Technic and Economic assessment of a PV system (On-Grid) with storage

André Marques Mesquita
andre.m.mesquita@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Abstract

The growing demand for projects that promote decarbonisation has led to an exponential growth in the number of photovoltaic (PV) plants installed in Portugal. In the near future, not only the installation of photovoltaic systems will be a reality, but also the expansion of existing systems and the introduction of energy storage systems. The simulation and calculation of the economic benefit of an expansion, in capacity and storage, of an already installed photovoltaic systems, is something that is still underdeveloped in the simulation software available nowadays. Therefore, a methodology was developed to quickly obtain the economic benefit of possible expansions.

The methodology was implemented in a real case study where several expansion possibilities were projected for the existing photovoltaic park of YKK (a factory in north area of Lisbon), which has 240 kW of converting power and 288 kWp of installed capacity. This project has the main objective of obtain the maximum, with a minimum rate of 60%, considering among other an maximum investment of 300 000 euros. The five expansion proposed were all with the same installed power, 223 kWp, but with different storage capacities.

The results revealed that it was not possible to achieve the intended objectives. Complying with the restrictions imposed, the highest self-production rate obtained was 58.3%. The developed methodology proved to be a very useful tool in obtaining the necessary data for decision making.

***Keywords*:** Self-Consumption, Economical Benefit, Photovoltaic Energy

1. Introduction

The increasing investment in renewable energy sources in Europe contributes not only to decarbonisation, but also to a reduction in energy dependence. In 2019 the European Union's energy dependence, including electricity, was around 61% (Eurostat, 2020), i.e., more than a half of all raw materials used in energy production came from other countries outside EU.

Solar energy is considered one of the most interesting options within the scope of renewable energies available in Portugal. The Portuguese territory has a high sun exposure throughout its entire extension, which is one of the factors that has led to investments in solar energy, either in self-consumption or in production projects for injection into the grid.

The production of solar energy in Portugal has had a strong growth in recent years and in 2020 was produced around 1650 GWh of energy through an installed capacity of 1 GW (DGEG, 2021). This energy source tends to grow due to various policies in the energy sector, namely the possibility of sharing photovoltaic energy produced within energy communities, which is possible since the DL 162/2019 (25 Oct) is in force, and the urgent need of decarbonisation.

2. Methodology

The developed methodology intends to calculate the economic benefit of an expansion (B) of an existing photovoltaic system (A), which is characterized by the increase of the installed capacity as well as the implementation of a storage system that receives energy from both systems; initial (A) and its expansion (B). The system schematic can be seen in Figure 1. This methodology will only be applied to photovoltaic systems of the same nature as the one mentioned below and which purpose is self-consumption, where the production of photovoltaic energy replaces the energy supplied by the grid.

The design of the different expansion hypotheses is a step that must be performed prior to the application of the methodology. Further ahead the application of the developed method in a real case study will be done and, therefore, the various expansion hypotheses will be sized and analysed.

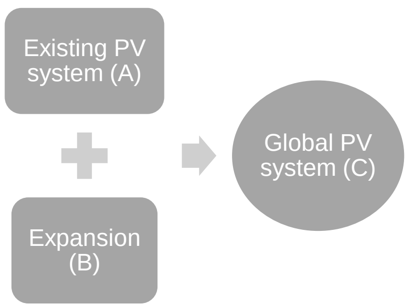

Figure 1 – Components of the Global PV system (C).

To characterize each possible hypothesis of expansion (B) in both energetically and economical level, it is firstly necessary to define the existing photovoltaic system (A) in order to understand its impact on the user's energy needs. In the next phase, the global system (C) must be characterized, since the storage system receives energy from the existing system (A) and from the expansion (B). These interactions are presented Figure 2. The last phase of the methodology is the economic analysis of the different hypothesis of expansion.

