Management of Energy Consumption Produced by Photovoltaic System with Storage

Francisco dos Santos Carvalho
francisco.santos.carvalho@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisboa, Portugal

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Abstract

This dissertation focus on the study and development of an Energy Storage System, in synergy with photovoltaic solar production, for applications on industrial surfaces of high energy consumption. Being in a constantly developing and growing area, the production of energy through renewable sources, in this specific case, the photovoltaic power plants can be aided and exponentiated through efficient consumption and production management, causing a significant reduction of energy demanded by the grid for each installation and hence an economic benefit to consumers. In this project the energy and economic impacts of the implementation of this type of solution, using the VBA platform, were studied and a system model was developed, with the respective controller, in the Matlab/Simulink platform for the desired effect.
Keywords: Energy Storage, Photovoltaic Production, Consumption and Production Management

1. Introduction

Energy dependency is becoming more difficult today, in times past. Consistent with this view, the European Union as a major consumer worldwide, has set a target for 2020 that 20% of energy production shall be provided by renewable sources, which would allow a significant reduction in the amount of imported energy and, consequently, associated costs. In this context, and focusing attention on photovoltaic production for being the renewable source under study in this dissertation, it increased, worldwide between 2011 and 2016, about 260 gigawatts, of which 45.2 gigawatts in Europe. In 2017, growth was very close to 30% compared to 2016 [1]. As a form of synthesis, the data described is illustrated in the figure below.

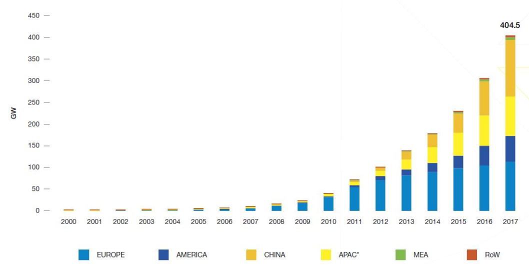

Figure 1: Worldwide evolution of installed capacity

On the other hand, it is also important to consider the beneficial environmental impact with the addition of this type of technology, given the successive worsening of climate change and its consequences worldwide. In this logic, the EU committed itself by 2020 to focus 20% of energy production from renewable sources, increasing energy efficiency saving 20% of EU energy consumption and a 20% reduction in the emission of gases with greenhouse effect, this being the orientation taken into account by the European countries in a strategic and political plan.

Thus, Portugal has an active and growing role in this type of technology, having extended and exploited its energy policy over time. Increasingly, there is concern with energy efficiency and deployment of renewable energy by the general population and large industrial consumers in particular. In the graph below, it is possible to verify the evolution of the installed power, in Mainland Portugal, over the years.

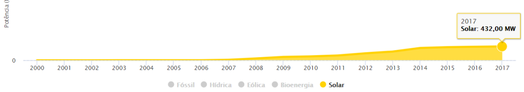

Figure 2: Evolution of installed capacity in the ilectroproducing centers of mainland Portugal

In order to continue the development in this area, it is explored in this project the possibility to join to the existing business model an energy storage strand with ambition to obtain economic benefits and energy use for consumers, in this case, industries.

This addition allows a series of improvements, highlighting:

1. Energy Optimization

   The solar supply curve is variable and coincides only partially with the typical curve of energy needs. Thus, combining photovoltaic and storage for example, storing the surplus generation and injecting it into later periods of demand.

2. Fixation of Solar Energy

   Allows the output of the photovoltaic system not to increase or decrease very rapidly. The advantage of having a solar and storage system working synergistically is that the variations short-term supply and demand can be stabilized. The storage can, in the limit, make the output of the photovoltaic system completely dispatchable.

3. Power Peaks

   This combined system allows for better management of the generation power peaks, allowing that the same existing electrical network supports a larger volume of photovoltaic installations.

1.1. Objectives and Methodology

The main objective of this work is to study the technical and economic viability of the of an energy storage system associated with a pre-sized photovoltaic power plant for self consumption. That said, we intend to simulate the system as a whole in order to test the methodology developed, using the Matlab / Simulink platform. Within this different customers with similar consumption profiles (but of different order of magnitude), in different areas of the country operating in the same tariff cycle in order to understand the impact this type of solution may have. Thus, it is possible to divide this work, in a generic way, into four major steps:

1. Sizing the ideal stored battery power to the consumer in cause;

2. Management of the consumption and production of energy generated by the photovoltaic system with storage, through the development of an appropriate methodology;

3. Energy and economic analysis of the dimensioning carried out;

4. Simulation of the complete system using the Matlab/Simulink platform;

1.2. Dissertation Structure

This project is divided into five chapters.

