# Self-Consumption and Battery Bank PV Systems in the Residential Sector in Portugal

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***Abstract*— The Self-Consumption regulation in Portugal was released in the beginning of 2015 and states that the grid injection tariff is based on the Iberian market average (around 0.04€/kWh) while the average electricity tariff is 0.16€/kWh. This clearly shows that injecting the surplus energy produced by the PV System into the grid is no longer the main purpose since exporting into the grid generates some revenue that is lower than the savings and the payback time is negatively affected. Based on this information we were motivated to analyse the economic feasibility of different size PV Systems (1kW, 3kW, and 5kW) based on the self-consumption regime and also supported by a battery bank. The purpose of this paper is to determine whether the battery bank is profitable in Portugal and what city is the most attractive to invest in. Overall, we found that the PV Systems linked to a battery bank is not as profitable as standalone PV Systems in the Portuguese self-consumption regime. This is because the price of the battery bank is still too expensive. The mainland presented better values than the islands for the 1kW and 3kW PV Systems. The islands present better profitability values than the mainland for the 5kW PV System even though the initial investment cost is higher. Due to economical factors, the investment in PV Systems is always changing. The main contribution is to analyse if under the current situation in Portugal it compensates to invest in PV Systems with or without a battery bank.**

***Index Terms* — Battery bank, Grid-tied PV System, IRR, Self-Consumption.**

## I. INTRODUCTION

Feed-in tariffs for small-scale (up to 3.68kW) PV Systems in Portugal started out in 2008 with a value of 0.65€/kWh. This feed-in tariff has been declining over the years due to the bad economic situation of the country and to the cost reduction of the PV Systems [1], [2].

The number of new PV system installations in Portugal has been decreasing since 2012 due to the continuous cuts made to the feed-in tariffs. Portugal has a target to install 720 MW of solar PV systems by 2020 [3]. In January 2015, the feed-in tariffs for the small-scale solar productions were cut and a new tariff based on the Iberian market value is attributed to the producers who inject energy into the grid. Up to now, self-consumption was not recognized in Portugal, but solar producers will be able to self-consume as well as inject the excess energy into the grid.

This new Self-Consumption regulation states that exporting the surplus solar energy into the grid is allowed at an average tariff of approximately 0.04€/kWh and this value varies according to the OMIE (Operator of the Iberian Energy Market) electricity market price. At the moment, the electricity tariff is approximately 0.16€/kWh (Excluding VAT) which is almost 4 times higher than the grid injection tariff. As the savings made on self-consumption is much higher than the gains made when injecting the solar production into the grid, the new regulation favours the self-consumption regime and helps limit the possibility to oversize the PV Systems [4].

Since injecting the surplus energy from the PV System into the grid is not very profitable in Portugal we were motivated to determine if injecting the surplus solar energy into a battery bank would be more profitable. The purpose of this paper is to determine whether investing in Photovoltaic systems in Portugal is still profitable since all the attractive incentives were cut, to determine if a PV System linked to a battery bank is profitable, and to determine which size PV system and respective city is likely to make the most profit.

Battery banks are still considered to be expensive even though the prices have lowered over the years. The Lead-Acid and Gel batteries are the most common among the battery banks linked with the PV Systems. The lead-acid batteries are known to have an 8-year lifecycle while the gel batteries have a 12-year lifecycle. In this work we will analyse both these battery banks [5], [6].

Portugal can be divided into three regions namely the mainland, the archipelago of Madeira and the archipelago of Azores. The cities representing those areas (because they presented the highest solar radiation) were respectively Aljustrel, Calheta, and Vila do Porto. The three regions practice different electricity tariffs, VAT tax rates and PV System investment costs. The economic parameters used to determine the attractiveness of the investment are namely the Internal Rate of Return (IRR), the Profitability Index (PI), and the Discounted Payback Period (DPBP) of the Investment.

The overall organization of the paper is as follows. After the introduction, we describe the methodology used to calculate the economic measures in order to analyse the economic assessment of the PV Systems in Section II. The results of the main findings of the data analysis are reported and discussed in Section III. The main conclusions made in this paper are explained in Section IV.

## II. METHODOLOGY

In this section, all the methods that were used to calculate the profit of the investment are described.

In order to analyse the cost-effectiveness of the PV systems, several indicators were taken into account. The most common methods to determine the profitability and economic aspects of this type of project are namely the Internal Rate of Return (IRR), the Discounted Payback Period (DPBP) and the Profitability Index (PI). These methods are used in this work to evaluate the economic feasibility of a 1kW, 3kW and a 5kW PV system with and without batteries in Portugal. A brief description of all the economic methods is provided in section A.

