Comparison of Different Photovoltaic Nanocells

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***Abstract*—Renewable energies for producing energy for self-consumption are growing, namely solar energy. This work focuses on the comparison of photovoltaic systems for energy production for self-consumption on a property, in three different regions of Portugal, using traditional and emerging technologies, without batteries' implementation. According to Portuguese Law, there is no stipulated value for selling the surplus energy produced by a Self Consumption Unit (UPAC), to the Public Grid (RESP). In order to analyse the economic viability of the project, two scenarios are studied: the delivery, at zero cost, of the surplus energy produced to the RESP, and its sale. Furthermore, the same analysis is carried out considering partial shading on the photovoltaic generator. The results show that, if there is no surplus production sale to RESP, the project becomes not economically viable for the four PV technologies. Otherwise, for the traditional technologies, the project is economically viable presenting a payback time (PR), lower than 10 years. When applying partial shading on the generator, the project becomes, in all the scenarios under study, not economically viable. It can be concluded that the introduction of nanostructures in solar cells to power an infrastructure is not, for now, the best solution from an economic point of view, taking into account the current legislation. In addition, the shading makes the projects under study not viable, as it is a factor that cannot be controlled in its entirety.**

***Index Terms*—economic analysis, nanostructures, photovoltaic technology, shading, solar energy, viability**

I. INTRODUCTION

Since the 1970s, the concern with the environment has become a topic of special attention. Economic development, associated with the accelerated growth of industrialisation and the increasing of the world population, led into rising in the use of natural resources in an unlimited way, which proved to be unsustainable. Over the years, the growth of the CO_2 concentration levels has been exponential, which contributed to the intensification of global warming. During the second decade of the XXI century, the annual global greenhouse gas emissions average reached its highest value and, consequently, the global average temperature was at its highest level ever [1]. In terms of global environmental points, it is, in fact, a significant alarming factor. So, the transition to a cleaner energy model is urgent in order to minimise greenhouses gas emissions, and it can be done by using renewable energy sources [2]. This type of energy contributes to the economic development of each country, has a lower environmental impact and it's a never-ending source, having another record-breaking year in 2021 [3]. Also in 2021, solar energy reached its peak and it is considered one of the most important renewable sources. It has huge power and if the Sun's energy would be daily harvested, the Earth's energy needs would be ensured for one year [4], [5].

The photovoltaic effect was discovered in 1839 by Alexandre Edmond Becquerel, but only in 1954, a silicon semiconductor cell was developed by Bell Labs, whose efficiency was improved in the following years [6], [7]. Due to several factors, like different materials used and different techniques employed, solar cells have been grouped into several generations over the years [2]. Recently, nanotechnologies have demonstrated amazing results in new devices, and the third photovoltaic generation joins nanotechnologies with solar technologies, in order to have solar cells with higher efficiencies. The introduction of nanostructures in solar cells, as Quantum-Dots (QDs) and Nanowires (NWs), allows the control of the band gap due to their small size, providing flexibility in charge recombination and the radiation confinement. [7].

In our daily life, traditional technologies, i.e., first and second's generations solar cells, are commonly used, but the emerging technologies that use nanostructures are not applied, by now, in particular, if talking about buildings, that generate power for self consumption, contributing to a more sustainable world. Portugal is one of the European countries that has the most sunlight hours per year and is, therefore. one of the most favourable places for the introduction of photovoltaic generators to produce energy for self consumption. However, obviously, this represents an economic investment that most people are not willing to make and, this is, in fact, where the decision to invest in energy renewable systems for self consumption starts. Nowadays, The Portuguese law does not define a reference value for the sale of the surplus energy produced in self consumption to the RESP, being up to the parties involved in an agreement regarding the value to be practised. Therefore, governments have an important role in taking measures to encourage investment in renewable sources.

II. LITERATURE REVIEW

In the last decades, the development of the technologies behind solar cells has been remarkable, evolving into three technological generations of various semiconductor materials and different architectures [6], [8]. Besides, the reduction in production costs, combined with the reduction of operation and maintenance costs and, at the same time, efficiency increase is one of the priorities in the photovoltaic industry.

The first generation photovoltaic cells (GI) concerns crystalline silicon structures (c-Si) widely used, so far, and have higher efficiency. These types of cells are dominating the technology market, since silicon is abundant material on Earth, with a non-toxic manufacturing process, presenting a study basis for over 50 years of longevity, performance, and reliability [9]. Chapin *et al.* developed the first silicon solar cell in 1954, with an efficiency of 6% [7], [10] and, currently, this value is 26.1% [2], due to the application of a pulsed UV laser, leading to a saturation current density of 6 fAcm^{-2} and an open circuit voltage of about 727 mV [11]. The second generation photovoltaic cells (GII) is based on thin-film technologies, like CIGS solar cells. This photovoltaic generation presents lower production costs, but its efficiency is not as high as GI's [2], [6]–[8], [12]. In 1976, the first CIGS solar cell was developed by Kazmerski *et al.* with an efficiency of 4.5% [13] and, in 2019, it was reported a maximum efficiency value of 23.4%, due to the replacement of conventional CdS buffer layers with the double buffer layer of Zn [14]. In 2016, a reduction of the levelized cost of electricity associated with PV energy to €0.03/kWh by 2030 was set as a goal and, in 2020, PV systems were benchmarked of €0.05/kWh [15]. For the goal to be achieved, one of the key points is the minimum sustainable cost associated with solar modules. In 2019, crystalline silicon technologies showed a cost of around €0.25-€0.27/W and CIGS a cost of €0.48/W. The high value associated with CIGS is largely due to the costs associated with labour and equipment.

The third generation photovoltaic cells (GIII) cover solar technologies that are still emerging, using other materials. In addition, some of these cells enjoy their small dimensions in order to increase solar efficiencies, like Nanowires (NWs) and Quantum-Dots (QDs). These cells are capable of tuning the band gap energies with composition changes [2], [6]–[8], [12]. In the literature, it was demonstrated higher efficiencies of 18.9%, since c-Si photovoltaic modules were found to perform best with the application of NWs, and, with localised back contact, being the current density reached of 34 mA/cm^2. This result is explained by the reflectance spectral of the module surface varying with the length of the structure [16]. QDs, whose active layer is composed of PbS, are pointed out as the best solar cells developed, since the band gap can be tuned to infrared frequencies, which represents more than half of the solar spectrum, being able to absorb most of the energy coming from the Sun [13], [17], [18].