In the present, the first, a framework is elaborated, summary of the situation point of this study area, the motivations inherent to this work and the respective objectives to be achieved.

In the second, we describe the case studies present in this dissertation, the processes for the dimensioning of the capacity of the bank of batteries to install in these same premises and the methodology developed and to be applied.

The third chapter is devoted to the detail of the elaborated simulation model and its results of the methodology applied in Matlab/Simulink platforms.

Subsequently, in the fourth chapter, a detailed energy and economic analysis is developed application of the photovoltaic system with storage to the case studies chosen before the algorithm referring to the developed methodology, using the VBA platform.

Finally, in the fifth and final chapter, the conclusions of this study are consolidated, the objectives set out, together with the associated limitations and possible suggestions for future works of this concept and its consequent application.

2. Case Studies and Methodology

In the scope of this study, two industrial energy consumption profiles are considered for analysis using the methodology adopted and described in the next sub-section. Both operate in the usual working period, ie weekdays between 9:00 am and 6:00 p.m., but energy levels of different order of magnitude. From now on, designated as "Installation 1" and "Installation 2". Installation 2 has the particularity of being part of a project with European funds whose consequence, can be summarized by the fact that it can not sell the surplus production to the RESP. This case was chosen in so far as it is expected that the storage solution presented in this work has greater economic impact. In order to improve the comparison, both facilities operate with the same tariff cycle: Weekly Cycle in Continental Portugal. Thus, two graphs are shown illustrating the load diagrams of each of the consumers combined with the PV production forecast.

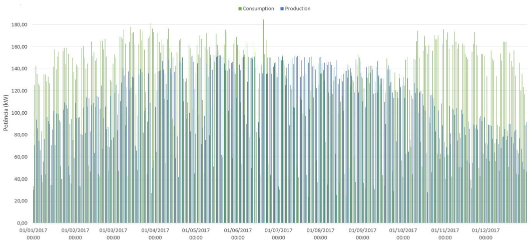

Figure 3: Consumption and Production diagram for Installation 1

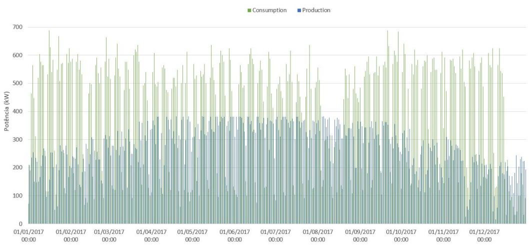

Figure 4: Consumption and Production diagram for Installation 2

2.1. ESS Capacity Sizing

For the elaboration of this project, the chosen energy storage system (ESS) is a bank of batteries. Within the various possibilities, the lithium batteries shows up as on of the best solutions given the high energy density and efficiency presented, as well as the average life span. Another important aspect is that they support an high charge/discharge cycles, essential for this type of application. Within existing technologies, the ferrous lithium battery (LiFePO4) is chosen. The B-BOX Pro 13.8 [2] model of the BYD brand was chosen for the contacts that took place within Profit Energy with its commercial partners. Thus, they are presented in the following table the main data of this battery, taken from the datasheet.

Type	$LiFePO_4$
Energy	13.8 kWh
Max Output Power	12.8 kW
Peak Power	13.3 kW, 60s
Efficiency *Round-Trip*	95.3%
Rated Voltage	51.2V
Voltage Range	43.2V - 56.4V
Scalability	32 (Parallel)

Table 1: *B-BOX Pro* 13.8 Data

The first step of this project is to obtain the best possible value for the to be implemented in each installation. Read "best possible value" as the one that translates a better balance between supply/consumption deficit supply, peak power, physical space at occupy in the Installation, investment and payback.

Thus, the following factors are analyzed hour by hour during the full year 2017:

1. Consumption;
2. Production;
3. Production Surplus;
4. Self-consumed energy;
5. Injected energy into the grid;
6. Generated economy by self-consumption;
7. Generated economy by the use of the battery bank;
8. Generated remuneration by the energy injection in the grid.

