Small Production Units: Does law impair generation and financial viability?

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***Abstract*—Portuguese law considers two generation profiles for renewable energy: Small Production Units (UPP) and Self-Consumption Production Units (UPAC). For UPPs, connection power is limited by the contracted power. Oftentimes contracted power is smaller than the generation potential in the property therefore, some concerns are raised about the power and financial viability of UPP projects. This work focus on the financial and power viability of UPP projects designed according to the current law *versus* the projects developed to take advantage of the available solar power.**

To study this, three solar systems are designed with the help of Building Information Modelling software, laboratory tests and satellite images. Two of these projects are designed with the intent of maximising generation while still being conceivable: one using solar glass and the other is designed to replace the carport cover on the property. The third project is designed according to legal power limitations.

It's observed that the project that uses solar glass has a negative Net Present Value (NPV), meaning it is not viable. The other two projects have a positive NPV. Project three has lower initial investment and a smaller payback period. The difference in generated power is not significant. Hence, one can conclude that Portuguese law does not impair the UPP energy and financial viability.

***Index Terms*—Small Production Units; Photovoltaic Systems; Financial Viability; Power Generation; Residential Photovoltaic Systems.**

I. Introduction

One of the major concerns at a global level is the reduction in the consumption of energy derived from fossil fuels. Amidst the European Union member states, 60% of the energy consumption happens in service and residential buildings. From these 60%, residential buildings alone contribute with two thirds of consumption [1]. The consumption of energy sourced from fossil fuels at buildings can be reduced by improving the building's energy efficiency and by implementing clean energy generation on site. Since the year 2000, the European Union has been developing programs and laws that encourage and force the member states to increase clean energy generation and to promote near zero energy building's construction and reformation. Portugal has adopted these measures through programs like *Plano Nacional de Ação para a Eficiência Energética* and *Plano Nacional Integrado Energia e Clima*.

Currently, Portuguese legislation allows for renewable energy generation under two categories: self consumption (UPAC) and small production (UPP) [Decreto-Lei n.º 153/2014, Portaria nº14/2015, and Portaria nº15/2015]. UPP dominates the solar market for these solutions require lower initial investment.

For UPPs, connection power is limited by the contracted power. Connection power is defined as the rated output power of the inverter (in kW or kVA) that can be injected in the grid. Contracted power is the power limit set in the power control device contracted by the energy supplier. Residential properties in Portugal often benefit from a generation potential that is higher than contracted power, especially in rural areas hence, connection power limitations raise questions on the viability of UPP projects in rural areas and on how much more clean energy could be generated if these laws were different.

The work of João Alexandre [2] addresses the financial viability of solar projects in Portugal under the current law. However, his work only covers generation under the self consumption category and takes as input for simulation the consumption of the average family in Portugal.

Hence, the aim of this work is to study the financial viability of solar systems in rural areas considering the legal generation threshold *versus* exploring the existing solar potential. This goal is achieved with the use of digital tools for 3D building simulation, laboratory tests to prove the performance of novelty materials and computation of financial indicators used for project evaluation and selection. Three possible systems are designed: one that minimises the building's heat gain while generating power, other that generates the maximum energy possible without taking up floor space or disrupting the property's appearance, and the last one that does the same and abides by law.

The present work is divided into five sections. Section I is a brief introduction to the work that presents the motivational factors that lead to it and its objectives.

Section II, Methodology, describes the steps taken to research the problem and to reach the purposed objectives. The simulation environment and laboratory procedures are described. The computation methods used to size each component of the projects are presented.

Results, Section III, presents the output obtained from applying the methods described before. This part of the work consists of images resulting from simulation, results from laboratory tests, tables with information about the designed systems and the indication of initial investment for all projects.

In Section IV, Discussion, the results are analysed. The results obtained are compared to typical values.

Lastly, Conclusions, Section V, discusses the results obtained before, indicates some limitations of the present work and proposes future work on the topic.

II. Methodology

A. Case Study:

The residential property (fig. 3) to be studied is located in the Municipality of Faro, in the Algarve region of southern Portugal. The property is located 11 km away from the shore at an elevation of 69 m above sea level. The total area of the property is approximately 15000 m^2 , of which 373 m^2 correspond to the main building surface. There is one year-round resident. Besides the main building there is a 91.1 m^2 carport that, according to the property owner, is never shaded and can withstand up to 1500 kg.

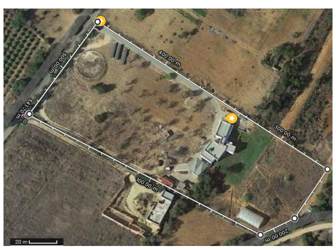

Fig. 1: Aerial view of the property.

Fig. 2: Aerial view of the carport.

Fig. 3: Satellite images of the property.