A photovoltaic generator is composed of photovoltaic modules, solar inverters, batteries, cables and protection devices. The solar modules have the best lifetime of 20-30 years [19], while the solar inverters' lifetime is lower than 15 years [20] and the batteries' is 3-5 years [21]. The temperature is one of the parameters that can change the performance of the photovoltaic modules as well as the irradiance [2], [22]. Because of the exposure of the photovoltaic generator to nature, and due to the dust and small particles and leaves, the shading effect occurs, which leads to a decrease in energy production. The use of protections, like bypass diodes, is one way to minimise the shading effect. These diodes are connected in parallel and reversed biased and, when one cell/group of cells are shadowed, the bypass diode will conduct, providing an alternative path for the current flow. These diodes are extremely important in big photovoltaic generators since they contribute to a slower degradation time of the cells [2].

III. METHODOLOGY

A. Solar Cells

The solar cells under analysis are represented using the simplest model, the 1M3P. The output current, I, as a function of the output voltage, V, is obtained by [2]

$$I = I_{pv} - I_o \left(e^{\frac{V}{bV_T}} - 1 \right), \tag{1}$$

being I_{pv} the photogenerated current, b the junction non-ideality factor, I_o the reverse saturation current of the p-n junction and V_T the thermal voltage described by equation 2, where T is a certain temperature, k the Boltzmann's constant and q the module of the electron charge.

$$V_T = \frac{kT}{q} \tag{2}$$

The output power, P is obtained by multiplying the output voltage, V, with the output current, I. The maximum power that the solar cell is capable of producing is called maximum power point (MPP), which corresponds, from a mathematical point of view, to the point where the partial derivative of the power P in order to V is zero. The 1M3P model is characterised by three parameters (I_{pv}, b, I_o), that vary with temperature and irradiance as follows [2]:

1) The junction non-ideality factor remains unchanged, such that $b = b^r$;
2) The reverse saturation current of the p-n junction I_o varies only with temperature, through

$$I_o(T) = I_o^r \left(\frac{T}{T^r} \right)^3 e^{\frac{E_g}{b}} \left(\frac{1}{V_T^r} - \frac{1}{V_T(T)} \right), \tag{3}$$

where E_g is the band gap energy of the cell material;

3) The photogenerated current varies only with irradiance and is described by

$$I_{pv}(G) = \frac{G}{G^r} I_{pv}^r. \tag{4}$$

Applying the equation 1, based on the above assumptions, it is possible to obtain the characteristic curves of the solar cell.

B. Solar PV

Assuming that all cells of a solar PV are equal, having the same performance, it's possible to create an association of z cells based on electrical models. Consider an association of $m \times n$ solar cells, the PV total current, voltage and power can be given by equations 5, 6 and 7, respectively [2].

$$I^{\text{panel}} = n \times I^{\text{cell}} \tag{5}$$

$$V^{\text{panel}} = m \times V^{\text{cell}} \tag{6}$$

$$P^{\text{panel}} = z \times P^{\text{cell}} = (m \times n) \times P^{\text{cell}} \tag{7}$$

C. Residential Property Assessment

Two parameters in the infrastructure need to be assessed: the area available for the placement of solar panels and the amount of solar radiation in a given time interval, per square meter of surface. The Autodesk Revit 2022 ® programme was used for this purpose, through Insight Solar tool, running a custom study of cumulative insolation. Changing the residential property's location, external conditions like temperature and irradiance change as well, which changes, for better or worse, the PVs' performance. Therefore, the study of changing the property's location was carried out to analyse the economic factors and the viability of the project depending on its location. External conditions data at each place were obtained through the PVGIS tool [23], which corresponds to the latest one.

1) Load Sizing: The monthly average consumption for the period under analysis is obtained by consulting the electricity bills. From here, an algorithm that evaluates the consumption of the load was developed, throughout the day of each month. The minimum operating interval of each load was considered to be of 15 minutes. In addition, throughout each month, the load distribution all over the day varies similarly on two types of days, working and nonworking days. This means that each month is represented by only two significant days that repeat themselves x times during the month.

D. Photovoltaic System Sizing

Consider a photovoltaic generator with Z panels, with M connected in series and N connected in parallel. Equations 5, 6 and 7 are valid, but now for the generator as follows:

$$I^{DC} = N \times I^{\text{panel}} \tag{8}$$

$$V^{DC} = M \times V^{\text{panel}} \tag{9}$$

$$P^{DC} = Z \times P^{\text{panel}} = (M \times N) \times P^{\text{panel}} \tag{10}$$

1) Inverter: The correct inverter sizing has to fulfil the condition 11, where P^{DC}_{MPP} corresponds to the maximum DC power provided by the generator, in the worst conditions, i.e., for the minimum irradiance and maximum temperature [24].

$$0.7P^{\text{DC}}_{MPP} < P^{\text{inv}}_{n} < 1.2P^{\text{DC}}_{MPP} \tag{11}$$

The inverter is characterised by a maximum input voltage, V^{inv}_{max}, a minimum input voltage, V^{inv}_{min} and a maximum input current, I^{inv}_{max}. Since we have M and N panels connected in series and parallel, respectively, these variables have to fulfil the conditions 12, 13 and 14 [24]. Regarding the output variables, it's important to verify the grid frequency and the grid voltage, which are 50 Hz and 230/400 V, in Portugal.

$$V^{\text{inv}}_{max} > M \cdot V^{\text{panel}}_{oc}(G_{max}, T_{min}) \tag{12}$$

$$V^{\text{inv}}_{min} < M \cdot V^{\text{panel}}_{MPP}(G_{min}, T_{max}) \tag{13}$$

$$I^{\text{inv}}_{max} > N \cdot I^{\text{panel}}_{n} \tag{14}$$

2) DC Sizing:

- Row Cable
  This cable will connect the M panels in series. The maximum cable current, I_z, has to fulfil the condition 15.

$$I_z \geq 1.25I^{\text{panel}}_{sc}(G_{min}, T_{max}) \tag{15}$$

  The maximum cable length and the cable cross section must be chosen taking into account that power losses, across each row, must be lower than 1%. The cable cross section must be chosen according to equation 15 and the maximum cable length is computed through equation 16.