2.2. Methodology

Through the abovementioned analysis, it is then possible to suggest a the bank of batteries to be applied in each installation, describing, in this section, its applicability. Firstly, a production forecast should be made for each day in order to have a knowledge as close to reality as possible of the surplus production that will exist, fundamentally, in the peak period. In this work no forecast algorithm is applied the forecast output of the software used by Profit Energy (PVSOL). This program, sized the photovoltaic solar power plant, is based on the region of implementation, 10-year meteorological data and all materials chosen for the central. It is therefore a fairly realistic estimate for this. However, for the better performance of the system developed in this work, since it decides daily according to the value of the system variables, it will be fundamental to develop a daily production forecasting algorithm that supports the battery bank controller that is based on the methodology described below. With this production forecast information, it will be decided whether or not the battery bank is, loaded daily through RESP in the Super Vazio period of the dawn of the same day of use. Only loading order will be given when excess production is foreseen in the peak period, ie when there is no need for energy to suppress consumption. After this, throughout the day, the stored energy will be discharged during peak periods and, when there is remnant, energy stored in the subsequent flood period applies. In order to optimize this methodology, the following is also performed: in the legal winter time period, there are two distinct periods of Ponta (09:30 to 12:00 and 18:30 to 21:00). In this case, it will load the battery in the period of Vazio before the 2nd period of Ponta of the day to later spend in the latter. Thus, and as the Cost of Energy and Access to Grid is roughly twice the of Cheia, there will also be some economic gain. This methodology will increase the charge and discharge cycles of the battery, increasing its profitability in that it is in constant operation. In addition to this regular operation, two situations are still considered verify and operate as another priority over the one described above. They are: storage of surplus energy whenever the battery is in a state of charge of less than 80%; whenever the requested power value exceeds a certain value set for each installation, the battery discharges the energy differential to compensate for the same deficit. It is second measure is aimed at significantly reducing the contracted power of the installation, hence, an energy saving required from the grid and, consequently, an economic saving. This scenario was executed by an algorithm developed in VBA, in order to resort and work data files of the plant in question, loading and forecasting schedules.

3. Model and Simulation

In this chapter, a model of the operating system was developed on the Matlab/Simulink platform, following the methodology of the previous chapter.

The various components used will be explained in detail in the following sections.

3.1. Grid

In the sense of simulating the electrical network that feeds the industrial installation in question, a three-phase generator on the Simulink platform. The installation, in real case, is connected to a 15kV MT that will pass through a transformer and will later power the facility to BT. However, for the simulation, the generator is projected with BT data:

Phase-Phase RMS Voltage	400V
Frequency	50Hz
Connection	Yn
Short-Circuit Power	100MVA
X/R	7

Table 2: Three Phase Generator Features

3.2. ESS

According to the datasheet of the model, the battery presents usable energy of 13.8 kWh, on conditions 100% of discharge depth and 0.5C of loading and unloading.

To describe batteries, the discharge current is usually described by a C-ratio so as to normalize according to the capacity of a given battery [3]. This ratio is a measure of rate at which a battery is discharged in relation to its maximum capacity. For example, 1C means that the discharge current will discharge the entire battery in one hour, while 0.5C means that half the discharge current will discharge the entire battery in two hours. In this case,

$$C_{bat}[Ah] = \frac{E_{BAT} \cdot Nr\ Batteries[Wh]}{Vn[V]} \quad (1)$$

$$C_{bat} = \frac{13800 \cdot 4}{51,2} = 1078,125Ah \quad (2)$$

Thus,

$$\frac{C_{bat}}{2} = \frac{1078,125}{2} = 539,063Ah \quad (3)$$

For simulation purposes, the simplified battery model of an RC in series with a capacitor), in parallel with a diode in order to limit the voltage the value provided in the datasheet (56.4V). Using the data presented in the table above, it is possible to calculate some missing quantities.

For the average current of the capacitor, we have

$$I = C\frac{\Delta V}{\Delta t} \quad (4)$$

Manipulating the equation and replacing it with the given data:

$$C = I \cdot \frac{\Delta t}{\Delta V} = 539,063 \cdot \frac{2h \cdot 3600s}{56,4 - 43,2} = 294\,034,36F \quad (5)$$

For simulation purposes it is considered 1h = 1s and, therefore,

$$C' = \frac{C}{3600s} \approx 81,67F \quad (6)$$

3.3. Inverters

An inverter is a switched converter that converts continuous electrical quantities to alternating, through the switching of semiconductor power devices.

In the implementation of the inverters, it was chosen to describe the problem in a macroscopic way, working with power flows. The inverter can actually operate as an inverter or rectifier (conversion of AC quantities for DC), depending on the power flow so justifies, in the particular case of loading or unloading the drums. It is considered positive power (and current, therefore) in the phase of loading and power negative in the discharge phase.

