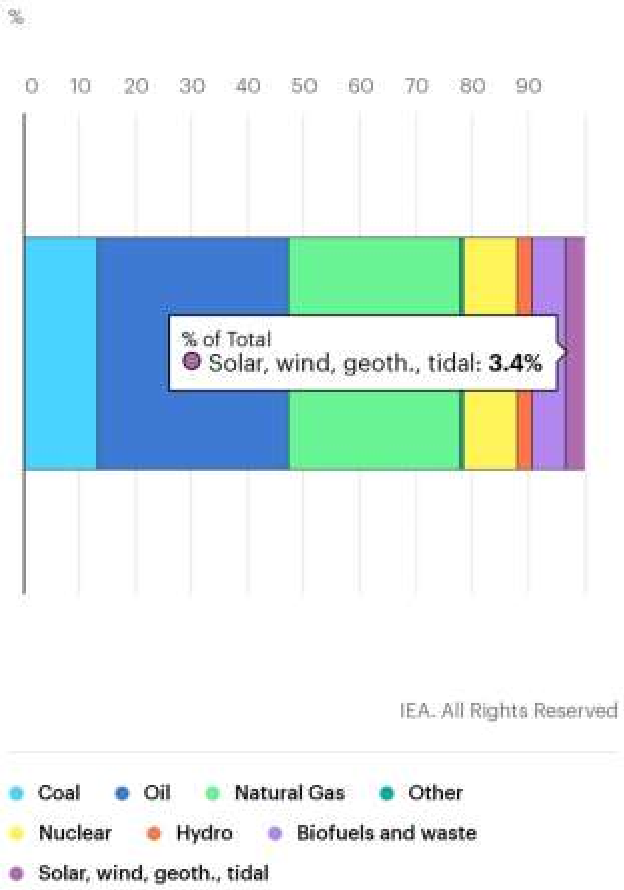

Figure 3: “Fuel shares in OECD total energy supply, 2020” [3].

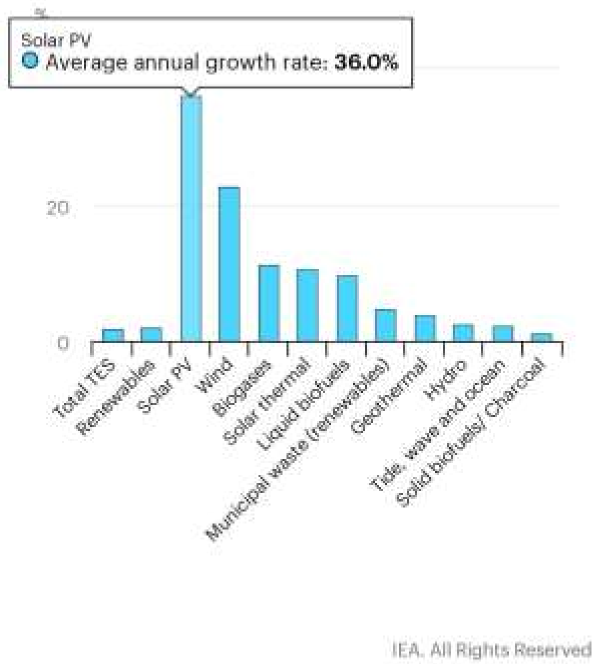

Figure 4: “Average annual growth rates of world renewables supply, 1990-2019” [3].

As a consequence of the COVID-19 pandemic, the renewable energy generation in ODCE has increased approximately 6,9% in 2020. For comparison, the increase between 2018 and 2019 was 4%. This phenomenon might be due to many factors, such as market options, public policies fostering renewable energies, or even the growth in energy demand of lockdown policies [3].

Among the many solar energy production technologies is Organic Photovoltaics (OPVs). Usually, when one thinks of solar panels, the image that comes to mind is of a silicon-based panel: a big, rigid, heavy blue rectangle that is seen on rooftops. Unlike silicon panels, OPVs can be produced in various sizes, shapes, and colors. Their average weight is 500 g per square meter, whereas silicon panels weigh around 11 kg per square meter. OPVs also can be installed vertically or horizontally, as their dependency on the solar incidence angle is lower; this does not occur in the silicon ones, which have to be installed at a specific angle according to the local latitude. Additionally, OPVs are a semitransparent material, meaning they can be installed as insulfilms and retain heat, as they absorb the infrared and ultraviolet light spectra. These characteristics allow OPVs to be installed in windows and buildings. Beyond that, they are flexible, as shown in Figure 5, which reveals a wide range of applications.