Currently, contracted power is 20.7 kVA, the highest power that can be contracted on the bi-hourly rate tariff. Assuming that the inverter's power factor is 0.8, the connection power must be close to 16.56 kW.

B. Financial Indicators for Project Evaluation

When performing the financial evaluation of a project it is necessary to determine the present value of future cash flows. This is done through the discount rate.

The discount rate is the opportunity cost of capital (as a percentage of the value of the capital). The opportunity cost of capital is the return on investments forgone elsewhere by committing capital to the investment under consideration [3]. The **real discount rate** (%), a, is a function of two parcels (risk-free rate of return and equity risk premium). The risk free rate of return represents what the investor would expect from a risk free investment over a period of time. Equity risk premium refers to the extra return available to investors that opt for a project with associated risk. Estimating the discount rate of any project is not a trivial process. The discount rate value considered is the result of a survey ran by Grant Thornton to gauge investors' perception of cost of capital in several European countries [4].

The **NPV** (€) is a financial indicator used to assess the financial viability of a project. It is difference between the present value of cash inflows and the present value of cash outflows, over a period of time - Equation (1) where CF_t - cashflow during a single period t (€), a - real discounted rate (%), t - number of time periods. A NPV of less than zero (NPV $<$ 0) means that the project is expected to result in a net loss for the investors. At NPV greater than zero (NPV $>$ 0) the investors should expect profit. If NPV = 0, the project is not expected to bring profit nor loss, so the investors should make a decision about the project taking into consideration non-monetary factors.

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+a)^t} \tag{1}$$

The payback period (PP) (years) is the times it takes to recover the cost of an investment - Equation (2) where: A - he last year with a negative cumulative cash flow, B - the absolute value of cumulative cash inflow at the end of Year A, (€), C - total cash flow during the year after Year A, (€). The PP is a very simple indicator that does not include money value updates (discount rate). For uneven cash inflows, payback period is given by Equation (2).

$$PP = A + \frac{B}{C} \tag{2}$$

The levelized cost of energy (LCOE) (€/kWh) describes the cost of each unit of power generated over the lifetime of the project. This indicator does not account for interest rates and does not include the discount to present value - Equation (3) where: I_0 - initial investment (€), $O\&M_t$ - operations and maintenance costs during a single period t (assumed to be constant) (€), n - Number of time periods that correspond to the project's lifetime assumed to be 30), E_a - energy generated during a single period t, (MWh).

$$LCOE = \frac{I_0 + \sum_{t=0}^{n} O\&M_t}{\sum_{t=0}^{n} E_{a\ t}} \tag{3}$$

C. Laboratory work

Besides the more well established technological solutions for domestic PV generation, there are CdTe solar panels. These panels offer the great advantage of being transparent with cells that can't be seen from up close. However, since this is a novelty technology, it can be enlightening to test its performance before trying to incorporate it on the project.

To do so, six coloured panels were tested (green, red, grey, blue, orange and yellow) with transparencies of 40% and 50%. Tests were performed in a darkened room, using artificial light sources (halogen spotlights) that were kept at a set distance from the solar panels (85 cm). Solar panels were placed at zero degrees of inclination in relation to the horizontal plane, and a black matte cloth was placed under the solar panels in order to minimise reflections.

Instruments used for laboratory work are: two halogen spotlights (Smartwares HL400 500 W), solderless breadboard

(Farnell ABSMCBB830), carbon composition resistors (from 25 Ω to 2000 Ω), ammeter (Center 122 Multimeter), voltmeter (Center 122 Multimeter), handheld pyranometer (RS Pro ISM400), and thermometer (RS Pro Dual Thermal/Clock). Each solar panel went through the same set of experimental tests that go as follows:

1) Panel and spotlights are placed on the demarcated positions. The rest of the material is set-up. Lights are turned on and the system is left to warm-up for 10 minutes. This ensures the light source is working at its full power and that the solar panel will be under a relatively stable temperature.
2) The load is steadily increased from values close to short circuit (short circuit current, I_{SC}, is recorded), up to values close to open circuit conditions (open circuit voltage, V_{OC}, is recorded). For each load level current and voltage are taken and recorded.
3) The irradiance value is taken by placing the light sensible disk of the pyranometer at the same level as the solar panel, in parallel with the cells. Panel temperature is measured and recorded.
4) All the retrieved data is organised so that the characteristic I-V curve can be plotted. Through the data, it is also possible to plot power as a function of voltage (P-V) by multiplying current and voltage for each load level.
5) Efficiency at test condition is computed through $\eta = \frac{P_{MP}}{P_{in}} = \frac{I_{MP}V_{MP}}{GA}$ where P_{MP} stands for maximum power point, P_{in} stands for the modules' power input, I_{MP} and V_{MP} are the current voltage at maximum power point, G is the incident irradiance and A is the module's surface area.
6) Efficiency at standard test conditions (STC) is computed according to the method described in [5] and [6].