### A. IRR, DPBP, and Profitability Index

To calculate the IRR, the DPBP, and the Profitability Index, the annual cash flow has to be calculate first, which is the subtraction between the cash inflow and the cash outflow, as shown in equation 1 [7], [8].

$$SCF_y = Cash\ inflow_y - Cash\ outflow_y$$
$$SCF_y = \sum_{y=1}^{Y} (Ts \times Es + Te \times Ee)_y - \sum_{y=1}^{Y} (M)_y \quad (1)$$

Where Y is the lifetime horizon of the investment, $Ts$ and $Te$ are respectively the self-consumption tariff and the grid injection tariff, $Es$ is the annual electricity (kWh) generated by the PV System used in self-consumption, $Ee$ is the electricity produced by the PV System that is exported into the grid and $M$ is the maintenance cost.

The Discounted Cash Flow (DCF) contains the time value of money and represents the Simple Cash Flow (SCF) value in the future. The DCF value is updated with the interest rate and it´s formula is shown on equation 2.

$$DCF_y = \frac{SCF_y}{(1+r)^y} \quad (2)$$

The $r$ is the interest rate in equation 2.

The DPBP considers the value of money over time since it uses the DCF values to calculate the number of years needed to breakeven. The IRR is an indicator that should be compared to a discount or interest rate [9]. A high IRR indicates that the investment opportunity is favourable, and it should be higher than the rates mentioned above. Additionally, the time value of money is considered in the method and it allows a comparison across locations without considering the regional discount rates [10]. Equation 3 shows the IRR formula.

$$0 = \frac{\sum_{y=1}^{Y} C_y}{(1+IRR)^y} - C_0 \quad (3)$$

Where Y is the lifetime horizon of the investment, $C_y$ is the yearly net cash flow, $C_0$ is the initial investment of the PV System, and $r$ is the interest rate.

The Profitability Index (PI) identifies the relationship between the investment and its return, and indicates how much profit or loss the project makes in a certain amount of time. The PI is calculated by dividing the NPV of a project by its initial investment and adding 1, just as shown on equation 4.

The NPV compares the present value of all cash inflows with the present value of all cash outflows associated with an investment project. The NPV takes the present value of the money into consideration and is the most accepted standard method used in financial assessments for long-term projects. However, its main drawback lies in the need for assuming an interest rate. NPV and IRR are commonly used to evaluate the profitability of an investment by calculating the difference between the discounted values of cash flows over the lifetime of the projects.

There is a breakeven when PI is equal to 1.00 and when PI is equal to 2.00 the profit is double the investment. The time of the investment assumed for this work is 25 years [11].

$$PI = \frac{\text{NPV}}{\text{Initial Investment}} + 1 \quad (4)$$

### B. Assumptions

In this section, all the assumptions are defined in order to explain how the results of this study are obtained.

The PV System sizes used in this work were the 1kW, the 3kW and the 5kW and all assumed to be used in the residential sector. There are two types of self-consumption scenarios (100% and 70% self-consumption) and three types of PV Systems:

- PV System **without** a battery bank
- PV System with a **lead-acid** battery bank
- PV System with a **gel** battery bank

Portugal has currently an instantaneous net-metering regime. This means that self-consumption will only happen if the energy is consumed at the same instant it is being produced, as opposed to other net-metering systems (see the United States or Brazil) where a monthly balance is done in order to define the resulting balance between consumption and production. As a result, Portuguese consumers will receive 0.04€/kWh (on average) while paying 0.16€/kWh (plus VAT). Because of the instantaneous net-metering system, the 70% self-consumption scenario (or even lower if the PV system is over-sized) is very likely to happen in Portugal.

The scenarios are as follows:

- **Scenario 1** – **100%** self-consumption, PV System **without** batteries;
- **Scenario 2** – **70%** self-consumption, PV System **without** batteries;
- **Scenario 3** – **100%** self-consumption, PV System with **lead-acid** batteries;
- **Scenario 4** – **70%** self-consumption for PV System with **lead-acid** batteries;
- **Scenario 5** – **100%** self-consumption for PV System with **gel** batteries;
- **Scenario 6** – **70%** self-consumption for PV System with **gel** batteries;

As stated above, in this paper, both Lead-Acid and Gel batteries are studied. We assumed that the solar producer does his own maintenance of the acid-lead batteries in order to keep the initial investment values as low as possible. The autonomy capacity for all the systems is assumed as 1 day (5 hours of consumption) and the Depth of Discharge is 50% in order to have a lifecycle of approximately 8 years for the lead-acid batteries and 12 years for the gel batteries [5], [6].

The prices and sizes of the battery banks considered for this work are presented in Table I. The prices assumed for the battery bank sizes were the same for all the cities in Portugal.