$$L_{max} = 0.01 \times \frac{M \cdot V^{\text{panel}}_{oc}(G_{max}, T_{min}) \cdot N \cdot I^{\text{panel}}_{n} \cdot \sigma \cdot s}{2I^{\text{panel}^2}_{n}} \tag{16}$$

- Fuses
  Fuses must be sized considering the nominal current of the series connection, in order to protect the row's cable against overcurrents. Fuses' rated current, I^{fus}_{n}, has to be higher in 25% of the rated row current, and lower than the fuse's breaking capacity, which cannot be higher in 15% of the maximum cable current - condition 17.

$$1.25I^{\text{panel}}_{n} \leq I_z \leq 1.15I_z, \tag{17}$$

- Main DC Cable
  This cable connects the N rows to the inverter. The maximum cable current, I_z, has to verify the condition 18.

$$I^{\text{Main Cable}}_{z} \geq 1.25I^{\text{panel}}_{n} \tag{18}$$

  As in the Row Cable, the power losses have to be lower than 1%. The cable cross section must be chosen according to equation 18 and the maximum cable length is computed through equation 19.

$$L^{\text{Main Cable}}_{max} = 0.01 \times \frac{M \cdot N \cdot P^{\text{panel}}_{MPP} \cdot \sigma}{2\left(N \cdot I^{\text{panel}}_{n}\right)^2} \tag{19}$$

Once the system has been sized, as well as cables and DC protection devices for each type of photovoltaic technology under analysis in the different locations, the energy generation curves can be obtained. These curves consider both the temperature and the irradiance of the place for each time interval. As each month is analysed taking into account two significant days - working and nonworking days - both variables are averaged for the respective days under analysis of each month. With this data, the I-V and P-V curves of the generator are get for the different temperatures and irradiances, so the points at which the maximum DC power occurs are obtained, which corresponds to a vector of ϵ positions. Although this vector shows the maximum power values of the generator curves, considering inverter's sizing, it is necessary to verify that these power values, as well as the voltage ones, are within the operating voltage ranges of the inverter. Finally, the maximum AC power generated is obtained by multiplying the maximum

DC power and the inverter's efficiency. In sum, two AC generation curves are obtained for each month, one for each significant day under analysis, and this scenario is repeated for each technology and each location under study.

E. Shading

The partial or total shading effect on the generator influences its performance, which needs to be tested and taken into consideration.

Over a one-year analysis, the shading effect was simulated using the Autodesk Revit 2022 ® programme. The first step is to measure the area of the infrastructure cover for the implementation of the generator that ends up in shadow, and then it is possible to evaluate which part of the generator is in shadow. This will make it possible to check when the protections of each module act so that a certain current flows in each module, thus achieving the system voltage.

F. Financial Indicators for Project Evaluation

In order to evaluate the economic viability, it is necessary to determine some financial indicators like the present value of future cash flows, which is done through the real discount rate, a_r, if it is assumed that the analysis will be done at constant cost values. The Net Present Value (VAL) represents the difference between the present value of cash inflows and the present value of cash outflows up to date, over a time period, which is computed through equation 20 [2], where I_0 is the initial investment, considered to be done in year 0, and R_t is the revenue in the year t.

$$VAL = \sum_{t=1}^{n} \frac{R_t}{(1+a_r)^t} - I_0 \tag{20}$$

The Payback Period (PR) is the times it takes to recover the cost of an investment and can be computed through equation 21, where A is the last year with a negative cumulative cash flow, B is the absolute value of cumulative cash inflow at the end of year A, and C is the total cash flow during the year A+1. The smaller the PR, the better for the investor.

$$PR = A + \frac{B}{C} \tag{21}$$

The financial factors can be evaluated from two different perspectives: if the surplus is sold to the RESP and, therefore, there is a benefit for the investor, and if there is no sale to the RESP. In the first case, consider the selling price to the grid of the surplus energy to be the value of its purchase price.

To achieve the best viability and the best generator in the first year, an optimisation algorithm was developed. The first constraint of this algorithm is the area occupied by the generator, which has to be lower than the available area. The second one is related to viability, which means that the generated power must be higher than the consumed power, in each time interval. The better the viability of the generator, the better the PV system will be able to cope the load. The third and last constraint is the number of properties, with the same consumption, that the generator can cover, always bearing in mind that the goal is to achieve the best project viability. The optimisation algorithm was applied to all locations under study, for all technologies under analysis and also for the cases of selling, or not, the surplus to the grid.

IV. RESULTS

A. Solar Cells

Consider four different types of solar cells, whose parameters, under STC conditions, are presented in Table I. In what concerns the traditional technologies, c-Si and CIGS solar cells with higher efficiency registered by NREL [25] were analysed. It's important to notice that these cells are laboratory-tested cells, so their parameters have ideal values due to the simulation conditions.

TABLE I: Solar cells' parameters @STC (AM1.5, 1000 W/m^2, 25° C).

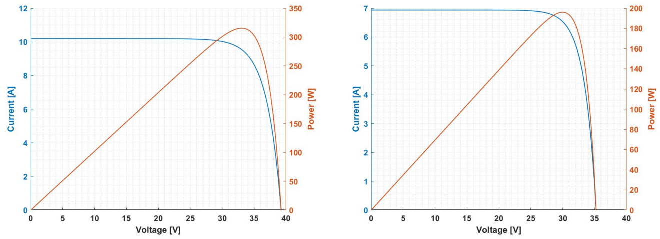
Solar Cell	Area [cm^2]	J_{sc} [mA/cm^2]	V_{oc} [mV]	E_g [eV]	FF [%]	η [%]	Ref.
c-Si	3.986	42.620	726.6	1.121	84.280	26.100	[11]
CIGS	1.043	39.600	734.000	1.080	80.400	23.350	[14]
c-Si NWs	1.000	39.500	608.000	1.121	78.700	18.900	[16]
CsPbI$_3$ QDs	0.058	15.246	1162.600	1.750	76.630	13.430	[26]

B. Solar PV

Consider four different types of solar panels, each one with z solar cells, whose parameters are presented in Table II. Figure 1 shows the characteristics curves of the solar panels.