In the case of the requested power to the network, it follows the same reasoning and is regarded as positive when requested and negative when it is sold, in the scenario of production surplus. Consumption power is always regarded as positive and production is negative. Thus, it is necessary to establish several equations to describe the problem in the best way possible.

$$P_{AC} = v_1 i_1 + v_2 i_2 + v_3 i_3 = v_\alpha i_\alpha + v_\beta i_\beta = v_d i_d + v_q i_q \quad (7)$$

$$Q_{AC} = v_\alpha i_\beta + v_\beta i_\alpha = v_d i_d + v_q i_q \quad (8)$$

Obtaining the power on the continous side,

$$P_{DC} = U_{DC} I_{DC} \approx P_{AC} = v_d i_d + v_q i_q \quad (9)$$

Thus,

$$I_{DC} = \frac{v_d i_d}{U_{DC}} \wedge i_d = \frac{P_{AC}}{v_d} \quad (10)$$

This gives the I_{DC} value that can take positive or negative values as the system in the process of charging or discharging, respectively. On the other hand, the value of i_d is also obtained, which, after a new conversion of coordinates, in three current sources, corresponding to each phase.

With these expressions, it is then possible to describe the inverter in a macroscopic manner so as to convert continuous quantities into alternating quantities.

Analogous to the reasoning applied to the inverter of the battery, the inverter was developed to solar production.

Instead of the previous case, the production power in this scenario arises via a vector whose data come from the photovoltaic simulation software used by Profit Energy, PVSOL.

3.4. Variable Load

Regarding the consumption of the installation, it was decided, in terms of simulation, to use the values actual consumption of imported loads from the load diagram used in energy and economic analyzes, by means of a vector containing the same data. It is important to leave the caveat that is assumed constant power for each hour, coming from the load diagram. The energy consumption was then divided in two ways: a portion of the same to be injected directly into current sources corresponding to each phase and the ramaining is translated in resistors. Thus, the resistances translate the minimum consumption value of the installation current sources increase, over the analysis period, the remaining real value of consumption.

3.5. Controller

Regarding the controller, the objective is, given several inputs and the restrictions mentioned in the previous sections of this paper, decide when the battery should charge or discharge and define quantitatively the power value for the chosen action. In this sense, this controller is divided exactly in this reasoning: a first block that defines the loading / unloading action and another block that dynamically adjusts the maximum and minimum value determines the defined action.

3.5.1 Voltage Control

For the generic mode controller and this particular voltage control section, they serve the month and day in line with the energy consumption and production vectors applied previously, the battery voltage (in this case in percentage terms, since it was the way it was worked in the sense of relating it directly to the state of charge of the battery), and the vectors of consumption and production of the installation. With these data, it is then possible to define zones of action of charging and discharging the battery based on the reasoning developed in the methodology. The output of this controller is then the reference voltage to which it is desired to converge. In this dissertation it is considered that the SOC is directly associated to the battery voltage, that is, it is admitted

$$SOC[\%] \approx V_{BAT}[\%] = \frac{V_{BAT} - V_{min}}{\Delta V} \quad (11)$$

Being V_{BAT} the battery voltage, $V_{min} = 43.2$V the minimum voltage and $\Delta V = V_{max} - V_{min} = 56.4$ - 43.2 = 13.2V the difference between the maximum and minimum voltages.

3.5.2 Power Control - *Fuzzy* Solution

Fuzzy logic has gained popularity within the scientific community, in particular the engineering branch, because it is an effective vehicle that allows the incorporation of language development of nonlinear controllers [4]. Contrary to control theories fuzzy logic is not worked using mathematical models but, instead, to qualitative and heuristic considerations applied to the concepts of fuzzy controllers can work with inaccurate inputs, non-linearity and insensitivity to disturbances superior to most nonlinear controllers. In this sense, the limits are not the concept of "true or false", thus opening space for "partial" with a certain degree of belonging to each of the defined states. So this is a choice justified in cases where there is solid practical knowledge on the subject, eventually, conventional nonlinear controllers.

For this project were chosen the following membership functions and rules present below.

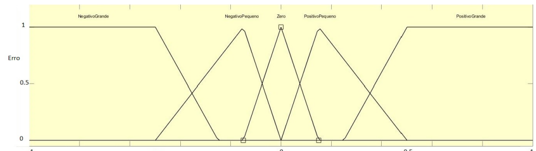

Figure 5: Membership functions in the discourse universe addressed

The following table shows the rules applied in the fuzzy controller of this project.