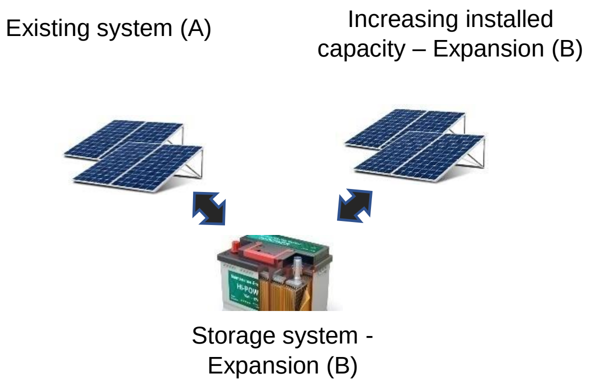

Figure 2 – Global system (C) interactions

Hence, the model can be generally divided in three phases:

- **Phase 1:** Existing PV system characterization (A);
- **Phase 2:** Characterization of the global PV systems (C);
- **Phase 3:** Characterization of the expansions (B);
- **Phase 4:** Economic analysis of the expansions (B).

For this methodology, the *PVsyst* simulation software will be used as a reference.

2.1. Phase 1: Existing PV system characterization (A)

In Phase 1, it is intended to characterize, energetically and economically, the existing system (A). Determine the amount of energy that is used for self-consumption, the amount that is going to be sell to the grid, its value and the impact of the PV system (A) in the user´s grid energy needs. This data can be obtained through an energy monitoring system or, if it does not exist or if the photovoltaic system is not yet installed, the data can be obtained using a simulation program.

For this methodology the was assumed that the data was obtained using the *PVsyst* software. The outputs to be extracted by the software are:

1) $\mathbf{AE_E}^h$ (kWh) – Energy injected into the grid at each hour of the year;
2) $\mathbf{AE_{FR}}^h$ (kWh) – Energy supplied by the grid at each hour of the year;
3) $\mathbf{E_{sh}}^h$ (kWh) – Energy consumption by the user at each hour of the year;
4) $\mathbf{AE_A}^h$ (kWh) – Energy supplied to the user by the PV system at each hour of the year.

The economic benefit of self-consumption (AB_A) is the product of the energy used for self-consumption with the energy price (T_h) that the energy would have cost if it had come from the grid. The grid energy has different prices according to the hour of the day and the time of the year. This can be formulated as:

$$AB_A(Euros) = \sum_{h=1}^{h} {AE_A}^h \times T_h \qquad (1)$$

Where:

AB_A (Euros) – Annual economic benefit inherent to self-consumption in the existing system (A);
T_h (Euros/kWh) – Grid energy price at h hour.

The economic benefit of selling energy (AB_E) to the network can written as:

$$AB_E\ (Euros) = AE_E \times T_E \qquad (2)$$

Where:
AB_E (Euros) – Annual economic benefit inherent in the sale of excess energy in the existing system (A);
AE_E (kWh) – Annual energy injected in the grid by the existing PV system (A);
T_E (Euros/kWh) – Energy selling price.

The sum of both self-consumption and energy selling benefits, give us the total economic benefit of the PV system:

$$AB_T\ (Euros) = AB_E + AB_A \qquad (3)$$

Where:
AB_T (Euros)– Annual economic benefit of the PV system (A).

The impact of the existing photovoltaic system in the user grid energy needs can be measured by calculating the energy self-sufficiency. The formula can be seen below:

$$AR_S\ (\%) = \frac{AE_A}{E_S} \times 100 \qquad (4)$$

Where:
E_S (kWh) - Annual energy supplied to the user by the grid with the existing system (A);
AR_S (%) - Installation self-sufficiency rate with the existing system (A) implemented.

The other parameters to be calculated for the existing PV system (A) can be found in Table 1:

Table 1 - Variables to calculate in Phase 1

Variables to calculate in phase 1		
Initials	**Designation**	**Units**
AE_{FR}	Annual energy supplied by the grid to the user with the existing system (A) implemented	kWh
ACr	Cost of energy obtained from the supplier with the existing system (A) implemented	Euros
AE_U	Useful energy produced by system (A)	KWh

2.2. Phase 2: PV system (C) Characterization

In Phase 2 is made an energy and financial characterization of the global system (C) for each of the expansion hypothesis (B) proposed. These expansion proposals must already be defined before applying the methodology, as explained above. By applying the same method of Phase 1, we are able to obtain the same parameters for the Global system (C). Those can be seen in Table 2:

Table 2 - Variables to calculate in Phase 2

Variables to calculate in Phase 2		
Initials	Designation	Units
E_E	Annual energy injected in the grid by the Global PV system (C)	kWh
E_{FR}	Annual energy supplied by grid to the user with the global PV system (C) implemented	kWh
E_A	Annual energy supplied to the user by the Global PV system (C)	kWh
B_A	Annual economic benefit inherent to self-consumption of the Global PV system (C)	Euros
B_E	Economic benefit inherent in the sale of excess energy in the Global PV system (C)	Euros
B_T	Total economic benefit of the Global PV system (C)	Euros
C_R	Cost of energy obtained from the supplier with the Global PV system (C) implemented	Euros
E_U	Useful energy produced by Global PV system (C)	kWh
R_S	Installation self-sufficiency with the Global PV system (C) implemented	%

2.3. Phase 3: Expansion (B) characterization

In Phase 3, the objective was to calculate the total benefit of each proposed expansion (B) hypothesis, being that benefit sub-divided in the two parcels: installed capacity and storage system. The variables to be calculated in this step are shown in Table 3.

To determine the economic benefit of the installed capacity (NB_{AP}), it was used the same methodology of Phase 1, but considering in the simulation only the increasing of the installed capacity (excluding the storage system) and the new grid user needs (after the installation of system (A)).

The batteries benefits (NB_{AB}) can be obtained by subtracting to the energy produced for self-consumption in Global System C (B_A), the energy produced for self-consumption by the existing system A (AB_A) and the energy produced new installed capacity in expansion B (NB_{AP}). This can be written as:

$$NB_{AB}\ (Euros) = B_A - AB_A - NB_{AP} \qquad (5)$$

The calculation of the economic benefit inherent to the sale of excess energy produced by each expansion (B) hypothesis is not linear. The energy is first sent to the storage system until it reaches the maximum capacity and only then the energy is injected into the network. It is not possible to predict which of the systems, the existing one (A) or the expansion (B), sends its energy to the grid. Hence, an estimate will be made based on the installed capacity ratio between the global system (C) and the new system (B). The formulation can be seen below:

$$NB_E\,(\text{Euros}) = \frac{CN}{CT} \times E_E \times T_E \qquad (5)$$

$$NE_E\,(\text{kWh}) = \frac{CN}{CT} \times E_E \qquad (6)$$

Where:
NB_E (Euros) – Economic benefit inherent in the sale of excess energy in the PV expansion (B);
C_N (kWp) – Installed power capacity in expansion (B);
C_T (kWp) – Installed power capacity in Global system (C);
NE_E (kWh) - Annual energy injected in the grid by the PV expansion (B).

The other parameters to be calculated in Phase 3 can be summarized in Table 3.

Table 3 - Variables to calculate in Phase 3

Parâmetros a calcular na Fase 3		
Initials	Designation	Units
NE_{AP}	Annual energy supplied to the user for self-consumption by the increased capacity of the PV expansion (B).	kWh
NE_{AB}	Annual energy supplied to the user for self-consumption by the storage system of the PV expansion (B).	kWh
NE_A	Annual energy supplied to the for user self-consumption by the PV expansion (B)	kWh
NE_u	Useful energy produced by PV expansion (B)	kWh
NB_T	Total economic benefit of the PV expansion (B)	Euros

2.4. Phase 4: Economic analysis

From Phases 1 to 3, where described the steps to calculate the economic benefits that each possibility of expansion (B) bring to the user in the first year of the project. In Phase 4, a long-term analysis will be carried out to understand the profitability of the system, the impact of the production degradation and the increase of services costs associated with the system. For the long-term financial analysis, it must be assumed that the installation's consumption remains constant over time. At this stage should be calculated the Net present value (NPV), the internal rate of return (IRR) as well as the levelized cost of energy (LCOE).

3. Case Study

The main objective of this chapter is the sizing of the expansion (B) of an existing PV system (A) and the study of its economic feasibility by using the methodology previously presented, in a real case study. Several expansions hypothesis will be proposed to be evaluated.