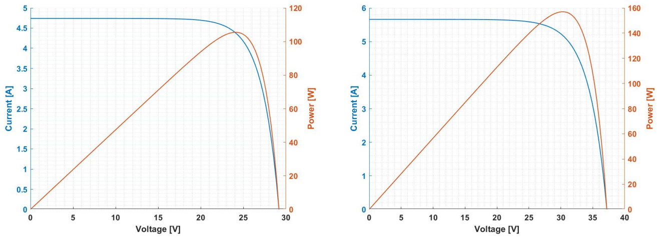
TABLE II: Solar panels' parameters @STC (AM1.5, 1000 W/m^2, 25° C).

Solar Panel	z cells	Area [m^2]	I_{sc} [A]	V_{oc} [V]	P_{MPP} [W]	I_{MPP} [A]	V_{MPP} [V]	η [%]
c-Si	3240	1.291	10.192	39.236	315.536	9.550	33.041	24.430
CIGS	8064	0.841	6.939	35.232	196.094	6.560	29.894	23.310
c-Si NWs	5760	0.576	4.740	29.184	105.505	4.403	23.962	18.320
CsPbI$_3$ QDs	204800	1.188	5.660	37.203	156.980	5.206	30.154	13.220



(a) c-Si.

(b) CIGS.



(c) c-Si NWs.

(d) CsPbI$_3$ QDs.

Fig. 1: Solar panels' characteristics curves.

C. Residential Property Analysis

The infrastructure under analysis is a residential and is in Santa Iria de Azoia. Castro Verde and Vila Real are other locations to be studied, in order to evaluate the photovoltaic system performance. The simulation results are shown in Figure 2. The colour coding shows that the part of the roof with the most Sun exposure is the one facing south. However, the existence of the window on the top floor of the property ends up causing some shadow and, in addition, the available area for the placement of solar panels decreases. In the remaining locations, the simulation results match the colour coding of Figure 2 and, therefore, it was chosen the east-facing roof, which corresponds to the second part of the roof with greater solar exposure. The available useful roof area is 50.8068 m^2.

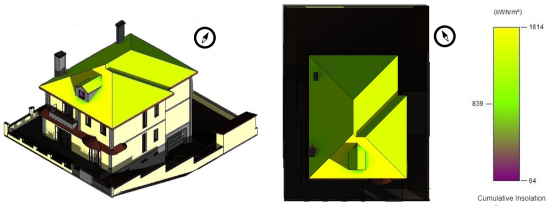
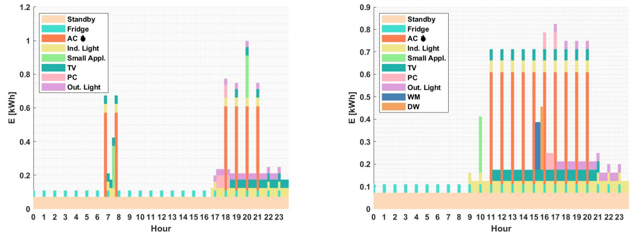


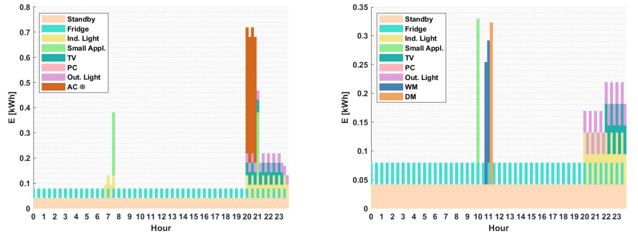
Fig. 2: Simulation results: 2021's annual cumulative insolation.

1) *Load Sizing:*

2021's electricity bills show january and august as the highest and lowest consumption months, with 540 kWh and 313 kWh of consumption, respectively. Considering 15 minutes as the minimum operation time of each load, the daily load profile on working and nonworking days in the months under analysis, are shown in Figure 3. These profiles correspond to an average of the daily profile of consumption on each type of day per month, which leads to the monthly consumption that is presented in the electricity bills.



(a) January: working day. (b) January: nonworking day.



(c) August: working day. (d) August: nonworking day.

Fig. 3: Daily load profile, in each time interval.

D. Photovoltaic System Sizing

For the three locations, the photovoltaic system sizing is carried out. The optimisation algorithm presents, as the best solution, the generators whose data are inserted in Table III. For these generators, the characteristics of the inverters chosen must comply with the values shown in Table IV and, in order to avoid electrical problems, the cables and protection devices shall correspond to the values shown in Table V.

TABLE III: Photovoltaic System Sizing for the three places.

	M	**N**	**Area occupied by generator [m^2]**	**Number of Properties**
c-Si	9	4	46.489	1
CIGS	10	6	50.464	1
c-Si NWs	9	9	46.656	1
CsPbI$_3$ QDs	7	6	49.889	1

TABLE IV: Inverter characteristics.

		P_n^{inv} [kW]	V_{min}^{inv} [V]	V_{max}^{inv} [V]	I_{max}^{inv} [A]
Santa Iria de Azoia	**c-Si**	[9,622; 16,495]	$]-\infty; 167]$	$[373; +\infty[$	$[41; +\infty[$
	CIGS	[9,883; 16,942]	$]-\infty; 180]$	$[370; +\infty[$	$[42; +\infty[$
	c-Si NWs	[7,456; 12,782]	$]-\infty; 102]$	$[284; +\infty[$	$[43; +\infty[$
	CsPbI$_3$ QDs	[5,631; 9,653]	$]-\infty; 91]$	$[276; +\infty[$	$[34; +\infty[$
Castro Verde	**c-Si**	[9,855; 16,894]	$]-\infty; 160]$	$[376; +\infty[$	$[41; +\infty[$
	CIGS	[10,111; 17,334]	$]-\infty; 174]$	$[372; +\infty[$	$[42; +\infty[$
	c-Si NWs	[7,670; 13,148]	$]-\infty; 96]$	$[287; +\infty[$	$[43; +\infty[$
	CsPbI$_3$ QDs	[5,775; 9,899]	$]-\infty; 86]$	$[278; +\infty[$	$[34; +\infty[$
Vila Real	**c-Si**	[9,991; 17,127]	$]-\infty; 169]$	$[379; +\infty[$	$[41; +\infty[$
	CIGS	[10,237; 17,550]	$]-\infty; 181]$	$[375; +\infty[$	$[42; +\infty[$
	c-Si NWs	[7,816; 13,3993]	$]-\infty; 103]$	$[290; +\infty[$	$[43; +\infty[$
	CsPbI$_3$ QDs	[5,861; 10,048]	$]-\infty; 92]$	$[281; +\infty[$	$[34; +\infty[$

Note that the inverter efficiency value used was 98%.