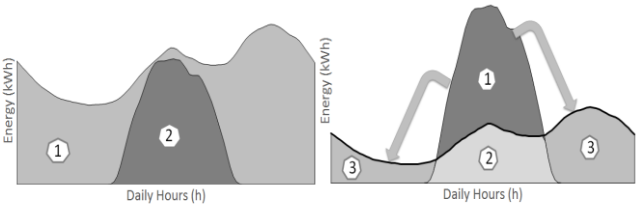
It should be noticed that the battery sizes considered are minimal in order to keep the low price. Their purpose is solely to augment the self-consumption level of the system since injecting into the grid is much less profitable.

Since instantaneous net-metering is applied in the Self-Consumption regime in Portugal the relation between the contracted power (CP) and the PV System size depends on the consumer behaviour. We received three quotes for each of the battery banks. In the calculations of the economic methods, the average battery bank cost shown in Table I was used as the battery bank replacement cost in all the regions. In general, the CP recommended is the one shown in Table I.

TABLE I: INFORMATION ABOUT THE BATTERY BANKS

| PV System | CP w/o Battery kVA | CP w/ Battery kVA | Battery bank size | Cost Range | Lead-Acid Cost | Gel Cost |
|---|---|---|---|---|---|---|
| 1kW | 10.35 | 3.45 | 2 x (12V/250Ah) | Min | 420€ | 426.00€ |
| | | | | Avg. | 430€ | 477.33€ |
| | | | | Max | 440€ | 506.00€ |
| 3kW | 20.7 | 6.9 | 8 x (6V/250Ah) | Min | 1.680€ | 1,704.00€ |
| | | | | Avg. | 1.720€ | 1,909.33€ |
| | | | | Max | 1.760€ | 2,024.00€ |
| 5kW | 27.6 | 10.35 | 12 x (6V/250Ah) | Min | 2.520€ | 2,556.00€ |
| | | | | Avg. | 2.580€ | 2,864.00€ |
| | | | | Max | 2.640€ | 3,036.00€ |

In Portugal the hourly tariffs associated to the contracted power of up to 20.7kVA is chosen between the Mono and the Bi-hourly tariff. For contracted powers between 27.6kVA and 41.4kVA only the Tri-hourly tariffs can be used and for contracted powers superior to 41.4kVA only the Tetra-hourly tariffs are used. The hourly tariff that most benefits the PV System associated to a battery bank is the Mono-hourly tariff since it generates the most profit because of the high value that is practiced in the off-peak hours compared to the same hours in the Bi-hourly tariff. Figure 1a) illustrates how the PV system size should be limited to the consumption value of the household during the day in order to limit grid injection. Figure 1b) shows us a PV System linked to a battery bank, setting in which the PV System size can be much higher than the consumption value of the household since the surplus solar production is injected into the batteries to later be used in the off-peak hours of the day.




(a) 100% self-consumption (b) batteries

Fig. 1. Consumption, Self-Consumption and battery bank storage.
1 – Household Consumption / Battery bank storage
2 – Self-consumption / solar production
3 – Surplus solar production injected into the batteries

Considering the three mentioned regions, we initially used *Solterm* for analysing the production. *Solterm* is a PV System dimensioning software developed in Portugal and has all the climate information of 308 cities in Portugal. The meteorological information that was of interest for this work included the solar radiation and respective location (latitude and longitude) of each of the cities. We sorted all the cities based on their solar radiation values and analysed 60 cities from the mainland, 10 cities from the island of Madeira and 19 cities from the island of Azores [12]. Unfortunately the climate information that *Solterm* uses has only one year of data from each of the cities so we decided it would be best to use *Retscreen* version 4 [13] software and respective NASA meteorological database which is calculated based on the monthly average over 23 years [14]. *Retscreen* is a software tool used to analyse energy projects and it is possible to obtain the climate data of a specific location if the latitude and longitude coordinates are provided. Therefore, the location information that we obtained from the *Solterm* software was used to calculate the climate information in *Retscreen* since this software does not have the cities that we needed in its default location database. The cities that presented the highest horizontal solar radiation values in *Retscreen* were Aljustrel (mainland) with 5.05 kWh/m2/d, Calheta (Madeira Island) with 5.33 kWh/m2/d and Vila do Porto (Azores Island) with 4.71 kWh/m2/d.

*Retscreen* was also used to calculate the solar production of each of the PV systems in the respective cities. First, we needed to select the type of solar module and inverter that was going to be used on all of the PV Systems. Secondly, we had to insert the slope and azimuth values according to the city. Optimum slope for Aljustrel is 33º, for Calheta is 28º and for Vila do Porto is 32º. Finally, the annual solar production is calculated on *Retscreen* and the result outcomes are shown in the results section.

The annual solar production calculated in *Retscreen* for the three PV System sizes will be used for both PV System types (with and without battery banks). In this case the values are overrated because we did not consider the battery losses, which can go up to 15% for the lead-acid batteries and a little bit lower for the gel batteries according to [15].