D. Simulation

Satellite images are used to survey potential areas on the property where PV systems could be integrated, but they don't convey any information on how much energy reaches those areas, or if there are other areas of interest on the building itself. Hence, the use of Autodesk Revit 2020 software to simulate incident Solar radiation on some of the building's surfaces.

Autodesk Revit 2020 is a building information modelling software that supports modelling in 3D with accuracy and precision. The steps taken to simulate cumulative insolation for one year period are as follows:

1) Uploading architectural blueprints to Autodesk Revit 2020. Setting geographic location (coordinates) and facade orientation. Blueprints were kindly provided by the original architect, Paulo Charneca. Location (37.06, -7.89) is used to download weather data from the closest weather station that is located less than 5 km away.
2) 3D modelling of the building taking into consideration design, materials and scale.
3) Adjusting sun settings: one year solar study, dates from 01/01/2019 to 31/12/2019, one day time interval.
4) Simulating: through Insight Solar tool, running a custom study of cumulative insolation (kWh/m^2) on the selected surfaces.

This method produces an output file discriminating cumulative insolation for one year period, the area of each selected surface, and a visual representation of insulation on the 3D model. The input data is collected by the nearest weather station. The list of weather stations can be consulted on the 2007 ASHRAE Handbook.

E. PV System Sizing

All components in the PV system are sized following the methods described in The Solar Guide [7]. However, the starting point for sizing PV systems depends on the end goal. The first two PV systems are designed with the goal of utilising the maximum solar power available while having minimal or a positive impact on the property's appearance and functionality. Sizing these projects begins with the selection of solar panels according to their physical characteristics (transparency, size, weight, etc), efficiency and power output.

The third PV system is designed to ensure the inverter is selected according to the maximum connection power and operates at rated power for the majority of the time.

F. Initial Investment

The quotation for each project includes the required materials, installation costs and legalisation fees. All prices mentioned include the value-added tax (VAT) of 23%, currently applicable in Portugal. It is considered that the installation cost is 30% of the total cost of the project. This value was quoted via e-mail by Onyx Solar. Legalisation fees for UPP projects are presented in Portaria n.º 15/2020 23 de janeiro (all in Portuguese).

III. Results

A. Simulation

The purpose of the simulation is to evaluate the buildings generation potential. After creating the 3D model of the building, the procedure described in Section II-D was repeated for all the glass surfaces and for the horizontal rooftop. Table I indicates what are the glass surfaces on each facade and how much energy reaches them during one year period.

TABLE I: Simulation results on cumulative annual insolation for the windows.

Window Orientation	Glass Area (m^2)	No. Windows	Total Annual Energy (kWh)	Total Monthly Energy (kWh)	Total Monthly Irradiance (kW/m^2)
N	8.66	11	147497.7		
S	49.18	10	816390.7		
W	0	0	0		
E	5.90	1	142734.5		
Total	63.74	22	1106622.9	92218.57	1.99˜

Table II indicates how much energy reaches the horizontal surface of the roof. The carport was not on the original blueprints of the building, so it was not modelled on Revit

2020. The carport is basically a horizontal plane at the same height as the main building. Therefore, it is assumed that the energy that reaches the carport is proportional to its area taking as a base the energy that reaches the rooftop.

TABLE II: Simulation results on cumulative annual insolation for the carport and horizontal roof.

Surface	Surface Area (m^2)	Total Annual Energy (kWh)	Total Monthly Energy (kWh)	Total Monthly Irradiance (kW/m^2)
Horizontal Roof	287.72	29500.56	258424888	8.54
Carport	91.00	9330.46	81734832	8.54