TABLE V: DC Sizing.

		Row Cable			**Fuses**	**Main DC Cable**		
		I_z [A]	s [mm^2]	L_{max} [m]	I_z [A]	I_z [A]	s [mm^2]	L_{max} [m]
Santa Iria de Azoia	**c-Si**	14.303	2.5	25.572	16	25.480	6	22.963
	CIGS	9.737	2.5	37.249	10	26.021	6	22.807
	c-Si NWs	6.65	2.5	41.819	6	26.662	10	26.297
	CsPbI$_3$ QDs	7.94	2.5	34.058	8	21.222	10	32.022
Castro Verde	**c-Si**	14.492	2.5	25.767	16	25.480	6	22.963
	CIGS	9.866	2.5	37.501	10	26.021	6	22.807
	c-Si NWs	6.740	2.5	42.272	6	26.662	10	26.297
	CsPbI$_3$ QDs	8.047	2.5	34.328	8	21.222	10	32.022
Vila Real	**c-Si**	14.504	2.5	26.001	16	25.480	6	22.963
	CIGS	9.875	2.5	37.802	10	26.021	6	22.807
	c-Si NWs	6.745	2.5	42.823	6	26.662	10	26.297
	CsPbI$_3$ QDs	8.054	2.5	34.643	8	21.222	10	32.022

E. Shading

Figure 4 presents the result of the simulation of the shading effect on infrastructure roof, during one year of analysis. The area outlined in yellow corresponds to the useful area of the roof that is not affected by annual shading and, the zone delimited in blue, due to its reduced area, will not affect the generator. Due to the limitations of the Autodesk Revit 2022 ® programme, the area outlined in yellow is 12 m^2, which corresponds to an approximated value.

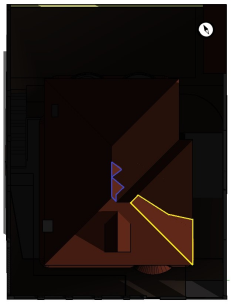
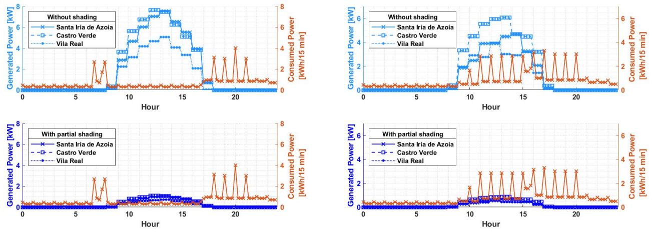
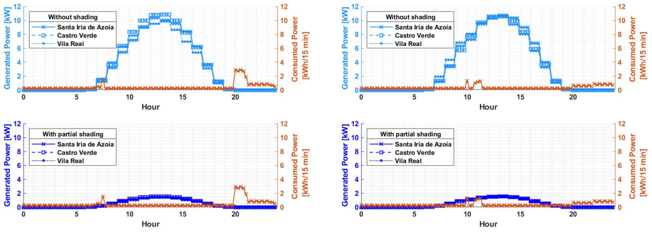


Fig. 4: Simulation result of the shading effect.

The optimised generators, whose data are shown in Table III, when the shading effect occurs, a decrease from 13% to 17.5% at the production level, at STC conditions, occurs as well, depending on the technologies used. Following the methodology presented in section III-D, the consumption-generation curves for two significant days of the extreme consumption months, with and without the application of partial shading, are presented from Figure 5 to Figure 8. The aim is to present the curves in a qualitative and visual way, abstracting from the quantitative values. In this way, it is possible to analyse, in each time interval, whether, or not, the load is covered by the generator under study. The consumption curves correspond to the profiles shown in Figure 3.

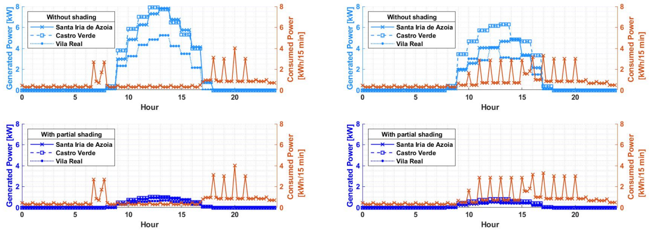


(a) January: working day. (b) January: nonworking day.

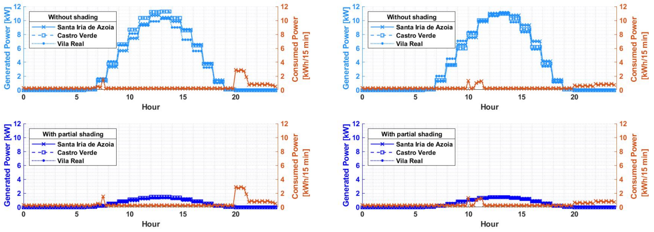


(c) August: working day. (d) August: nonworking day.

Fig. 5: Generation and consumption curves for c-Si modules.

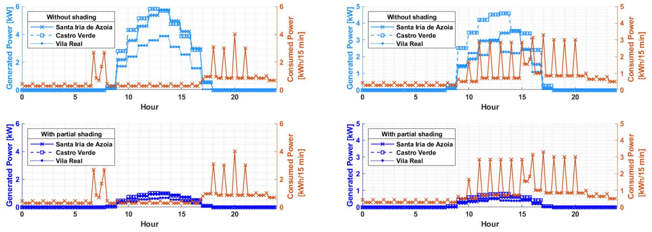


(a) January: working day. (b) January: nonworking day.

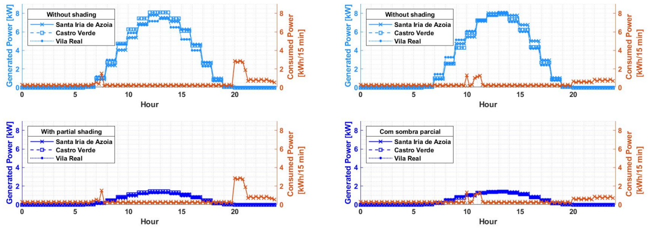


(c) August: working day. (d) August: nonworking day.