All the steps taken to obtain the annual solar production are explained in the following subsections.

### 1) *PV Module and Inverter Selection*

For this work, the Solar World 245W Polycrystalline PV modules were selected since they are very efficient and obtained a perfect score (evaluated as “very good”) in the PV+Test2.0 in 2013 according to [16]. The chosen PV module type is crystalline silicon, and the lifecycle is usually assumed to be within 25-30 years [17]. Thus, in this work the lifetime of the system investment is assumed to be equal to 25 years.

Among all the components of a Residential PV system, only the inverter is expected to be replaced, at least once, within the lifetime of the system. Commonly, 10 years is considered as the inverter´s lifecycle [18]. We assume in this work that the inverter replacement takes place in year 10 and in year 20. The inverters selected for the PV Systems without inverters for this work were the *SMA - Sunny boy* 1300TL, 3000TL and 5000TL since they present the best efficiency values. The efficiency of the inverters referred above is as follows: for the 1kW, 3kW and 5kW PV Systems are 94.3%, 96.1%, and 97.5% respectively [19]. The inverters selected for the PV Systems with batteries were the *Victron Multipuls* 24/1200, 24/3000 and the 48/5000 since they present the best efficiency rates and for the fact that they are hybrid inverters. These types of inverters have the advantage of injecting the solar energy into either the batteries or the grid. The efficiency of the inverters referred above is as follows: for the 1kW, 3kW and 5kW PV Systems are 94%, 94%, and 95% respectively [20]. First, the solar energy is injected into the household grid for self-consumption, secondly the surplus energy is then directed into the batteries and when these are full and there is no consumption in the household the solar energy is injected into the distribution grid. Table III presents the inverter replacement cost rate assumed for each of the PV System sizes.

### *2) Performance Ratio (PV system losses)*

For PV Systems, a performance ratio (PR) between 75-90% is commonly considered, which is caused by all losses generated in the inverter, wiring (length, diameter and material), and module soiling (i.e. dust, snow, etc.) [21], [22]. In the methodology guidelines on life cycle assessment of PV systems it was recommended to consider a default value of 0.75 for roof-top installations [23]. Thus, in this work the PR is assumed as 0.80.

In order to calculate the economical methods (NPV, IRR, DPBP and PI) it was essential to have, for every region, the following parameters:

- Annual solar production value;
- Average electricity escalation rate;
- Euribor Interest rate;
- Inflation rate
- Electricity tariff;
- Battery injection tariff;
- PV system and Battery bank cost (initial investment);
- Maintenance and Operations cost;
- Inverter substitution cost;
- Battery bank substitution cost;
- Degradation rate of the PV modules.

All three regions in Portugal present different solar production values, PV System initial investments, electricity tariffs for the various hourly electric supply charges, and also the VAT tax rates. All the cities in Portugal practice the same maintenance and operations rate, inverter replacement rate, battery bank replacement rate, electricity evolution rate, the Euribor interest rate and the inflation rate.

The steps taken to obtain all the parameters mentioned above are explained in the following subsections and the outcome is presented in the results section.

### *1) Economical parameters*

In order to roughly predict the electricity price during the next 25 years we calculated an escalation rate of the electricity price based on the past 25 years [24]. The average grid injection evolution rate was based on the OMIE values since the year 2011 [25]. The electricity tariffs that are considered in this work are the ones that are practiced at the present moment in all the cities (year 2015) [26]–[28]. For scenarios 1 and 2 the 1kW and 3kW PV System will be associated to both Mono and Bi-hourly tariffs since both of them are frequently used in the residential sector and the 5kW PV System will be associated only to the Tri-hourly tariff. For all the other scenarios the Mono-hourly tariffs will be associated to all the PV System sizes linked to a battery bank since this tariff has the highest off-peak tariff out of all the tariffs.

A share of the total annual production was associated to the on-peak, regular and off-peak hours of the hourly tariffs according to the summer and winter months, as shown in Table II [29]. ERSE has solar production data (15 minute sampling time) from a microproduction installation in the mainland and we used this to calculate the share rate of each hourly tariff for both summer and winter months [30]. In general, the share percentages of the on-peak hours are higher in the islands than in the mainland when comparing the same hourly tariffs therefore the islands are prone to having higher saving than in the mainland.