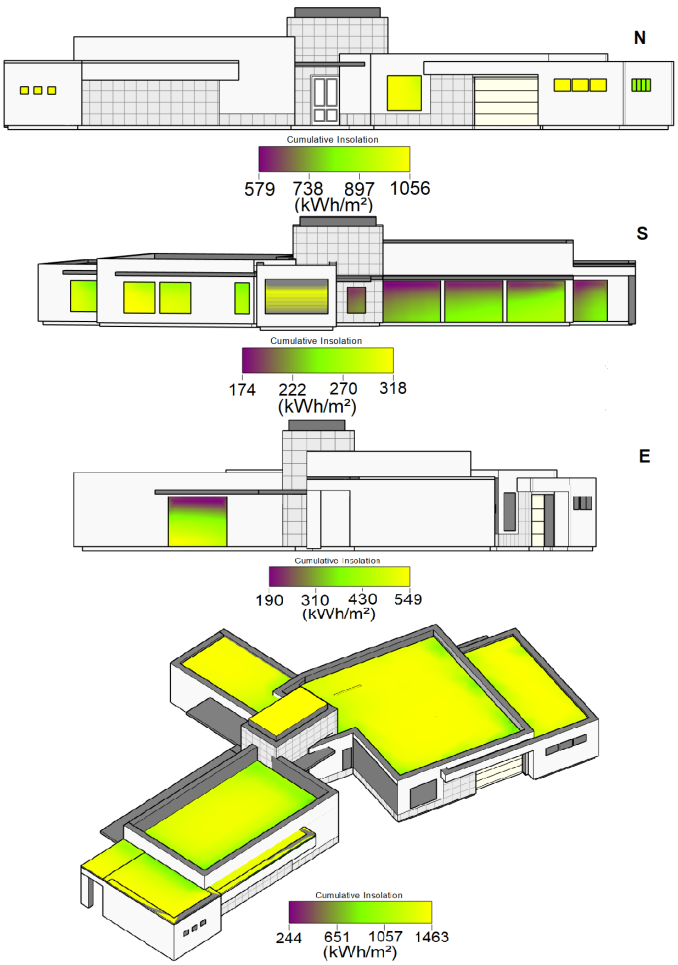

Fig. 4: Annual cumulative insolation for the windows and rooftop of the building. Simulated using Autodesk Revit 2020.

B. Laboratory Work

CdTe thin film solar panels are a novelty technology so there is not a vast amount of resources on the behaviour of these solar panels. Hence, energy sizing for the project must include laboratory tests on the panels' efficiency.

During laboratory tests, it was observed that the glass solar panels are composed of two layers of glass and only one of them is coloured. The panels do not generate any energy when the coloured layer is facing the light therefore, all results refer to the generation output when the clear glass side is facing the light source.

According to [5] and [6], cell temperature is the factor that affects efficiency the most. According to these sources, the effect of temperature on efficiency is linear, so efficiency at STC can be estimated through the laboratory results using that proportionality. Since the grey panels render a higher efficiency at STC this is the value that will be considered going forth on the study.

TABLE III: Experimental key-point results, efficiency and FF.

	V_{MP}(V)	I_{MP} (A)	P_{MP}(W)	V_{OC}(V)	I_{SC}(A)
Green	67.7	0.027	1.828	90.2	0.033
Red	73.5	0.033	2.426	93.4	0.042
Grey	74.	0.038	2.812	95.9	0.044
Orange	74.3	0.034	2.526	96.3	0.039
Blue	71.0	0.027	1.917	91.3	0.032
Yellow	77.9	0.031	2.415	94.4	0.039

	Exp. Fill Factor	Exp. Cell Temp. (°C)	Exp. Irradiance ($W\backslash m^2$)	Exp. Efficiency	Exp. Efficiency at STC
Green	0.614	30	144.2	0.01760	0.01467
Red	0.618	31	141.2	0.02386	0.01925
Grey	0.666	28.5	149.2	0.02618	0.02296
Orange	0.673	28	139.7	0.02512	0.01743
Blue	0.673	27.5	138.9	0.01917	0.01743
Yellow	0.656	28	138.9	0.02415	0.01743

Table III shows the experimental results for short circuit, maximum current and maximum and open circuit voltage. Using the expressions mentioned on Section II-C it is possible to compute the experimental efficiency and fill factor ratio.

C. Initial Investment

To obtain the initial investment of each project it is necessary to first size an select all components of the systems. Some components are common to all projects like the energy meter, the fuses, connection and circuit boxes.

Energy meters selected must allow for telemetric readings. There must be a energy meter dedicated to reading the energy injected in the grid and another to measure consumption. All energy meters must be approved by Direção Geral de Energia e Geologia (DGRG).

Fuse, connection and breaker boxes must comply with IEC 61439-2. Fuse boxes must allow for easy fuse replacement.

Another expense common to all projects is the legalisation fees. Legalisation fees for UPP projects are presented in Portaria n.º 15/2020 (in Portuguese). For UPPs under 1000 kW of installed power issuing fees are twice the installed power in kW plus 2000 € (Table I in the source document). Inspection and productions fees are 960 € (Table II in the source document), and the registration fee is 1000 € (Table III in the source document). These fees are paid once before the beginning of the project. All the legal documents and procedures are done through the DGEG online platform.

1) Generate Maximum Energy: To generate the maximum amount of energy possible the maximum surface area must be covered in solar panels. However, one must take into consideration that the project has to be realistic: it is not reasonable to design a system with solar panels covering the entire property or all the facades. There are many criteria to choose solar panels and technologies but for this project choices are based on placement and double functionality. Hence, this work considers two possibilities: replacing the windows by transparent solar panels and replacing the carport cover by opaque solar panels.

Replacing the windows by transparent solar panels is a new solution more common for big scale projects like apartment buildings and businesses, but still uncommon for small residential properties. For this project the windows must remain see-through and offer thermal insulation, so CdTe and a-Si thin film modules would be the most convenient solutions. However, transparent CdTe modules are more easily accessible for purchase, so this was the selected technology.