Fig. 6: Generation and consumption curves for CIGS modules.



(a) January: working day. (b) January: nonworking day.



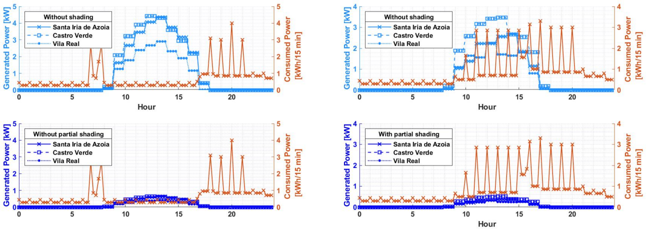
(c) August: working day. (d) August: nonworking day.

Fig. 7: Generation and consumption curves for c-Si NWs modules.

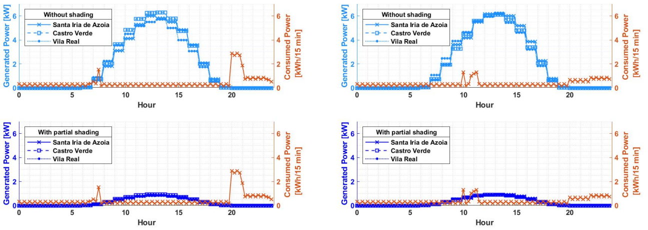
Note there is a discrepancy in production by the system according to the place under study, due to atmospheric conditions, which allow, for better or worse, the performance of solar technologies, and the maximum production of the generator with the use of modules from emerging technologies is lower than its maximum production when traditional technologies are used. Also, the generation curves with partial shading present lower values when compared with the generation curves without the shading effect and, in addition, in some instants, and according to the technology under analysis, the generation curve is not able to cope the load.

F. Financial Indicators for Project Evaluation

Table VI shows the parameters required to calculate the annual cash flows. The values of the tariff and contracted power are the values shown in the monthly electricity bills of the infrastructure, and the contracted tariff presented here corresponds to the simple tariff. In what concerns the real discount rate, a_r, in Portugal, its value is considered to be 6.1%. For solar nanotechnologies, the value used for the module degradation factor corresponds to the value of the



(a) January: working day.
(b) January: nonworking day.



(c) August: working day.
(d) August: nonworking day.

Fig. 8: Generation and consumption curves for $CsPbI_3$ QDs modules.

CIGS module degradation rate, in order to obtain results in the best situations. Table VII presents the initial investment values, I_0, for each generator under study.

TABLE VI: Input parameters for cash flow computation.

	Eff. Degradation Rate [%/year] [27]	**RDR [%]** [28]	**VAT [%]**	**Cont. Tariff [€/kWh]**	**Cont. Power [€/day]**	**Deprec. [%/year]**	**O&M Costs [€/kW/year]** [29]
c-Si	0.64	6.1	23	0.1441	0.6027	4	16.76
CIGS							
c-Si NWs	0.96						
$CsPbI_3$ QDs							

TABLE VII: Initial investment for different photovoltaic generators, using different technologies.

	c-Si	**CIGS**	**c-Si NWs**	**$CsPbI_3$ QDs**
I_0 [€]	8088.118	12398.863	14056.454	10800.134

The financial indicators were obtained using an analysis time period of 1000 years. The optimised results for the scenario without shading effect of the financial factors are presented in Table VIII and, in addition, the viability in the first year of analysis, and the year in which viability is null, is presented. In practice, it corresponds to the year that there is no time interval in which production is greater than consumption. For the case with partial shading, the results are in Table IX.

For all three places, and considering partial shading or its nonexistence, if there is no sale of the surplus to the RESP, the PR is presented as being infinite (∞). This means that in the period under analysis, there was no recovery of the initial investment. It is important to point out that if the PR did not occur until the year in which zero viability is verified, it will not occur anymore. It is important to note that this analysis period can be changed and the same algorithm can be put into practice, since it is prepared for eventual changes by the user.

TABLE VIII: Financial Indicators in the three locations under analysis, where the values highlighted in green correspond to those with a PR of less than 10 years.

		Without selling to the RESP		**With selling to the RESP**		**Viability in 1^{st} year [%]**	**Year of zero viability**
		VAL [€]	PR [years]	VAL [€]	PR [years]		
Santa Iria de Azoia	**c-Si**	-25902.288	∞	19588.346	4.434	44.178	647
	CIGS	-33167.066	∞	11811.527	6.858	44.238	435
	c-Si NWs	-35521.716	∞	-5353.050	20.743	43.188	402
	$CsPbI_3$ QDs	-30079.375	∞	-9001.194	∞	42.158	375
Castro Verde	**c-Si**	-25926.163	∞	23145.022	3.968	44.481	650
	CIGS	-33149.910	∞	15364.535	6.059	45.088	437
	c-Si NWs	-35414.614	∞	-2891.284	15.927	43.467	403
	$CsPbI_3$ QDs	-29963.774	∞	-7033.547	∞	42.529	377
Vila Real	**c-Si**	-26136.880	∞	15899.477	5.049	43.898	650
	CIGS	-33408.105	∞	8124.153	7.955	43.993	436
	c-Si NWs	-35830.063	∞	-7890.932	∞	42.760	403
	$CsPbI_3$ QDs	-30510.232	∞	-11029.577	∞	41.104	376

TABLE IX: Financial Indicators in the three locations under analysis, with partial shading applied.