TABLE II: SHARE PERCENTAGES OF THE HOURLY TARIFFS

| | **Mainland** | | **Madeira** | | **Azores** | |
|---|---|---|---|---|---|---|
| | **Winter** | **Summer** | **Win** | **Sum** | **Winter** | **Summer** |
| **Bi-hourly tariff** | | | | | | |
| **on-peak** | 77% | 78% | 96% | 95% | 99% | 99% |
| **off-peak** | 23% | 22% | 4% | 5% | 1% | 1% |
| **Tri-hourly tariff** | | | | | | |
| **on-peak** | 22% | 19% | 20% | 26% | 18% | 22% |
| **regular** | 56% | 59% | 76% | 70% | 81% | 77% |
| **off-peak** | 23% | 22% | 4% | 5% | 1% | 1% |

*Solterm* provides the solar production profile of each city in Portugal therefore providing information on the monthly solar production of each city. Only the Mono-hourly tariff rate did not have a share rate associated to it since the Mono-hourly tariff is the same in all hours of the day. Based on all this information it was possible to obtain the share rate for all the hourly tariffs (Bi-hourly and Tri-hourly) in both summer and winter months.

To predict the Euribor interest rate for the next 25 years an average was calculated based on the past 16 since the Euribor is associated to the Eurozone that was only founded 16 years ago [31].

The inflation rate was also considered in this work in order to obtain realistic values for the maintenance labour and operations costs during the 25 years.

In order to use realistic investment costs in this paper we had to obtain at least three quotes from different companies from each region and make an average investment value for each region. All the quotes are turnkey solutions, which include all the components of the PV System, battery bank, mounting structure, delivery, and installation. This process is not easy to achieve since many companies are not familiar with the new self-consumption regulations.

### *2) Operating and Maintenance Cost*

In order to calculate the profit of the investment it is necessary to consider the inverter replacement costs as well as the costs associated with the operations and maintenance (O&M) along the system's lifespan. According to [32]–[34], the maintenance cost is estimated between 1-3% of the initial investment per year. Table III presents the operations and maintenance rate for each of the PV System sizes.

### *3) Degradation Rate*

Since PV modules have a relatively long lifecycle, the power output of the system can be significantly influenced by degradation phenomena. The degradation of the modules reduces the efficiency of the system over time [23]. Consequently, the predicted generation of the PV system and its economic payback period analysis can be affected by this issue. The methodology guidelines on the lifecycle assessment of PV systems statements, recommends considering a linear degradation, reaching 80% of the initial efficiency at the end of a 30 years lifetime (i.e., 0.7% per year) [23], [35]. We assumed the PV degradation as 0.7%/year.

## III. Results and Discussion

All the results obtained from the methodology section are presented in this section.

All the parameters presented in Table III are common to all the regions in Portugal and they include maintenance and operations rate, inverter replacement rate, electricity evolution rate, the Euribor interest rate and the inflation rate. All the costs related to the battery banks are presented in the Methodology section of this paper in Table I.

TABLE III: Information common to all regions in Portugal

| Parameter Description | | Value |
|---|---|---|
| **Maintenance and operations rate** | **1kW** | 3% |
| | **3kW** | 1.5% |
| | **5kW** | 1.5% |
| **Inverter Replacement cost rate** | **1kW** | 15.0% |
| | **3kW** | 13.0% |
| | **5kW** | 10.0% |
| **Grid injection Tariff based on OMIE 2015** | | 0.0377 € |
| **Grid injection Evolution rate** | | 4.250% |
| **Electricity Evolution rate** | | 2.428% |
| **Euribor Interest rate** | | 2.644% |
| **Inflation Rate** | | 1.48% |

Table IV shows all the values of the parameters according to the three different regions. All three regions have different solar production values, PV System Investments, electricity tariffs for the various hourly electric supply charges, and VAT tax rates. Table IV shows three types of PV System Investments, the first is related to the PV System used only for self-consumption (scenarios 1 and 2) without battery banks. The second refers to the investment that includes a PV System linked to a lead-acid battery bank and the third investment is associated to a PV System linked to a gel battery bank.

Madeira Island has the highest solar production values while the Azores Island has the lowest, for the cities under consideration.

The values presented in Table IV were used together with the values from Table III to calculate the IRR, Profitability Index and Discounted Payback Period for the 1kW, 3kW and 5kW PV systems of each region for each of the six different scenarios. Table IV shows us that the overall investment costs for the self-consumption PV Systems is the lowest in the mainland and highest in the Madeira Island. We can verify that in general the bigger the PV System size, the cheaper the investment per Watt in all the regions.

The hourly tariffs are mostly higher in the mainland and lowest in the Azores Island.

All investment costs and electricity tariff prices presented in Table IV are excluded from the VAT tax rate.