The most common PV designs for residential building are based on opaque solar panels that are installed at optimal tilt on the roof. For this project this was not possible. Given the dimensions of each solar panel, the number of solar panels required, and the minimum distance between each other to avoid shading, the roof was not big enough. So, the solution considered is replacing the carport cover by solar panels.

Solar carports are usually done using semi-transparent solar panels. However, traditional opaque solar panels offer higher efficiency, are easily available, are less expensive and completely shade the area, so the selected technology is mono-Si opaque solar panels.

TABLE IV: Panels' model and specifications at STC, 70°C and -10°C.

Panel	P_{MP} (Wp)	I_{MP} (A)	V_{MP} (V)	I_{SC} (A)	V_{OC} (V)
Solar First SF-ST1-48W 40% Grey CdTe	48	0.55	87.00	0.59	116.00
I'M.SOLAR 340W Monocrystalline	340	9.88	33.47	10.00	41.58

Panel	$I_{SC\ 70°C}$ (V)	$I_{SC\ -10°C}$ (A)	$I_{SC\ -10°C}$ (A)	$V_{OC\ -10°C}$ (V)
Solar First SF-ST1-48W 40% Grey CdTe	0.61	0.58	74.44	129.03
I'M.SOLAR 340W Monocrystalline	10.18	9.86	28.35	46.53

Table IV presents more information on the solar panels selected for the projected designed to generate maximum energy. In this table P_{MP} stands for maximum power point, I_{MP} and V_{MP} for currenct and voltage at the maximum power point, I_{SC} short circuit current and V_{OC} open circuit voltage.

TABLE V: Number of modules per scenario.

	Surface Area (m^2)	**Module's Area (m^2)**	**No. Modules**	**Installed Power (Wp)**
Windows	63.74	0.72	90	4368
Carport	91.00	1.67	55	18700

The area to cover on each scenario can be divided by the surface area of each panel in order to obtain the number of panels required - Table V. For the solar windows, although the calculations recommend 91 panels, only 90 panels were considered since 91 solar panels would require the use of two inverters.

TABLE VI: Selected inverters' basic datasheet information.

		Input						
	Inverter	η	P (W)	MPPT's Voltage Range (V)	V_{max} (V)	I_{max} (A)	Connectors per MPPT	MPPTs
Windows	SMA Sunny Tripower 5000TL-20	0.971	5100	245-800	1000	11	4	2
Carport	Huawei Technologies SUN2000-17KTL	0.983	19100	200-950	1000	18	6	3

		Output					
	Inverter	P (W)	S (VA)	Power Factor	I_n (A)	I_{max} (A)	V_n (V)
Windows	SMA Sunny Tripower 5000TL-20	5000	5000	0.8	5.2	7.3	400
Carport	Huawei Technologies SUN2000-17KTL	1700	18700	0.8	17.7	28.4	400

Inverters are selected based on the power range indicated in [7]. They all are certified by DGEG, therefore have CE marking, comply with IEC 62109-1: 2009 and at least one of the international standards: DIN VDE 0126-1-1:2006, EN 50438:2007, VDE-AR-N-4105:2011.

Table VI contains some basic information on the selected inverters. In table VI P and S stand for active and apparent power, MPPT stands for maximum power point tracker, V_{max} and I_{max} for maximum voltage and current, V_n and I_n for rated voltage and current, and η for efficiency.

It is important to note that the Huawei Technologies inverter has a 3W + N + PE output which means its connection with the grid must be done through a cable that consists of 3 live wires, 1 neutral wire and 1 protective earth wire. The earth wire must be connected to the building's earthing system. The circuit breaker for this inverter must have 4 poles. The SMA SunnyTripower inverter is connected to the grid through a 3 wire system, meaning its AC cable must have 3 wires and its circuit breaker must have 3 poles.

Solar panels in both projects are arranged in rows that are wired in parallel. The cables that connect the panels to each other are referred to as Row cable and will have a smaller cross section than the cables that connect the series in parallel to the inverter (Main DC Cable).