		Error Derivative V_{BAT} [%]				
		NG	**NP**	**Z**	**PP**	**PG**
	NB	NB	NB	NB	NS	Z
Error	**NS**	NB	NB	NS	Z	PS
V_{BAT}	**Z**	NB	NS	Z	PS	PB
[%]	**PS**	NS	Z	PS	PB	PB
	PB	Z	PS	PB	PB	PB

Table 3: Fuzzy Controller Rules

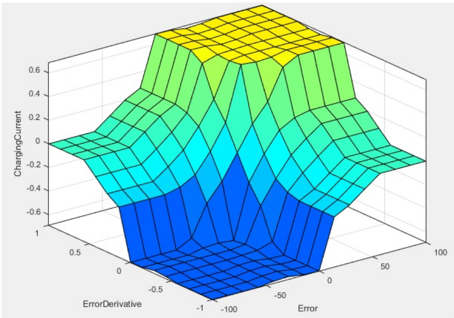

Figure 6: Three-dimensional model of fuzzy controller membership functions

Defined the universe of speech, membership functions and rules of the controller, the output of the latter is based on adding an increment/decrement in current value such that it is in agreement with the evolution of the intended loading/unloading process. This current value will then be integrated and multiplied by the battery voltage, resulting in thus at the desired power quantity.

Simulating the system based on this type of control gives the following results:

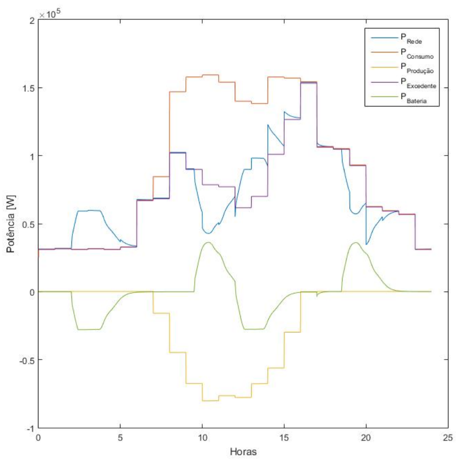

Figure 7: Fuzzy Logic - Day of **winter** in Installation 1: Evolution of System Powers

It is observed from the figures above that this type of approach, although in a general way the intended tasks, is not appropriate to the type of solution that is intended to be achieved and objectives reach. This is because, since it is a qualitatively based solution, a balance between the variables and their outputs and does not act quickly. Based on the economic analysis showed in the next section, we are faced with a business area with incomes, for now, scarce and the time that this controller takes to perform the intended actions can have a economic issue.

For this reason, a crispy solution of the same problem is then studied, insofar as the limitation of the time periods is also the same and, from this fact, it is important that the controller on the one hand, to the change of time and, on the other, to the abrupt which may arise in the installation influencing the value of power contracted by the consumer and which could affect the following 12 months in this respect.

3.5.3 Power Control - Non Linear Solution

Assuming, for simplicity, that the battery can be represented by a constant capacity, we have

$$i_{bat} = C\frac{dv_{bat}}{dt} \tag{12}$$

Obtaining the power relationship between AC and DC side,

$$P_{AC} = \frac{C}{2}\frac{dv_{bat}}{dt} \approx P_{DC} = V_{bat}I_{bat} \tag{13}$$

Using the Lyapunov Principle of Stability, knowing that Lyapunov's candidate function has to be continuous, descending and definite positive, it is defined

$$\frac{e^2_{v_{bat}}}{2} > 0 \tag{14}$$

To guarantee stability,

$$e^2_{v_{bat}}\frac{de^2_{v_{bat}}}{dt} < 0 \tag{15}$$

After some manipultation is it possible to obtain the battery average current,

$$I_{bat} = \frac{C}{2}K\frac{ev^2_{bat}}{v_{bat}} = \frac{C}{2}K\frac{V^2_{ref} - V^2_{bat}}{V_{bat}} \tag{16}$$

Applying this control method one has, for a winter day in Installation 1:

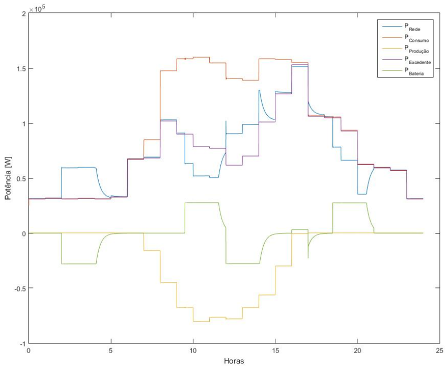

Figure 8: Non Linear Controller - Day of **winter** in Installation 1: Evolution of System Powers

Since no production surplus is foreseen, the battery will then receive charging order in the Super Vazio period (02:00 to 06:00). Then, in the first period of Ponta (09:30 to 12:30), will receive total discharge order as it is necessary all its energy to suppress the consumption of the installation. Nevertheless, it is possible to observe the required power to the grid which is not sufficient to suppress all consumption.