The case study addressed in this dissertation concerns a Portuguese factory in the Lisbon area, called YKK, whose future vision is to increase its share of energy self-production through the expansion of its PV system. This expansion may include an increase in the installed capacity and/or the installation of a storage system. For the study, some objectives and limitations were stated, which deserve the best attention:

Objectives

1) The company's objective is to obtain the largest possible self-production rate, with the minimum value being at least 60%

Limitations

1) The system already installed cannot be changed;
2) The type of system cannot be changed, that is, it will have to be a self-consumption solar system with the sale of excess energy;
3) The only area available for the installation of new photovoltaic panels is on the roof of the factory building;
4) Maximum available budget – 300 000 euros;
5) The 25 year NPV must be positive;
6) According to DL162/2019, the power connected to the grid cannot exceed the contracted power. Thus, since YKK's contracted power is 425 kW, only more 185 kW of connection power can be installed (The current system 240 kw of connection power).

3.1. YKK existing PV system characterization

The YKK existing PV system was recently installed, hence there not enough data to predict its production. The results were obtained in *PVsyst*.

The photovoltaic system is divided into two main areas: 1) Carpark; 2) Rooftop. The installed capacity and slope of the panels differ on the two areas. In the car park, the photovoltaic modules are supported by a sloping metal structure and provide a cover for parked cars. In the rooftop, the modules are fixed to a structure, which gives them the desired inclination. Photovoltaic modules on the roof have an interval distance from each other coinciding with the spacing of the support beams (approximately 5 meters), in which they are fixed. The summary of the existing equipment and power in each area can be seen in Table 4.

Table 4 - Characteristics of YKK PV system

Area	Parameters	value
Rooftop	Number of modules	238
	Installed Power (kWp)	88,06
	Inclination (º)	2º
	Orientation	South
	Number of 36 kW inverters	2
Carpark	Number of modules	540
	Installed Power (kWp)	199,8
	Inclination (º)	13º
	Number of 20 kW inverters	3
	Number of 36 kW inverters	3
	Orientation	South
Total	Installed Power (kWp)	287,86
	Converting power (kW)	240

A graphic design of YKK's photovoltaic system, drawn in the *PVsyst* software, is presented in Figure 3.

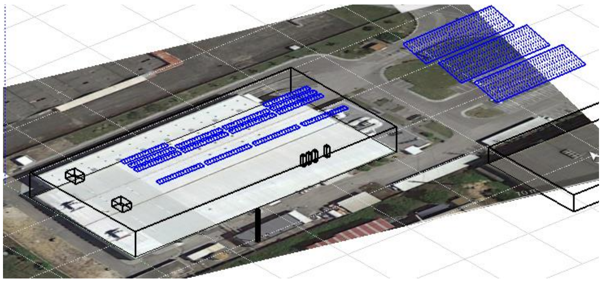

Figure 3 - YKK PV system drawn in PVsyst

3.2. User energy load Diagram

The user's consumption profile (load diagram), was provided by the energy distributor. The calendar year of 2019 was used as reference.

The YKK consumption is not uniform, during the months of August and December it is smaller due to the interruption of production for holidays. Seasonally we can also notice some fluctuations related to the nature of the clothing business. The monthly distribution can be found in Figure 4.

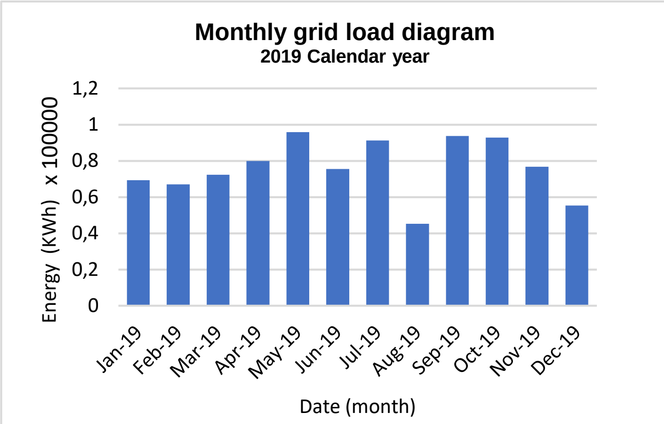

Figure 4 . YKK Monthly grid energy load Diagram

The results of the average and maximum power at each hour throughout the year can be found in Figure 5. We can observe that the period of highest consumption occurs between 6:00 and 24:00. From 24:00 to 6:00 the factory is usually stopped, the consumption verified is due to equipment's that is connected continuously.