Solar Windows Initial Investment - Figure 5

DESCRIPTION		QTY	UNIT PRICE	AMOUNT
Solar Panels:	Solar First 48 W 40% Grey	90	88.03	7922.70
Energy Meter:	Itron SL7000 Smart Trifásico	1	426.41	426.41
Inverer:	SMA Sunny Tripower 5000TL-20	1	1,379.00	1379.00
Cabling:				
Row Cable:	General Cable Class RV-K 1.5mm2	50	0.70	35.00
Main DC Cable:	General Cable Class RV-K 1.5mm2	50	0.70	35.00
AC Cable:	EuroCabos BT-CU-EPR 4+T 1.5mm2	100	1.50	150.00
Protection:				
Fuses:	Hager LF301PV	18	6.05	108.90
Fuse Boxes:	Hager L501PV	18	4.85	87.30
Connector Box:	Spelsberg PV-CB/1	1	91.59	91.59
Circuit Breaker:	Schneider Electric IC60N 3P 10A 500V	1	25.49	25.49
Circuit Box:	Hager IP55 1Fila	2	20.09	40.18
Legal:				
Administrative:	Request + Inspection + Issuing	1	10,640.00	10640.00
Generation Permit:	Registration + Issuing + Inspection	1	960.00	960.00
Commercial Permit:	Registration + Issuing + Inspection	1	1,000.00	1000.00
		SUBTOTAL (VAT Inc)		22901.57
		Installation		0.30
		Installation Cost		6870.47
		TOTAL (€)		**29772.04**

Fig. 5: Total cost of replacing the windows for glass solar panels.

Carport Initial Investment - Figure 6

DESCRIPTION		QTY	UNIT PRICE	AMOUNT
Solar Panels:	I'M.SOLAR 340W Monocrystalline	55	159.00	8745.00
Energy Meter:	Itron SL7000 Smart Trifásico	1	426.41	426.41
Inverer:	Huawei Technologies SUN2000-17KTL	1	2,298.00	2298.00
Cabling:				
Row Cable:	General Cable Class RV-K 2.5mm2	50	1.79	89.50
Main DC Cable:	General Cable Class RV-K 2.5mm2	50	1.79	89.50
AC Cable:	EuroCabos BT-CU-EPR 3 6mm2	100	2.49	249.00
Protection:				
Fuses:	Hager LF315PV	6	6.05	36.30
Fuse Boxes:	Hager L501PV	6	4.85	29.10
Connector Box:	Spelsberg PV-CB/1	1	91.59	91.59
Circuit Breaker:	Schneider Electric IC60N 4P 40A 400V	1	39.50	39.50
Circuit Box:	Hager IP55 1Fila	1	20.09	20.09
Legal:				
Administrative:	Request + Inspection + Issuing	1	39,400.00	39400.00
Generation Permit:	Registration + Issuing + Inspection	1	960.00	960.00
Commercial Permit:	Registration + Issuing + Inspection	1	1,000.00	1000.00
		SUBTOTAL (VAT Inc)		53473.99
		Installation		0.30
		Installation Cost		16042.20
		TOTAL (€)		**69516.19**

Fig. 6: Total cost of installing solar panels on the carport.

2) Generate Maximum Energy According to Legislation:: Knowing the contracted power is 20.7 kW and assuming that the inverter's power factor is 0.8, the maximum energy that can be injected into the grid is 16.56 kW. So, the rated output power of the selected inverter must be as close to 16.56 kW as possible. The inverter Zeversolar - Table VII - is certified by DGEG and its rated output power is 17 kW, close to 16.56 kW. It has a 3W + N + PE output which means its connection with the grid must be done through a cable that consists of 3 live wires, 1 neutral wire and a protective earth wire. The earth wire must be connected to the building's earthing system. The circuit breaker for this inverter must have 4 poles.

TABLE VII: Inverter's specifications.

		Output					
Inverter	η	P (W)	S (VA)	Power Factor	I (A)	I_{max} per phase(A)	V (V)
Zeversolar Eversol TLC17K	0.979	17000	18700	0.85	24.7	25.8	400

Input							
P_{max} (Wp)	V_{max} (V)	V (V)	I_{max} per string (I)	I_{max} per MPPT (I)	MPPT voltage range (V)	No. of MPPTs	Phases per MPPT
22100	1000	640	11	22	270-950	2	2

The system must be designed so that the inverter operates at rated conditions, using the smallest budget possible. To do so, due to its efficiency, the inverter has to be fed 17.365 kW by the solar panels. Taking into account the average insolation results given by the simulation, 8 solar panels (model: Sun Edison mono Si 260 W, 15.84% efficiency) would provide that power. These can be installed in the carport where they serve a double function and don't take any floor space.

The solar panels must be arranged so that the inverter operates at rated power for as long as possible. Table VIII presents the datasheet information on the solar panels and the inverter datasheet information that dictates how the solar panels must be distributed. Since the inverter has 4 inputs, there should be 4 strings of 21 panels each, in a total of 84 solar panels.

TABLE VIII: Number of panels per string and installed power.

Panel	I_{MP} (A)	$I_{n\ in\ inv}$ (A)	V_{MP} (V)	$V_{n\ in\ inv}$ (V)	Panels per string	$P_{PV\ tot}$ (Wp)
Sun Edison mono Si 260 Wp	8.40	11	31.00	640	21	21840

In Table VIII $I_{n\ in\ inv}$ and $V_{n\ in\ inv}$ stand for the inverter's rated input current and voltage, and $P_{PV\ tot}$ stands for the total PV power installed.