TABLE IV: 1kW, 3kW and 5kW PV System Information

| | | | Mainland - Aljustrel | | Madeira Island - Calheta | | Azores Island - Vila do Porto | |
|---|---|---|---|---|---|---|---|---|
| **PV System Solar Production (kWh)** | **1kW** | | 1529 | | 1566 | | 1409 | |
| | **3kW** | | 4577 | | 4687 | | 4218 | |
| | **5kW** | | 7610 | | 7793 | | 7014 | |
| **PV System Investment for self-consumption** | **1kW** | | 2,004.40 € | 2.00 €/W | 2,413.56 € | 2.41 €/W | 2,342.37 € | 2.34 €/W |
| | **3kW** | | 6,529.27 € | 2.18 €/W | 6,955.77 € | 2.32 €/W | 6,353.85 € | 2.12 €/W |
| | **5kW** | | 10,225.56 € | 2.05 €/W | 10,262.65 € | 2.05 €/W | 9,275.10 € | 1.86 €/W |
| **Lead-Acid Battery Bank + PV System Investment** | **1kW** | | 2,486.37 € | 2.49 €/W | 3,210.17 € | 3.21 €/W | 3,156.78 € | 3.16 €/W |
| | **3kW** | | 7,406.46 € | 2.47 €/W | 8,161.83 € | 2.72 €/W | 7,710.39 € | 2.57 €/W |
| | **5kW** | | 11,919.17 € | 2.38 €/W | 11,969.17 € | 2.39 €/W | 11,256.32 € | 2.25 €/W |
| **Gel Battery Bank + PV System Investment** | **1kW** | | 2,620.96 € | 2.62 €/W | 3,407.30 € | 3.41 €/W | 3,353.91 € | 3.35 €/W |
| | **3kW** | | 7,731.39 € | 2.58 €/W | 8,552.08 € | 2.85 €/W | 8,100.64 € | 2.70 €/W |
| | **5kW** | | 12,479.42 € | 2.50 €/W | 12,536.92 € | 2.51 €/W | 11,824.07 € | 2.36 €/W |
| **Electricity tariff Price** | **Mono-hourly** | | 0.1587 € | | 0.1609 € | | 0.1624 € | |
| | **Bi-hourly** | **On-Peak** | 0.1890 € | | 0.1843 € | | 0.1878 € | |
| | | **Off-Peak** | 0.0978 € | | 0.0979 € | | 0.0990 € | |
| | **Tri-hourly** | **On-Peak** | 0.2144 € | | 0.2095 € | | 0.2150 € | |
| | | **Regular** | 0.1704 € | | 0.1678 € | | 0.1638 € | |
| | | **Off-Peak** | 0.0978 € | | 0.0979 € | | 0.0990 € | |
| **VAT tax rate** | | | 23% | | 22% | | 18% | |

As previously stated, the Profitability Index gives us an idea of the amount of profit a certain investment can make during the 25-year period of our project. Breakeven takes place on the year of the Discounted Payback and in our paper, this breakeven takes place usually before the 12th year and the profit is accumulated from there onwards. We consider a good investment when the investment is doubled (PI=2.00) before the end of 25 years. Table V presents the IRR, PI and DPBP values of Scenario 1 (100% self-consumption regime) and Scenario 2 (70% self-consumption) PV System without batteries. The bi-hourly tariffs offer higher profit in the investment when compared to the mono-hourly tariffs in all cases. The profit over the investment is doubled only for the 3kW (all three regions) and 5kW (only islands) PV Systems. The city in the mainland does not make double the profit on the investment with the 5kW PV System under the tri-hourly tariffs but the Investment in the islands can make more than double the profit on the investment. This clearly shows how having higher share percentages in the on-peak hours, as shown in Table II, can be an advantage even though the investment costs are higher in the islands than in the mainland.

Overall, all the cities in all situations manage to have a profitability index value a little bit higher than the breakeven value (PI=1) by the end of the 25 year period except for the 1kW PV Systems in scenario 2. The PI values in the mainland have the highest values for the 1kW and 3kW (mono-hourly) PV Systems but the lowest for the 3kW (bi-hourly) and 5kW PV Systems reflecting the disadvantages that the hourly tariffs practiced in the mainland brings to solar producers. Even though the bi and tri-hourly tariffs are higher in the mainland, the hours that are practiced do not coincide with the peak hours of the PV System and this presents great disadvantages in the savings produced by adopting the self-consumption regime.

In general, the IRR values are always higher than the Euribor interest rate (2.644%) assumed in this work, which means that using a PV system in a self-consumption regime is a good investment all over Portugal. In order to double the profit of the investment the IRR has to be a little under 10% and the discounted payback period has to be just under 12 years.

In scenario 2, 70% of the solar energy is used for self-consumption and the rest is injected into the grid except for the 1kW PV System since this system sends energy into the grid at 0€/kWh because the grid injection registration costs are too expensive. In this case, there is always a 30% loss of solar energy. Overall, the scenario 2 results indicate that injecting the surplus solar energy into the grid is not profitable enough to make double the investment by the end of 25 years in any of the cases. The 1kW PV System presents the worst results. This information is very relevant to know since the 1kW PV System is the one that most households in Portugal should acquire for self-consumption since under the instantaneous net-metering they cannot take full advantage of higher power.