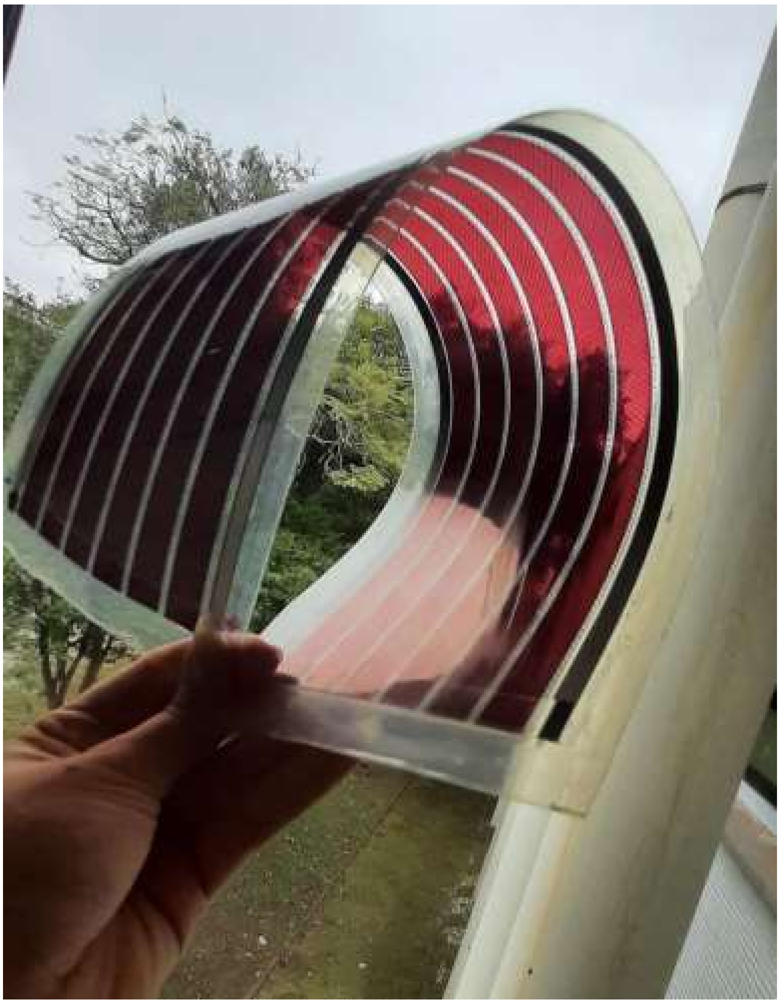

Figure 5: The flexibility of an OPV (picture from DiNE/UFPR)

The tubelike stations of Curitiba (State of Paraná, southern Brazil) are bus stations in a cylindrical shape, where the passenger can wait for their bus after an anticipated ticket payment; the stations offer weather protection, electric illumination, ease for wheelchair users, and level boarding.

Figure 6: Tubelike station in Curitiba [5].

The stations are separated by approximately 3 km on main lines; the city has a total of 357 stations. They are a city postal card and were highlighted in the Scientific American magazine in march of 1996 as an urban life quality advance, stamping its cover [6].
The tubelike stations are considered a city's historical patrimony; they were the first Brazilian product to receive an iF Design Award in 1992 [7]. However, it is not possible to add a silicon panel to them, as it would change their shape.

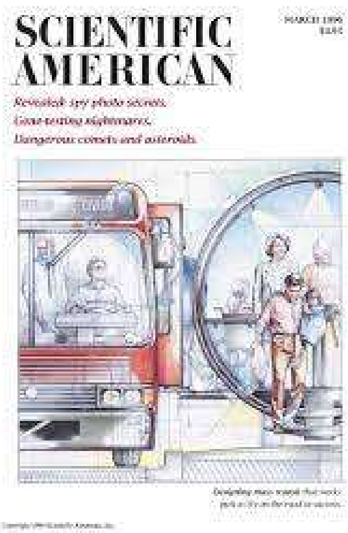

Figure 7: Scientific American magazine's cover, from March 1996, showing the tubelike stations of Curitiba [6].