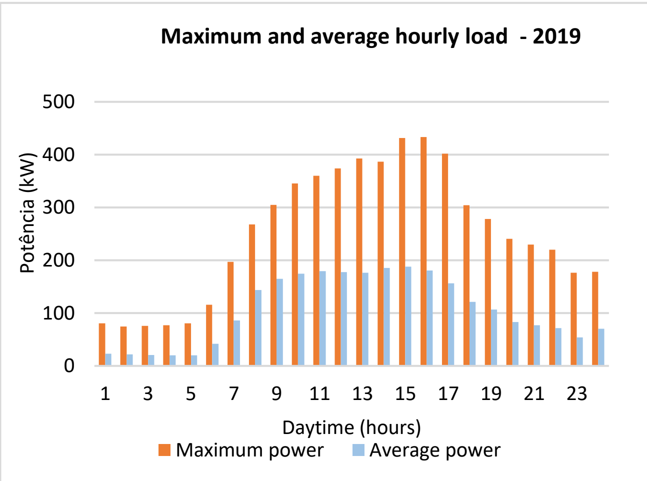

Figure 5 - YKK maximums and average loads – Annual hourly average

3.3. User energy load Diagram – After PV system installation

3.3.1. PV Generation Diagram

By inserting the system equipment previously mentioned, as well as the shadow elements and the system location in the *PVsyst* simulation software, the following generation diagram (Figure 6) was obtained, where the average annual production for every hour of the day can be seen. The system is expected to produce 455 MWh per year.

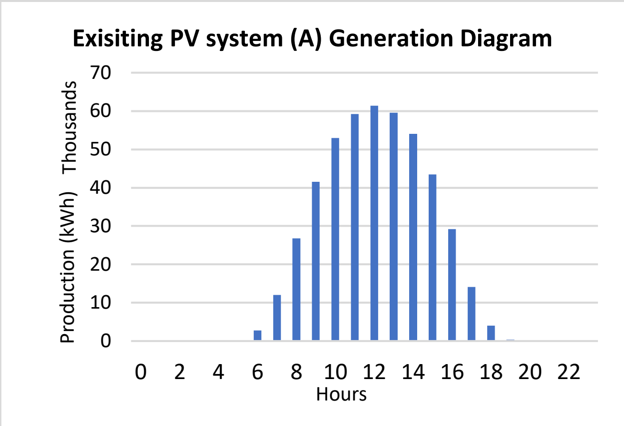

Figure 6 - Average annual production for every hour of the day in system (A)

3.3.2. PV Generation Diagram

With the existing PV system implemented, YKK energy supplied by the grid have significantly reduce. The impact in the user's grid energy consumption can be seen in Figure 7, where is shown the monthly grid energy consumption, before (Situation I) and after (Situation II) the PV system installation.

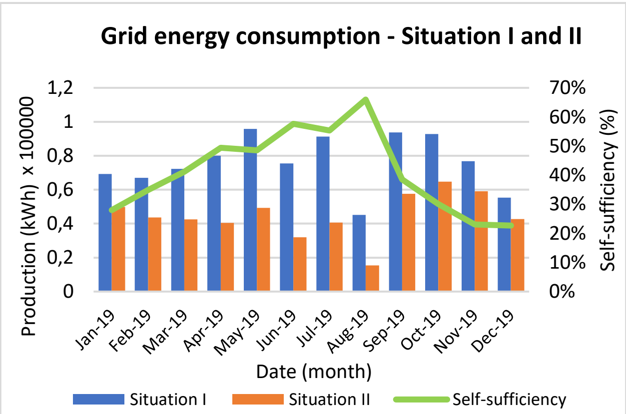

Figure 7 – Grid user needs with and without PV system (A) installed

It can be seen that in the best month, August, a rate of almost 70% of self-production is reached. The already existing PV system reduced YKK grid energy consumption from around 914 MWh/year to 530 MWh/year, which represents a self-sufficiency rate of 42%.