TABLE V: THE IRR, PI, AND DPBP OF SCENARIOS 1 AND 2 - PV SYSTEM WITHOUT BATTERIES

| | **100% self-consumption** | | | **70% self-consumption** | | |
|---|---|---|---|---|---|---|
| | **IRR** | **PI** | **DPBP** | **IRR** | **PI** | **DPBP** |
| | **1kW** - Mono-hourly tariff | | | | | |
| **Mainland** | 7.68% | 1.74 | 14 | 2.22% | 0.95 | > 25 |
| **Madeira** | 5.97% | 1.44 | 16 | 0.42% | 0.76 | > 25 |
| **Azores** | 4.42% | 1.24 | 21 | -1.06% | 0.60 | > 25 |
| | **1kW** - Bi-hourly tariff | | | | | |
| **Mainland** | 9.36% | 1.97 | 12 | 3.68% | 1.13 | 22 |
| **Madeira** | 8.14% | 1.77 | 13 | 2.55% | 0.99 | > 25 |
| **Azores** | 6.66% | 1.57 | 15 | 1.22% | 0.83 | > 25 |
| | **3kW** - Mono-hourly tariff | | | | | |
| **Mainland** | 9.14% | 1.94 | 12 | 5.52% | 1.38 | 17 |
| **Madeira** | 8.77% | 1.88 | 13 | 5.18% | 1.33 | 18 |
| **Azores** | 8.69% | 1.86 | 13 | 5.14% | 1.33 | 18 |
| | **3kW** - Bi-hourly tariff | | | | | |
| **Mainland** | 9.69% | 2.03 | 12 | 5.97% | 1.45 | 16 |
| **Madeira** | 10.80% | 2.22 | 11 | 6.82% | 1.57 | 15 |
| **Azores** | 10.86% | 2.23 | 11 | 6.89% | 1.59 | 15 |
| | **5kW** - Tri-hourly tariff | | | | | |
| **Mainland** | 7.98% | 1.75 | 14 | 5.06% | 1.32 | 18 |
| **Madeira** | 12.64% | 2.56 | 9 | 8.74% | 1.89 | 13 |
| **Azores** | 12.56% | 2.55 | 9 | 8.68% | 1.88 | 13 |

Table VI presents the IRR, PI and DPBP values of Scenario 3 (lead-acid) and 4 (gel), PV System with batteries in the 100% self-consumption regime. In general, none of the PV Systems linked to a gel battery bank is considered a good investment since the PI values are lower than 2.00. All the IRR values are just below 7% and the DPBP is higher than 16 years. These calculations takes the inverter replacement (every 10 years) and battery bank replacement (every 8 years for lead-acid and every 12 years for gel) into account therefore adding to the expenses during the 25-year period.

Overall, the lead-acid battery scenario presents better results compared to the gel battery scenario. The 1kW PV System linked to the lead-acid batteries is not a good investment in any situation (city or type of battery bank). The mainland presents the best results for the 3kW PV. For the 5kW, Madeira Island presents the highest results due to the high mono-hourly tariffs that are practiced even though the investment cost is a little bit higher than in the mainland. This clearly shows how the high mono-hourly tariffs play a greater role than the investment cost and the solar radiation values. The Azores Island presents very low values because of the low solar radiation even though it has a lower investment cost than the Madeira Island.

TABLE VI: IRR, PI, AND DPBP VALUES FOR SCENARIOS 3 AND 4 PV SYSTEM WITH BATTERIES (100% SELF-CONSUMPTION)

| | **Scenario 3 – Lead-Acid** | | | **Scenario 4 - Gel** | | |
|---|---|---|---|---|---|---|
| | **IRR** | **PI** | **DPBP** | **IRR** | **PI** | **DPBP** |
| | **1kW PV System – Mono-hourly tariff** | | | | | |
| **Mainland** | 2.74% | 1.01 | 25 | 1.58% | 0.89 | > 25 |
| **Madeira** | -0.83% | 0.65 | > 25 | -2.24% | 0.54 | > 25 |
| **Azores** | -2.70% | 0.51 | > 25 | -4.38% | 0.41 | > 25 |
| | **3kW PV System – Mono-hourly tariff** | | | | | |
| **Mainland** | 4.91% | 1.27 | 18 | 4.00% | 1.16 | 21 |
| **Madeira** | 4.17% | 1.18 | 21 | 3.23% | 1.07 | 22 |
| **Azores** | 3.25% | 1.07 | 22 | 2.21% | 0.95 | > 25 |
| | **5kW PV System – Mono-hourly tariff** | | | | | |
| **Mainland** | 5.91% | 1.41 | 17 | 5.02% | 1.29 | 18 |
| **Madeira** | 6.44% | 1.48 | 16 | 5.55% | 1.36 | 18 |
| **Azores** | 5.64% | 1.37 | 17 | 4.67% | 1.24 | 19 |

Table VII has the same information as Table VI except that 70% of the solar energy is used for self-consumption and the rest is injected into the grid except for the 1kW PV System, just as explained before. This situation is likely to happen even with batteries because they have limited capacity.