At the end of the Ponta period, it follows a period of Cheia (12:30 to 18:30) where the battery receives a loading order considering the period of the approaching point. However, and for this reason a day was chosen with this nuance so that it could be observed, it occurs at 17:00 the case in which the requested power to the network is over 155kW (value previously defined as power limit to be reached in this installation). Thus, by detecting it, the battery receives an unloading order in order to compensate for this part by not allowing the requested power to exceed the desired value, so as not to compromise the contracted power of the installation with 12 months effects. Lastly, in the second and last period, the battery is discharged and maintains its load state at 20 % until the Super Vazio period of the following day, thus ending the daily cycle of operation.

4. Energy and Economic Analysis

4.1. Energy Analysis

After describing the methodology implemented, this chapter presents the main results and economics of its application, using the algorithm developed in VBA, for the two plants under analysis. Here it is just showed the main results for the Installation 1.

In this section an energy analysis based on the photovoltaic power plant is consumers in two different scenarios: the first recital and the second with the complementarity of the storage system.

Two assessments are made for the distribution of energy: at the level of the Tariff Period and at the monthly, obtaining the same total energy values. The analyzed variables are:

1. Total Consumption: Total energy that the installation under analysis consumes for its normal operation during the full year 2017;
2. Total Production PV: Total energy produced by the photovoltaic power plant;
3. Self-consumption: Energy that is actually self-consumed, from that produced by the photovoltaic powerplant;
4. Surplus Energy: Energy corresponding to the surplus production which is subsequently sold to the RESP;
5. ESS: Total energy used by ESS to suppress energy consumption;
6. Non-avoided consumption: Total energy which, after self consumption and energy injected by the ESS, does not can be suppressed and will be purchased from RESP.

Período	Total Consumption [kWh]	Total Production PV [kWh]	Self-consumption [kWh]	Surplus Energy [kWh]	Non-avoided consumption [kWh]
Ponta	121 480,13	69 571,90	65 581,89	3 990,02	55 898,24
Cheia	370 201,13	160 826,18	142 858,00	17 968,18	227 343,12
Vazio	130 612,50	63 292,39	35 768,51	27 523,88	94 843,99
Super Vazio	76 275,00	4,78	4,78	0	76 270,22
TOTAL	698 568,75	293 695,26	244 213,18	49 482,08	454 355,57

Table 4: Energy Analysis by Period for Installation 1 - PV System

Período	Total Consumption [kWh]	Total Production PV [kWh]	Self-consumption [kWh]	ESS [kWh]	Surplus Energy [kWh]	Non-avoided consumption [kWh]
Ponta	121 480,13	69 571,90	65 581,89	10 324,05	2 632,69	45 574,19
Cheia	373 405,79	160 826,18	142 858,00	3 943,52	16 241,69	226 604,27
Vazio	130 612,50	63 292,39	35 768,51	0	25 338,80	94 843,99
Super Vazio	82 113,16	4,78	4,78	0	0	82 108,38
TOTAL	707 611,58	293 695,26	244 213,18	14 267,56	44 213,18	449 130,83

Table 5: Energy Analysis by Period for Installation 1 - PV+ESS System

In this project, the design of the photovoltaic power plant is not modified because it is the impact of the installation of the ESS on an industrial plant which may already have a photovoltaic power plant installed that is relevant to study. However, a future study of the photovoltaic power plant in synergy with the ESS from the very start of its development, considering over or under-dimensioning, for example, the plant itself and analyzing its impact in conjunction with the ESS.

Analyzing the results presented in the previous tables and graphs related to the Installation 1:

1. Total Consumption: In the ESS solution, the total energy consumption is higher due to the energy requested to RESP in periods of Cheia and Super Vazio for the charging of the ESS. In values total, it is possible to denote a significant difference that is approximately 9.04MWh/year;

2. Total Production PV: In this variable there is no change due to the fact that the sizing not be affected.

3. Self-consumption: For the same reason as above, there is no change here either;

4. In absolute values of energy, the solution with ESS presents a lower value of surplus production to the extent that part of it is absorbed for ESS charging, which represents total values close to 5.27MWh/year. Considering the surplus value generated in the solution that only contemplates the photovoltaic power plant, of about 10.65% of the same energy for of the ESS;

5. Non-avoided consumption: In the Ponta period the consumption not avoided is, as intended, lower in the solution with ESS given the discharge of the same in this period. In the period from difference is less because, although it is sometimes the target of discharge, it is also the loading period on winter days at the anticipation of the second peak period of each day. In total, a decrease of approximately 5.22MWh/year is noted.

6. ESS: In this segment the objectives are clear: discharge of the ESS in the expensive (Ponta and Cheia). In the energy values used by the ESS are also contemplated the discharge actions when exceeding the defined maximum power limit (for Installation 1, 155kW). A total use of 14.27MWh/year is observed at the total and annual level, which corresponds to about 2.02% of total Installation 1 consumption.