In 2017, Abraão Assad, the architect who created the original project of the tubelike stations of Curitiba, which were first implemented in 1991, was hired by the (National Public Transport Association (ANTP) to revise the tubelike stations, so they would be closed, climatized, and energetically autonomous. This project includes the implementation of OPVs[8]. A thermal blanket—made of recycled PET bottles—lining, aiming for better thermal comfort is also an implementation goal.

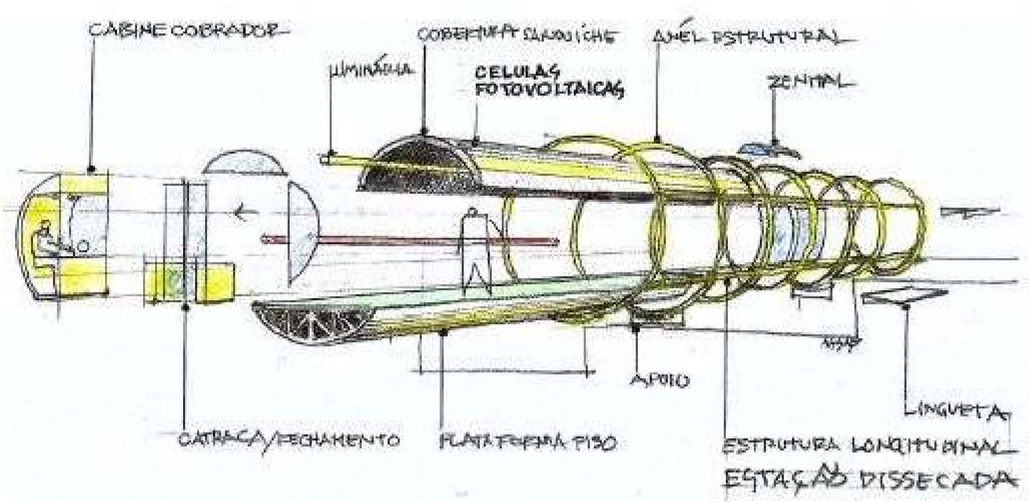

Figure 8 (a): Structural project of the new tubelike stations of Curitiba (Archive/ Abraão Assad).

Figure 8 (b): New stations' project in Curitiba's downtown (Archive/ Abraão Assad).

A station named *Estação de Pesquisa Tubo de Ensaio*' is used for studying organic solar panels in the tubelike stations of Curitiba [9]. It is located in the administration building parking lot of the polytechnic campus of the Federal University of Paraná. To apply solar panels in all the stations of the city, several influential factors must be well known in order to understand how the production of energy will variate throughout the year, such as the panels' degradation and their life expectancy, the replacement time of the OPVs in each station, the influence of shadowing over the panels, whether the application is useful in constantly shadowed stations, and the influence of the season.

Figure 9: *Estação de Pesquisa tubo de ensaio* station (Picture: Marcos Solivan)

This study's aim is to analyze the influence of degradation, shadowing, and seasons over the previous measures of Current and Voltage taken in the *Estação de Pesquisa Tubo de Ensaio* station.

MATERIALS AND METHODS

The main parameter for a photovoltaic cell performance characterization is its power conversion efficiency (PCE). This value is calculated by the ratio between the maximum power, given by the product of the current density (J) times the voltage (V), divided by the incident power, given by irradiance in W/m^2.

$$PCE = \frac{P_{max}}{P_{in}} = \frac{J \times V}{Irradiancia}$$

Another relevant parameter to be analyzed is the fill factor (FF). FF represents how close a device is to an ideal solar cell; it is given by the following equation:

$$FF = \frac{J_{max} \times V_{max}}{J_{SC} \times V_{OC}},$$

where J_{max} is the current density value when the power is maximized; V_{max} is the voltage value when the power is maximized; J_{SC} is the current density of the short circuit, given by current density when the voltage value is zero; and V_{oc} is the open circuit voltage, given by the voltage value when the current density is zero.