		Without selling to the RESP		**With selling to the RESP**		**Viability in 1^{st} year [%]**	**Year of zero viability**
		VAL [€]	PR [years]	VAL [€]	PR [years]		
Santa Iria de Azoia	**c-Si**	-30077.604	∞	-28487.070	∞	33.370	345
	CIGS	-37620.142	∞	-36555.198	∞	32.991	223
	c-Si NWs	-39560.585	∞	-38606.909	∞	32.160	221
	$CsPbI_3$ QDs	-34857.081	∞	-35184.148	∞	26.741	176
Castro Verde	**c-Si**	-29850.777	∞	-27963.636	∞	34.700	349
	CIGS	-37394.882	∞	-36082.597	∞	33.816	226
	c-Si NWs	-39334.671	∞	-38161.563	∞	33.319	223
	$CsPbI_3$ QDs	-34649.456	∞	-34885.575	∞	27.911	179
Vila Real	**c-Si**	-30391.133	∞	-29031.360	∞	32.186	347
	CIGS	-37931.620	∞	-37047.202	∞	31.655	225
	c-Si NWs	-39858.946	∞	-39068.720	∞	31.504	222
	$CsPbI_3$ QDs	-35199.583	∞	-35493.454	∞	25.117	178

Analysing Tables VIII and IX it is verified that the best place for the installation is Castro Verde, due to the higher viability values. With the CIGS technology, the highest viability is obtained without shading in the generator, whose value is 45.088%. This means that in 45.088% of the time intervals considered throughout the year, production is greater than load consumption. It can also be seen, in both scenarios, that the use of c-Si NWs and $CsPbI_3$ QDs modules translates into lower viability than the achieved with c-Si and CIGS technologies.

V. DISCUSSION

A. *Physical Factors*

The location of the implementation of the generator is one of the factors that affects the performance of the photovoltaic system. Santa Iria de Azoia, Castro Verde and Vila Real were chosen for the analysis because of being three regions located in different areas of Portugal that present discrepancies in temperature and irradiance.

Castro Verde is the place that presents the highest average temperature and irradiance values, except for august nonworking days. For this reason, using any technology, the highest values of energy produced are reached on all days of january and on the working days of august. Regarding august nonworking days, the highest generation values are reached when the place under analysis is Vila Real. This is justified by the simple fact that the local average temperature throughout the nonworking days is lower than the average temperatures experienced in the other places. It is verified, therefore, the huge impact of the temperature variation in the achievement of higher values of energy production.

From the economic point of view and by analysis of Table VIII, Castro Verde ends up being the place that best satisfies the investor due to the high production of the generators, and, in terms of the PR, using traditional technologies, the project ends up being recovered more quickly. In what concerns the viability of the sized systems, in the first year of analysis, Castro Verde presents the highest values reached, so there is a higher number of time intervals where the production is higher than the consumption.

B. *Financial Indicators for Project Evaluation*

From an economic point of view, the operation and maintenance costs associated with photovoltaic installation constitute the largest burden of operational expenses for the investor. In 2007, these costs were around €35/kW/year and, according to the latest data, in 2019, it has decreased to around €17/kW/year [29]. This shows the downward trend that these costs will have and, therefore, will be an economically significant reduction in the investment for the investor.

According to Table VIII, it is possible to analyse the financial indicators from two points of view: no sale of the surplus production to the RESP, and its sale. The fact that there is a production surplus and the investor does not benefit from it, by delivering, at zero cost, the surplus to the grid, implies that the project is not economically viable, which results in a negative VAL, regardless of the solar technology and place analysed. This leads to a decrease in investment in renewable energy systems and the continued use of non-renewable energy. In addition, regarding the PR of the investment, this cannot be recovered over the period under analysis. The installation of systems using renewable energy sources ends up being beneficial to the investor if his monthly electricity bill is lower. From year 0 to year 1 of the financial analysis, there is a reduction in revenues obtained, of about 73% to 75% when using c-Si or CIGS modules, and of about 66% to 72% when emerging technologies are used. On the other hand, to this reduction, the value of the initial investment should be added, which must be paid for and, since there is no benefit for the investor, in the medium-long term it will not be possible to recover the investment. Therefore, there is a saving in terms of electricity consumption, but there is also an investment that should be paid, without any kind of contribution to support it, only depending on the investor himself.

The sale of the surplus production to RESP leads, in some cases, to non-viable projects, demonstrated through the financial indicators presented in Table VIII. Note that the use of traditional technologies, in any of the places considered, leads to a positive VAL, which translates to the economic viability of the project, covering the initial investment and obtaining the minimum remuneration required by the investor. Furthermore, the PR is lower than 10 years, being that it ends up covering the warranties of the equipment used and, in addition, the lifetime of the photovoltaic panels [20]. On the other hand, when it comes to emerging technologies, their use is not viable, presenting a negative VAL. However, the c-Si NWs technology presents a PR of 15-20 years, which is a period that ends up exceeding some of the warranties of the equipment used and, in case of failure, the investor will be responsible for new investment, making the project more expensive and increasing, even more, its PR. Because the production of energy by the generators using nanocells is not so high, the surplus production ends up being lower, if compared with traditional technologies. Consequently, this lower production of c-Si NWs and $CsPbI_3$ QDs makes it neither economically beneficial nor viable for the investor. In this situation, the investor ends up benefiting from a reduction in electricity bills and, simultaneously, collecting the equivalent of its surplus production. Therefore, on a financial level, it is twice beneficial and ends up being an incentive for investment in renewable energy systems for self consumption.

C. *Social Factors*

The fact that there are no batteries and the system is on-grid leads to a loss of the surplus produced energy. Obviously, there can be a financial return with the non-consumed surplus produced energy, however, from the point of view of production and not storage, for consumption itself, it ends up being lost energy. The reason why the sized system does not consider batteries is the fact that these equipments make the project very expensive and, besides, they are equipments whose production is pollutant. By analysing Figure 5 to Figure 8, it can be seen that there is a large discrepancy, particularly during the working days, between the consumption and the production peaks in each time interval. Therefore, in order to take advantage of the surplus energy production and not losing it, the concept of a smart city can be applied. Commercial establishments in the nearby place where the photovoltaic installation was carried out, could benefit from energy production when infrastructure consumption is lower. It is a fact that, from Table III, the number of properties, from an economic point of view, that are viable to power is only one, regardless of the technology used for this purpose. However, this value was obtained taking into account that each infrastructure under analysis presents exactly the same load profile in each time interval. Thus, these establishments which could use the surplus energy produced by each generator may not present the same load profile considered at each time interval. If we consider that the commercial establishments' consumption, on working days, is higher during sunny hours, in opposition to the lower consumption of the infrastructure under analysis, on the same working days during the same conditions, the commercial establishments could be fed using the surplus production. This would be a way of contributing to the decrease in the use of energy from non-renewable sources. This way, it is possible to create more energy-efficient cities and contribute to fighting climate change. This solution ultimately ensures the reduction of energy consumption from the grid in several properties, which implies the reduction of greenhouse gas emissions associated with its production, ultimately contributing to the adaptation of cities to climate change.