3.4. YKK PV expansion Sizing

The PV expansion sizing has to meet the requirements demanded by the user, defined previously in this chapter 3. The main purpose of this section was to define several expansions hypothesis to be evaluated by the methodology formulated in chapter 2. The sizing steps will follow the method defined by Aghaei (Aghaei, M., Kumar, N., et al., 2020).

3.4.1. Type of system

The new system must be of the same type as the existing system, a system where the main destination of the solar energy produced is self-consumption. The AC energy coming from the inverters is sent to the main distribution board, which in turn distributes it to the sub-boards. When the energy produced by the PV system is not enough, the system receives the missing energy from the grid. The opposite is also possible, when the PV production exceeds the factory's consumption, there is still the possibility of injecting energy to the grid.

For the proposed expansion, will be included a storage system in order to maximize the self-production rate. The storage system will be of the hybrid AC-DC type, where the batteries will be an alternative energy supply to the inverters. In this case, the inverters will be able to receive energy from both the photovoltaic modules and the storage system. This connection method allows a reduction of the investment, but on the other hand it has a lower connection power than the hybrid DC-DC system (Meyer, T., 2004). In this arrange, arrays are connected to battery banks, which in turn are connected to inverters. The number of battery banks does not have to match the number of inverters, it depends on the system sizing. A schematic representation of the installation can be seen in Figure 8.

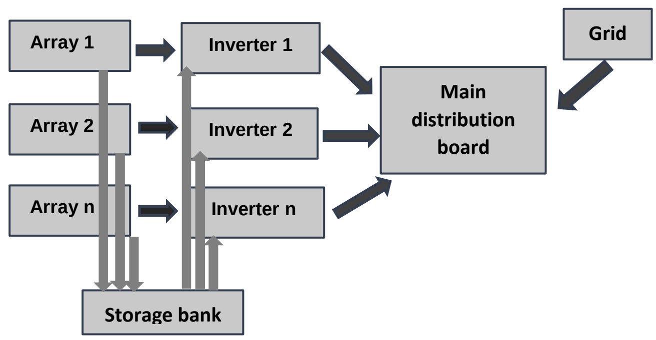

Figure 8 - Storage system configuration

Legend	
➡ (black arrow)	Direct connection
➡ (grey arrow)	Connection manage by a charge controller

3.4.2. PV modules

For this project was chosen the 410 Wp Jinko solar Cheetah 72M model, a monocrystalline panel constituted of 5 busbars and a conversion efficiency of 20,17% under standard test conditions (STC). Jinko solar brand, an international brand, was considered the best brand in 2020 in a performance study of photovoltaic modules promoted by the renowned German association, PVEL (Doyle, T., *et al.*, 2020). The chosen model has not only greater power but also greater conversion efficiency when compared to the model installed in the existing system. A summary of the characteristics of the selected panel can be seen in Table 5.

Table 5 - Jinko Solar Cheetah HC 410M-72H8410W) main characteristics

Jinko solar Cheetah HC 410M-72H(410W)	
Power under STC conditions	410 Wp
Efficiency under STC conditions	20,38 %
Cell number	144
Imp	9,69 A
Vmp	41,7 V
Isc	10,6 A
Voc	42,3 V

3.4.3. Inverter choosing and array sizing

The array sizing depends on the characteristics of the installation and the project objectives. In this case, the objectives aim to achieve the highest possible self-production rate with a mandatory minimum rate of 60%. As such, the system will be sized for the highest power possible, 185 kW. If it is verified that the cost of the project is higher than the available budget of 300 000 euros, the sizing will have to be redone.

The choice of the inverter and array will be based on a comparative study between several possible configurations, in order to understand which combination brings the lowest conversion cost for the project in question. The production simulations will be carried out in the sizing tool of the *PVsyst* software, which allows quick simulations of the various combinations.

The conversion cost will be calculated over a period of 25 years with a discount rate of 6%, a suited rate for PV projects in Europe (Grant Thorton, 2019). As the PV slope was not yet defined, the simulation was done with a 15º slope. It was also considered an inverters replacement in the year 15 (Sangwongwanich, 2017). The conversion cost over the considered period can be seen below:

$$CC_i \text{ (Euros/MWh)} = \frac{\sum_{j=1}^{n} \frac{C_i * N_i}{(1+a)^j}}{\sum_{j=1}^{n} \frac{Ei}{(1+a)^j}} \quad (7)$$

Where:

CCi (Euros/MWh) – Conversion cost;
Ei (MWh) – Annual production;
Ci (Euros) – Inverter cost;
Ni – Number of inverters;
a (%) – discount rate;
n (years) – Project lifetime.