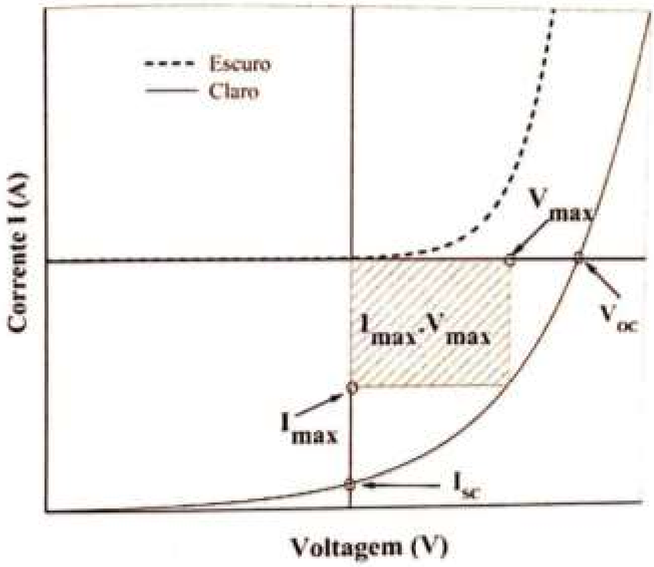

Figure 13: Graph of an I x V curve [10].

The *Estação de Pesquisa Tubo de Ensaio* has 28 organic Sunew solar cells, donated by Jchebly. The cells are organized in 14 sets of 2 by 2, and are connected in series. The IxV panel curve measures were previously taken by Talitha Canabarra, a Ph.D. student of the Nanostructured devices group of UFPR, during the development of her masters [11]. The complete data is also presented by Tempesta et al. [9].

To obtain the IxV curves, the high precision source Keysight B2901AⓇ was used. The active area of the panels is 7559.04 cm^2. For the irradiance measures, a digital portable luximeter PhyweⓇ was used; it provides the light intensity in klux, which is used to calculate the irradiance in W/m^2. The conversion factor was 1klux to 0,0079 W/m^2. All the graphs were developed in the program OriginPro 9.0Ⓡ.

As the measures were taken ahead of time, the dates were not equally distributed between seasons, as would be ideal for this analysis. The dates can be seen in Table 1.

Table 1: Previously made measures dates, distributed between seasons. (DD/MM/YYYY)

SUMMER	AUTUMN	WINTER	SPRING
	12/04/2018	31/08/2018	10/10/2019
	19/05/2020	12/09/2019	25/10/2019
	29/05/2020		30/11/2018
			05/12/2018
			11/12/2019
			06/11/2020

For the analysis, eight dates in which measurements occurred were selected, in a way that irradiances and temperatures can represent each of the seasons. For each season, two dates were selected: a recent and an old one, in a way that it is also possible to analyze the panels' degradation through time. Furthermore, two panel sets were selected: 2 and 14. This selection happened in a way that makes it possible to analyze the effect of the shadowing of the surrounding trees due to the lower solar incidence angle during winter in set 14. The selected dates for each season, its irradiances, and temperatures can be seen in Table 2.

Table 2: Selected dates for analyzes, and their irradiances and temperatures. (DD/MM/YYYY)

Season	Date (DD/MM/YYYY)	Irradiance (W/m^2)	T (ºC)	Date 2	Irradiance (W/m^2)	T (ºC)
Summer	05/12/2018	361.8	26	11/12/2019	357.7	24.5
Autumn	12/04/2019	309.5	28	19/05/2020	329.6	22
Winter	31/08/2018	229.1	21	29/05/2020	333.7	23
Spring	30/11/2018	381.9	25	06/11/2020	360.0	24

RESULTS AND DISCUSSION

The PCE and FF of panel sets 2 and 14 were calculated using the IxV calculus. The resulting data can be seen in Tables 3 and 4.