Project According to Legislation Investment - Figure 7

DESCRIPTION			QTY	UNIT PRICE	AMOUNT
Solar Panels:	Sun Edison Silvantis F260 MODUlE		84	233.72	19632.48
Energy Meter:	Itron SL7000 Smart Trifásico		1	426.41	426.41
Inverer:	Zeversolar	Eversol TLC17K	1	1,835.98	1835.98
Cabling:					0.00
DC Cable:	General Cable Class RV-K 2.5mm2		100	1.79	179.00
AC Cable Protection:	EuroCabos BT-CU-EPR 4+T	6mm2	100	3.97	397.00
Protection:					0.00
Fuses:	Hager LF312PV		4	6.05	24.20
Fuse Boxes:	Hager L501PV		4	4.85	19.40
Circuit Breaker:	Schneider Electric IC60N 4P 40A 400V		1	39.50	39.50
Connector Box:	Spelsberg PV-CB/1		1	91.59	91.59
Circuit Box:	Hager IP55 1FILA		1	20.09	20.09
Legal:					0.00
Administrative:	Request + Inspection + Issuing		1	6,160.00	6160.00
Generation Permit:	Registration + Issuing + Inspection		1	960.00	960.00
Commercial Permit:	Registration + Issuing + Inspection		1	1,000.00	1000.00
			SUBTOTAL (VAT Inc)		30785.65
			Installation		0.30
			Installation Cost		9235.70
			TOTAL (€)		**40021.35**

Fig. 7: Total cost of the system designed to generate maximum energy according to legislation.

D. Financial Indicators and Project Evaluation

The first step to run a financial analysis through NPV, PP and LCOE, is to obtain the annual cash flows for all projects. Table IX presents the input parameters used for cash flow calculation.

TABLE IX: Input parameters for cash flow computation.

	Initial PV η	Inverter η	PV η Degradation Rate	Incident Power (MWh)	Reference Tariff	Discount Rate	Property Depreciation
Windows	2.296%	97.1%	0.4%/y	1106.623	3.45€/MWh	5.5%	4%/y
Carport	19.738%	98.3%	0.36%/y	81734.832			
Legal Max.	15.840%	97.9%	0.36%/y	81734.832			

Initial PV efficiency is given by the module's datasheet or through experimental tests and it refers to module's efficiency during the first year of operation. PV efficiency degrades with time affecting the overall system efficiency for the project's lifetime [8]. Incident power refers to the total input power the solar panels collect during one year. This value is obtained through simulation.

The reference tariff for 2020 was set at 45/MWh in the document Portaria n.º 80/2020 25 de março 2020. The reference tariff changes annually, however since it is unpredictable, this value is used for the lifetime of the project.

The lifetime of the project considered is 30 years, since it is plausible that a PV system with frequent maintenance is still operating after this time [8]. Since even most optimistic manufacturers will only offer 25 year warranty of their solar products, it is considered that the tangible property will lose all value in 25 years at a rate of 4%/year.

According to the maintenance company Ao Sol, PV maintenance should happen at least every two years. The operation and maintenance costs considered were quoted by the company.

The financial indicators computed with these parameters are presented on Table X.

TABLE X: Net present value, payback period and levelized cost of energy of each project.

	Initial Investment	**30 Year Power Output**	**Annual Average Power Output**	**NPV**	**PP**	**LCOE**
Windows	29 772.04 €	10.605 MWh	0.35350 MWh	-730.943 €	30.014 years	2856.829 €/MWh
Carport	69 516.19 €	1973656 MWh	65788 MWh	835574.406 €	1.029 years	0.0354 €/MWh
Legal Max.	40 021.35 €	1577397 MWh	52579 MWh	668195.153 €	1.021 years	0.0256 €/MWh

IV. Discussion

A. Laboratory Work

The highest recorded experimental efficiency (2.618%) leads to an STC efficiency of 2.296%. Efficiency computed through datasheet information at STC is 6.667%. This corresponds to a discrepancy of 65.562%. Several factors contribute to this discrepancy:

- **Incident light spectrum:** The emission spectrum of a common halogen lamp reaches peak intensity around 650 - 950 nm of wavelength [9]. The absorption spectrum of CdTe modules reaches peak between 10 - 700 nm of wavelength. [10]. Therefore, these spectrums are mismatched. Ideally, tests would have been run under natural light or under a light source that better matches the absorption spectrum.
- **Load:** The resistors used as the load are carbon composition resistors with a rated power of 1 W. The maximum output power registered ranges from 1.828 W to 2.812 W, all values way above the resistors' rated power. Although voltage and current levels never exceeded the resistors' maximum, the overheating caused by excess power may have damaged the resistors, leading to less accurate readings. Instead of Carbon resistors, a rheostat or a potentiometer with adequate power and ohmic range could have been used as the load.
- **Thermometer:** For accurate temperature readings the thermometer probe must be in total contact with the surface of the module. However, it is difficult to ensure complete surface contact due to thermal expansion. This can be avoided by using an infrared thermometer.