Overall, the results indicate that injecting the surplus solar energy into the grid in this scenario is not as profitable as practicing a 100% self-consumption regime and is not advised due to the poor results. Once again, the 1kW PV System presents the worst results.

TABLE VII: IRR, PI, AND DPBP VALUES FOR SCENARIOS 5 AND 6 PV SYSTEM WITH BATTERIES (70% SELF-CONSUMPTION)

| | Scenario 5 – Lead-Acid | | | Scenario 6 - Gel | | |
|---|---|---|---|---|---|---|
| | **IRR** | **PI** | **DPBP** | **IRR** | **PI** | **DPBP** |
| | **1kW PV System – Mono-hourly tariff** | | | | | |
| **Mainland** | -5.22% | 0.37 | > 25 | -7.47% | 0.28 | > 25 |
| **Madeira** | -12.20% | 0.14 | > 25 | a | 0.06 | > 25 |
| **Azores** | a | 0.04 | > 25 | a | -0.04 | > 25 |
| | **3kW PV System – Mono-hourly tariff** | | | | | |
| **Mainland** | 0.51% | 0.78 | > 25 | -0.55% | 0.69 | > 25 |
| **Madeira** | -0.17% | 0.72 | > 25 | -1.29% | 0.62 | > 25 |
| **Azores** | -1.27% | 0.63 | > 25 | -2.59% | 0.53 | > 25 |
| | **5kW PV System – Mono-hourly tariff** | | | | | |
| **Mainland** | 0.11% | 0.74 | > 25 | -0.98% | 0.65 | > 25 |
| **Madeira** | 0.66% | 0.79 | > 25 | -0.40% | 0.70 | > 25 |
| **Azores** | -0.36% | 0.71 | > 25 | -1.59% | 0.61 | > 25 |

a - The IRR calculation for accumulated negative cash flows resulted in a very large absolute number that is not represented by excel. Nevertheless, the conclusion should be that the investment is not viable.

Out of all the scenarios, the 100% self-consumption scenarios for both PV System situations (with and without battery banks) present the best values and since the 100% self-consumption scenario presents better results than the 70% self-consumption scenario, grid injection is not advised. The PV Systems without batteries present better results than the PV Systems that are linked to battery banks due to the high replacement costs (inverters and battery banks) that are present during the 25-year period.

## IV. CONCLUSION

The PV System must be dimensioned to cover your instantaneous consumption only. More power than that will generate less return on the investment.

The cities that are more profitable to invest in a PV System without batteries are the ones of both islands but only for the 3kW and 5kW PV Systems. The mainland only doubles the profit on the investment with the 3kW PV System without batteries. The 3kW PV System has more profit when a bi-hourly tariff is practiced compared to the mono-hourly tariff. Even though the mainland presents the lowest initial investment costs and the highest hourly electricity tariffs, the islands had better results because the timetable of the hourly tariffs in the islands capture more of the solar production peak hours than the timetable set for the mainland.

We concluded that a PV System associated to a 100% self-consumption regime is more profitable than a 70% self-consumption regime whether it is linked to battery bank or not.

The lead-acid battery bank solution presented better results because the investment costs are lower. The PV Systems linked to battery banks takes into account not only the replacement of the inverter (every 10 years) but also the replacement of the battery bank. The battery bank replacement turns out to be very expensive over time. The lead-acid battery replacement takes place every 8 years and the gel battery replacement takes place every 12 years. Since the gel battery replacement was longer than the lead-acid battery we initially thought that it would be an advantage by lowering the replacement costs. It turns out that the gel batteries are very expensive and the longer replacement time does not give any advantage to the investment since the profit of the PV Systems with gel battery banks is always lower than the lead-acid batteries.

Overall, the PV System linked to battery banks are not considered a good investment since none of the scenarios present a double profit over the investment.

The 1kW PV System is not profitable in any PV System scenario and in any city. The majority of households have an annual consumption that can only support a 1kW PV System and as was seen this is the worst case to invest in since it only has a breakeven after twelve years. This is not an attractive investment. Not many households in Portugal have a consumption level during the daytime to absorb all the power produced by a 3kW and a 5kW PV system therefore making the 2020 Kyoto Protocol target harder to achieve through the residential sector investment since the investment is not attractive at this moment. The investment attractiveness can be improved if the PV system costs decrease and the electricity prices increase.

Both the PV System cost and the electricity tariff, apart from the solar radiation values, plays a big role on the possibility to double the investment in a period of 25 years.

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