Table 3: Calculated values of FF and PCE for OPVs set 2. (DD/MM/YYYY)

OPV2	Date (DD/MM/YYYY)	PCE	FF	Date 2	PCE	FF
Summer	05/12/2018	2.63	46.67	11/12/2019	0.98	23.17
Autumn	12/04/2019	1.69	48.65	19/05/2020	0.06	23.59
Winter	31/08/2018	1.76	44.05	29/05/2020	0.03	24.84
Spring	30/11/2018	2.71	50.27	06/11/2020	0.29	18.13

Table 4: Calculated values of FF and PCE for OPVs set 14. (DD/MM/YYYY)

OPV14	Date (DD/MM/YYYY)	PCE	FF	Date 2	PCE	FF
Summer	05/12/2018	299	59.46	11/12/2019	1.16	26.58
Autumn	12/04/2019	2.15	49.46	19/05/2020	0.04	24.41
Winter	31/08/2018	0.39	34.21	29/05/2020	0.04	24.57
Spring	30/11/2018	2.91	64.38	06/11/2020	0.47	21.48

Considering the calculated data, it is possible to observe the degradation of the panels through the two years. For the OPVs set 2, the efficiency became 11.03% of the highest obtained efficiency value. It also achieved 1.14% of the highest measured efficiency. Similarly, in OPVs set 14, the final efficiency was 15.72% of the initial efficiency, and 1.34% was the lowest measured value.

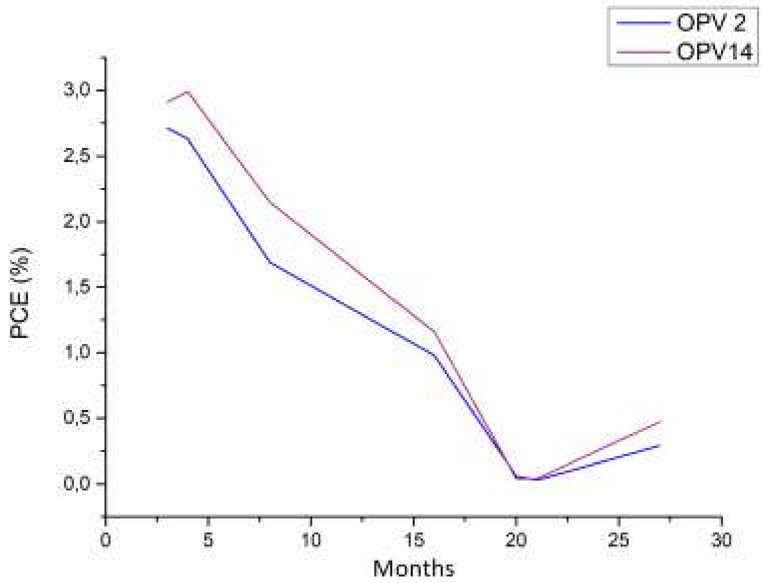

Figure 14: Graph of PCE by month since the first measure.

Set 2 had a lower degradation rate than set 14. This may be due to the higher amount of shadows in set 14 because, with direct irradiation, the metal of the station could reach a higher temperature than set 2. As one of the main factors listed in the literature as influential for organic solar cells is temperature, shadowing might have helped to preserve set 14. To support this hypothesis, measures of the station metal temperatures were taken sporadically, in highest solar incidence days. The values reached 58ºC. In W.R. Mateker's review article, M. D. McGehee, in the reference magazine Advanced Science News [11], pointed out that temperatures between 50 and 65ºC can influence organic solar cell degradation.

In our results, it is possible to see that there is a decrease between the summer and autumn parameters and between the autumn and winter ones, as well as a light increase between the parameters of autumn and summer. The winter PCE values in set 14 are significantly lower than set 2, which can be due to the lower angle of solar incidence during winter. In this case, it creates shadowing in set 14 due to the high trees in the surroundings. Figure 15 presents the variation of PCE compared to the previous season for each set of dates.