Fill factor is a measure of how close to ideal is the performance of a solar cell. Fill factor computed through datasheet data is 0.701. This value is slightly below the typical values for CdTe modules: 0.75 - 0.9 [11]. This indicates low manufacture quality that introduces parasitic resistances in the module.

Experimental results are similar to datasheet information, indicating a fill factor of 0.673. This small difference of 3.866% is mostly due to parasitic resistances in set-up system.

B. Financial and Energy Analysis

The most obvious conclusion that can the drawn from the data in Table X is that the solar glass windows is the least compelling.

The solar glass project generates the lowest power and presents a negative value of NVP. Since the present value of cash inflows is less than the present value of outflows (money earned is worth less than the costs) meaning this is a bad investment. Running the annual cash flow analysis it was observed that, while depreciation is happening, the annual cash flows are always negative. On the 27^{th} year, the cash flow is positive for the first time. This leads to a payback time greater than 25 years. This is a result way above the typical payback period for PV projects. LCOE is 2856.829 €/MWh, the highest value of all projects. On the other hand, this is the project with the smallest initial investment. Low module efficiency means low power output therefore, even with a small initial investment, the price per unit of power escalates.

The project designed to generate maximum power by covering the carport and the project designed to output the maximum power allowed by law end up generating approximately the same power over the course of 30 years. They also both have a positive NPV and similar LCOE. This points to the conclusion that the power limitations imposed by law still allow for the design of cost-effective solar systems and that these systems are on par with the systems designed to maximise sun power generation.

It is also important to note that, although these projects have close NPV and LCOE, the system designed according to the law requires a smaller initial investment and has a shorter payback time. Meaning, it is the most attractive investment.

V. Conclusions

A. Conclusions

As a response to European environmental concerns, Portugal has been creating programs and laws on renewable energy generation. The laws enforced on renewable energy generation at small scale present some power limitations that directly affect the PV system's design and size.

The impact that these laws have on self consumption has been studied previously, concluding that designing to cover 25% of annual consumption leads to the best financial results.

The aim of this work is to study the financial viability of solar systems in rural areas considering the legal generation threshold *versus* exploring the existing solar potential.

Before presenting the final conclusions on this topic, it is important to mention some factors that limit the extrapolation of findings to other case scenarios. Sources of result uncertainty are: annual weather conditions that can not be correctly predicted/simulated for a 30 year time period, component's cost changes and so does VAT. The reference tariff is updated annually and the discount rate changes from project to project. Besides that, the findings refer to a residential building located in Algarve therefore, results could vary if the location was set at a less ”sunny” part of the country. To minimise sources of uncertainty it was assumed that initial investment happened all at once in year zero. Although this is realistic for a domestic PV project, it is important to note that it is not the norm.

The solar glass system was designed as an attempt to maximise generation while reducing the building's heating load. This BIPV solution would have a small impact on the visual appearance of the building while generation energy. Unfortunately, as could be seen during the laboratory test, solar glass CdTe based modules that are easily accessible in the market for a competitive price still lack quality. Low module efficiency renders this project unviable since it generates the lower annual power between the three projects. Although it has the lower initial investment cost, the payback period and LCOE are the highest.

The other project designed to harness the highest amount of solar energy consists of replacing the carport cover by solar panels. This project presents the highest investment cost due to the price of the high power solar modules used. However, the high generation still renders the project viable with a NPV greater than zero and payback period of less than one year. This is a BIPV solution that does not take ground space and offers shading besides generating clean energy.

The project developed in order to generate the maximum power allowed by law is also viable and, in fact, it presents financial and energy results close to the previous project. The payback period is the smallest of all three projects being less than one year. The LCOE is the lowest, meaning that the one euro invested in this project renders the maximum output power.

When it comes to output power, the two viable projects are similar: the one developed according to law limitations only generates less 396 MWh every year. This value is not significant taking into account the total generated power.

From this analysis, it must be concluded that the Portuguese legal framework on Small Production Units does not render domestic solar projects in rural areas financially unviable and does not lead to wasted generation potential. On the contrary, it leads to projects on par with projects developed for maximum generation potential usage.

B. Future Work

- **Laboratory Work:** Module's efficiency should be re-measured under uniform, full spectrum illumination with the use of appropriate material, as cited in Section IV-A.
- **Project Location:** The residential building considered for this study is located in the South of Portugal where irradiance levels are high. Changing the location of the building to areas where irradiance is lower would ensure that the law limitation does not impair viability anywhere.
- **Building Type:** Residential urban buildings with several floors are physically very different from the building in this case study. Therefore, viability studies on high rise buildings in cities would complement the present study.

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