4.2. Economic Analysis

In this section we analyze the prediction of economic results, graphically illustrated, of the implementation of ESS in Installation 1.

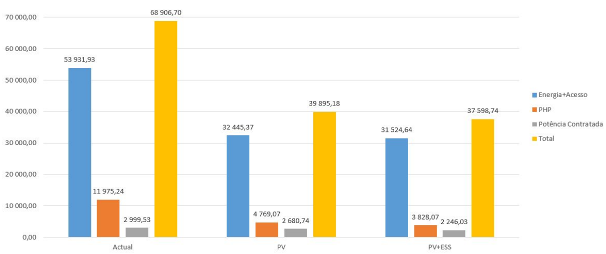

Figure 9: Monthly Costs for Installation 1 of the various solutions

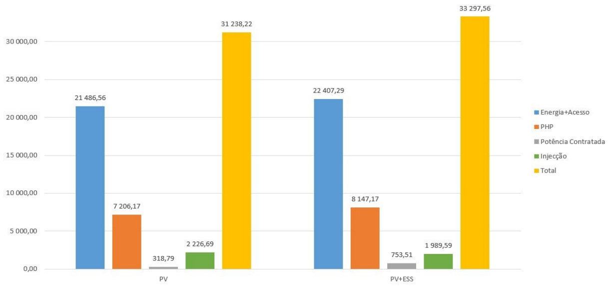

Figure 10: Monthly Savings for Installation 1 of the various variables

Analyzing the overall impact of the ESS for Installation 1, which is the focus of this dissertation, we have then the following final results in summary form:

	Annual Savings [eur]
Energy + Grid Acess	920,72
PHP	941,00
Contracted Power	434,72
Surplus	-237,10
TOTAL	2059,35

Table 6: Annual Savings for Instalattion 1

It is possible to observe that, as projected and intended, are generated economic savings in the all the aspects considered. The amount of energy injected into the RESP, being smaller due to its storage in the ESS, generates a lower financial remuneration, hence the negative value in the table above.

Payback [Anos]	**Accumulated Revenues [e]**	**LCOE [e/kWh]**	**NPV 10 Years [e]**	**IRR 10 Years [%]**
14.32	23 056.69	-0.23	-14 226.80	-6.92

Table 7: Economic Profitability - Installation 1

Based on the results of the profitability indicators for the installation under analysis it is verified that, due to the high investment required, the project is not, for the time being, interesting from the standpoint of own investment. However, some solutions may be considered and their results will be presented in the next section.

4.3. Economic Analysis Considering Future Prices

In this section it is analyzed a possibility of reducing future investment and respective indicators updated profitability.

The following graph shows the observed prices of batteries since 2010 and a forecast up to 2030 of them.

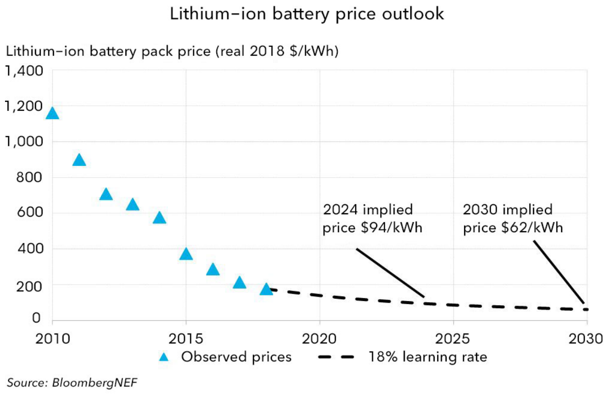

Figure 11: Lithium battery pricing chart [5]

With the constant development of batteries and application growth, a decrease is expected of the price of the same that can reach the value of 54 eur/kWh (62 $/kWh). For bi-directional power converters, there is also a its market price as its implementation becomes more and more entrenched. Assuming a decrease of 30% of its value, in line with the trend of PV investors in recent years as its implementation has grown, it is possible to recalculate profitability indicators for the two plants under analysis in this project.

Payback [Anos]	Accumulated Revenues [e]	LCOE [e/kWh]	NPV 10 Years [e]	IRR 10 Years [%]
4.41	23 056.69	-0.0791	7 093.15	23.68

Table 8: Economic Profitability - Installation 1

By means of the results obtained with the previously justified price forecast, it is possible to verify profitability for the project that justifies, in the medium term, the implementation of this solution.

5. Conclusions

In this dissertation a methodology of consumption management and energy production was developed to apply to an energy storage system that complements a photovoltaic solar power plant in the industrial sector. In this sense, a model of this same system was developed resorting to the Matlab/Simulink platform to simulate the same. Based on the objectives initially defined, the first step was to choose the capacity of the battery bank, that is, capacity such that, based on the load diagram in the case studies analyzed and the respective forecasts of energy production by the photovoltaic power station Profit Energy, had a significant energy and economic consumer concerned.