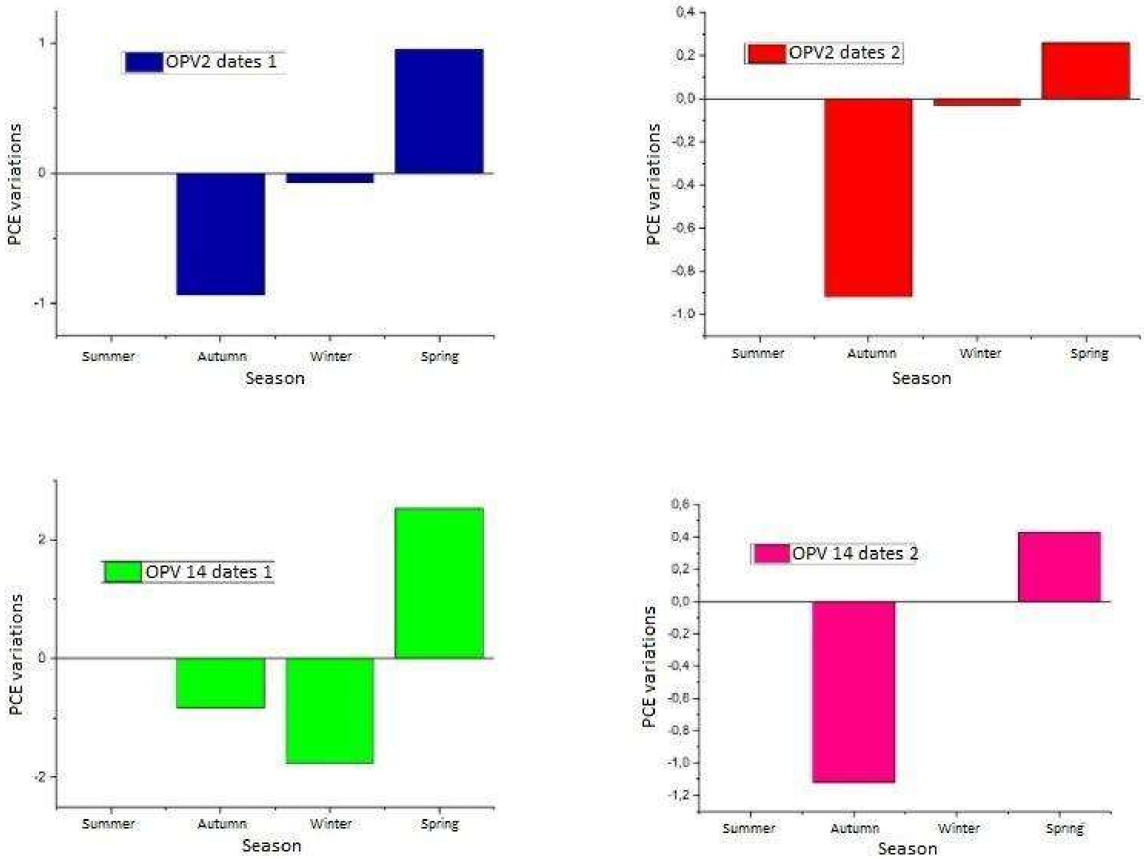

Figure 15: Graph presenting PCE variations of the set in each season, compared to the previous one.

Every graph in Figure 15 follows a pattern: all the relative PCE values decrease between autumn and winter and increase by the spring arrival. This shows that the seasons—through its temperatures, irradiation, and sun inclination patterns—influence the power conversion efficiency of an organic solar cell.

CONCLUSION

Through our analysis, it was possible to conclude that set 14 had a lower degradation rate than set 2, and presented higher efficiency during winter. This might be due to the higher shadowing in set 14 in winter, which may cause thermal control in the metal in which the panels are installed, preventing its degradation. Beyond that, it was possible to see the variation in efficiency of the panels throughout the year due to the change in seasons: the value of its efficiency decreases between autumn and winter, and increases with the coming spring, when it is at its highest solar irradiation level.

Future work could explore the IxV curves in constant gaps throughout the year to analyze the half lifetime of the organic dollar cells in these conditions, and also take specific measures when the difference between the shadowing is at its highest, such as the light intensities in the two areas. It could also be beneficial to track the temperatures of different station parts in order to confirm if set 2 is actually exposed to the highest temperature for a longer time then set 14.

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