D. Environmental Factors

The use of renewable energies greatly promotes the decrease in the emission of greenhouse gases, since the production of green energies occurs sustainably, without causing pollution. The energy that a citizen consumes from the grid is energy resulting from resources, which sooner or later will come to an end on Earth. Table VIII shows that, according to the technology used, the number of years until viability is zero change according to the place under analysis, taking on average around 649, 436, 303 and 376 years. If we think that a common plastic cup takes 20 years to decompose, the number of years needed until viability is null is no longer just numbers. This means that, on average, for all technologies, about 22 plastic cups would be decomposed so that, in all analysed regions, the production points show lower values than the consumption points, in each time interval. It is not expected that the production by the system, given the existing consumption, will last 303-649 years. However, considering the analysis carried out, which does not take into account equipment replacement, if there is an ideal rate of degradation of the equipment, then, throughout the degradation of about 22 plastic cups, there would be produced energy by the generator, ensuring some load points.

E. Shading Effect

The existence of total or partial shading on photovoltaic generators is an event that can occur since the falling leaves from the trees and the effects of nature cannot be controlled at every instant by the owner of the infrastructure that owns the photovoltaic generator. By analysis of Figure 5 to Figure 8, it is verified a significant decrease, in each time interval in which there is solar exposure. The nonworking days, especially the month of higher consumption - january - are the days with higher consumption during the sunny hours and, once again, by analysing Figure 5 to Figure 8, the production curve with the generator in partial shading is not able to meet the consumption in most of the time intervals, in all locations under analysis and photovoltaic technologies used. This implies that the investor will have to use energy from the RESP to have his load assured. The production of surplus energy, if compared to the consumption of the load, occurs mainly on working days, due to the reduced consumption of the load during sunny hours. However, the amount of surplus energy is not as high as in no shading applied scenarios. Once again, due to the fact that there is no reference tariff in the Portuguese legislation for the sale of the surplus production resulting from UPAC, being subject to an agreement between the several parties, the sale of the surplus to RESP can be remunerated or simply delivered to it.

By analysis of Table IX, regardless of whether there is sale or not of the surplus energy production to RESP, the VAL is negative for all technologies and locations, which indicates the clear non-viability of the project. Furthermore, for the period under analysis considered, there is no PR, which indicates that the investor will not be able, over 1000 years, to recover the investment made. Nevertheless, even if the surplus energy produced is delivered to RESP at zero cost, the use of the photovoltaic generator ends up being beneficial to the investor if the focus is the reduction of monthly electricity bills and not the investment he will have to make. However, with the existence of partial shading, these reductions translate into lower values if compared with no shading scenario. Considering the existence of partial shading, from year 0 to year 1 of the analysis, the reduction in revenues is around 43% to 48% when using c-Si or CIGS modules, and around 35% to 46% when using technologies with nanostructures, which means a reduction in savings of 27% to 30% in traditional technologies and 26% to 31% in emerging technologies.

Lastly, it can be seen that, regarding the viability in the first year under analysis, partial shading causes a decrease of between 10 and 16% of the viability presented in the scenario without shading, which means that production values higher than consumption ones are presented in less 10 and 16% of the considered time intervals. The number of years until viability is null decreases to about half of the values obtained in the scenarios without shading in the generator. This is justified by the fact that the production points in the partially shaded scenarios are not much higher than the consumption points in each time interval when compared to the non-shading scenarios, so, although module degradation occurs at the same rate, it takes less time before all production points are lower than the consumption ones.

VI. CONCLUSIONS

The energy crisis that the world is facing has been a major concern for the scientific community. Portugal has created conditions for the use of renewable energies to grow. However, the abolition of reference tariffs by the Government, so that the investor gains profit from what he produces, leads to each company being responsible for what it charges, and they are obviously free not to make a payment to investors. Nevertheless, the use of renewable energy systems leads to monthly reductions deducted from the respective bills. The impact of these decisions, namely in what concerns self consumption, may lead to the non-investment in renewable energy systems by land and/or infrastructure owners, being this the purpose of the work developed, based on photovoltaic solar energy, using four different solar technologies, in different regions of Portugal.

The analysis carried out with partial shading and non-shading on the different generators shows that shade is a problem for the good performance of the photovoltaic generators, decreasing to between 13% to 17.5% the maximum power of the generators, at the reference conditions. At the level of production in each time interval considered, the consumption-generation curves show that the shadow allows most of the load consumption peaks not to be supported by the generator, which, from an economic point of view, translates the clear non-viability of the project, with or without sale of the surplus production, regardless of the technology used and region under analysis. On the other hand, the lack of shading effect allows the generator to cover most of the load consumption peaks during sunny hours. In the case of selling the surplus energy to the RESP, the use of traditional technologies allows the project to be economically viable, presenting a PR lower than 10 years, covering the warranties of the different equipment. Emerging technologies have shown not to be, for now, the best solution for applications in photovoltaic generators for self consumption, since the production of these generators is lower than the production of generators using traditional technologies. In addition, emerging technologies present lower viability in the first year of analysis than generators using traditional technologies, in the same period. If the surplus energy production is delivered at zero cost to RESP, then the project becomes non-viable, regardless of the solar technology used and place under analysis.

Due to the absence of batteries, the surplus energy produced is not stored in order to be used when no production occurs. From a social point of view and in order to reduce the consumption of energy from the public grid, this surplus energy would be well used to supply other commercial establishments in the nearby of the infrastructure under analysis, contributing to the reduction of greenhouse gas emissions associated with the production of energy from the grid, and consequently, fighting climate changes.

It is, therefore, concluded, that the role of Governments in the implementation of measures that promote investment in renewable energy is crucial, being important in the determination of a fixed value for the sale of the surplus energy to the grid. Otherwise, the possibility of practising almost zero values for the sale of surplus energy to RESP prevents the project to be done by the investor. In addition, the location of the implementation of the generator, in order to verify the existence of barriers to solar production, that may accumulate in the generator itself, is an important factor to study, since the plausibility of the project also depends on the existence of shading, or not, in the photovoltaic generator.

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