Having said this, a methodology was developed that, based on the tariff period in use for each installation, allows the battery bank to be economically profitable with consequent higher value energy for the consumer.

This methodology was then applied, using the VBA platform, via an algorithm, it is therefore possible to carry out a detailed energy and economic analysis on an hourly basis for 2017. This application is based on the consumption, production forecast, tariff period of the consumer, capacity of the bank of batteries and applied tariffs. At the energy level, it is noted that the installation of this storage system allows to absorb approximately 10% of the production surplus of each photovoltaic power plant and, thus, generate (more than quadruple) of that which would be obtained by same power to the grid. On the other hand, an increase in the total energy consumption of each installation period will be re-used and translated for the energy consumption during those same periods and generating of the tariff differential of those same periods. These values are reflected in the of the ESS, in 59% of the charging energy coming via the network (in periods of Super Vazio and Cheia) and the remaining 41% due to surplus production. With regard to discharge of the battery bank, 67.22% of the energy is used in the Ponta period, while the remaining 32.78% in the Cheia period, these being the only tariff periods where the ESS is applied given their returns. Exceptional cases are those where it may be necessary to suppress peaks of the installation.

As regards the overall actual consumption required of the grid following the operation of the two technologies (PV + ESS), this is expected to decrease, thanks to the use of the surplus production that is stored is discharged by the ESS in the desired periods.

By analyzing the project economically and in more detail, it is concluded that, for the time being, does not present profitability that justifies its implementation. This conclusion of the fact that the investment value of battery banks of this order of magnitude excessively high and the annual savings generated are not sufficient to generate a positive annual cash flow.

These conclusions can be seen, for example, with the 10-year IRR value, which is in line with the battery guarantee periods, from -6.92% and -6.52% for the two plants under analysis, respectively. Focusing only on the battery bank, it is noted that a decrease of approximately 65% in the price of batteries, which translates to a value of around 135eur/kWh, so that the project presented a positive NPV, considering the rate of return of 6% and all other assumptions.

However, for future expected values for the price of batteries (54eur/kWh) and for a decrease of 30% of the bidirectional power converters, it is concluded that this is a future project with economic returns as evidenced by the 10-year IRR of 23.68% and 26.13% for the two Installations under analysis in this work, which justifies its implementation.

With regard to the simulation of the model developed in Matlab/Simulink, two approaches to the operation of the controller: a first using a methodology Fuzzy that was thought as a suitable solution in the face of manipulating a series of distinct variables and rules of execution without developing a mathematical model of complexity higher than fully encompassing them. However, although a satisfactory and fulfilled several of those that were the objectives, its slow implementation (by the the fact that the variables with different weights were balanced) did not allow the economic due to the temporal limitation of the tariff periods in practice (defined by the regulator and not subject to change). Therefore, this approach was not exploited and a second approach was developed. based on a non-linear control method, with the purpose of making the loading and unloading of the faster battery bank, always based on the data provided by the selected for the case studies and presented in the annex. It has been found to be a more appropriate solution in that it is much faster which is particularly important, on the one hand, when detecting power peaks of the installation that are within the defined limits and, on the other, in the reaction to the change of time and tariff period.

As a final and concise conclusion of this work, it turns out that the methodology is actually interesting and energy and economic benefits for industrial consumers. However, the initial investment of this solution remains a strong barrier to its implementation at the current date. Nevertheless, by the economic analysis carried out considering evolution in the prices of the batteries and two-way power converters, the design can become feasible and interesting. This statement is justified by the 10-year IRR of 23.68% and 26.13% for Installations 1 and 2, respectively.

Future Work

It is suggested as future work the energy and economic study of the methodology developed for other types of energy consumption profiles and other tariff cycles in force in order to establish a hierarchy of consumer profiles where this type of application developed here is best can fit.

In the context of components, it will be interesting to explore other options for energy storage, such as batteries, which can be applied in this type of solution and which may have performance.

It will also be essential to develop a real-time production prediction algorithm, given that in this work was used for the effect the output of the PV-SOL software used in the sizing of Profit Energy's photovoltaic plants. Despite the rigor of this forecast at the macroscopic level,

A real-time forecast is required to allow the battery bank controller to adjust its since the economic return of this system is short and it is vital that it is optimized.

With respect to the model developed in Matlab/Simulink, it will still be necessary to improve it, namely the components of the system: battery and inverters more detailed and close to reality, rather than a macroscopic analysis of the input and output powers of each component.

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