The inverters in which the array will be studied can be seen in Table 6. The choosing has in account:

• The inverters have to be of the same brand as the existing ones, Huawei;
• It will only be considered inverters of one single power.

Table 6 – Possible inverters to be installed in the new PV system

Inverter	Number of inverters	Connection power (kW)
SUN2000-36KTL	5	180
SUN2000-50KTL	4	184
SUN2000-90KTL-H2	2	180

The different arrays configurations to be tested can only have 16 or 17 modules, in order to fit in with the existing strings in the coverage (strings of 17 modules). In the eventual placement of 18 modules, the distance for people to pass between the strings could be compromised.

A string configuration of 16 and one of 17 modules will be chosen for each of the three inverter powers (Table 6) under study. Each hypothesis met the following requirements:

- Maximum number of modules cannot exceed 561 modules (maximum limit that can be installed on the roof);
- In each case, the strings must always be the same number of modules and the ratio of the power of the array in STC to the power of the inverters cannot exceed 1,35;
- The maximum number of strings that can be connected to each inverter must also be taken into account.

Table 7 - Array hypothesis to be tested

Inv. Power (kW)	Hip.	Modules per string	Nr of Strings
36	A	16	7
	B	17	6
46	C	16	8
	D	17	8
90	E	16	12
	F	17	12

One of the hypothesis, E, was excluded as the array maximum voltage is below the inverter requirements. The conversion cost results can be seen in

Table 8:

Table 8 - Conversion costs for each hypothesis

Hip	C_i (Euros)	P_i (MWh)	CC_i (Euros/MWh)
A	15 645 €	360	4,82
B	15 645 €	328	5,29
C	14 276 €	327	4,84
D	14 276 €	346	4,57
F	15 480 €	262	6,55

Based on the results obtained, the configuration that considers 4 inverters of 46 kW with strings of 17 modules in series and 8 strings in parallel, the hypothesis D, is the one with the lowest conversion cost with an expected average of

4,57 euros per MWh over the 25 years of the project. In this scenario, the inverter overload rate is 21% (224 kWp/185 kW), a value according with the optimal value considered in the study of Eduardo Martins (Deschamps, E. M., Ruther, R., 2019).

3.4.4. Modules Slope

According to the literature (Jadhav, V., 2018) the optimal inclination for Carregado is about 38º. In order to verify which slope generates the highest annual production for the system under study a simulation was carried out in the *PVsyst*. The annual production will be studied with different slopes starting at 0 degrees and increasing every 5 degrees until reaching 40 degrees, the multiple of 5 closest to the ideal slope. In the simulations, the characteristics of the modules, power and array previously defined will be kept constant.

The results can be seen in Table 9:

Table 9 - Production results for different slopes

Slope (°)	0	5	10	15	20	25	30	35	40
Annual production (MWh)	322	336	346	346	344	341	337	332	326

We found that at the optimal slope the system does not have maximum profitability due to the shading caused by the strings of modules in front. The slopes with the highest production are 10 and 15 degrees, with 346 MWh per year produced. The chosen slope will be 10º since it causes less impact on the installation's coverage.

3.4.5. Storage system

Depending on the installation self-sufficiency rate achieved by the new modules installed on the roof, it may be necessary to add a storage system to meet the project requirements.

A study was carried out with batteries of different technologies, in which the decisive factor will be the cost of storage energy discharged. The considered batteries can be found in Table 10:

Table 10 - Batteries considered for the study

Hypothesis	A	B	C	D	E
Brand	Concord	Deka solar	Rolls	Victron	LG chem
Technology	Lead - acid	Lead - acid	Lead - acid	Li-ion	Li-ion
Type	Sealed	Sealed	Sealed	LFP	-
Model	2580L	8G8D	12-cs-11PS	12.8V/200Ah	Resu 13
Lifetime cycles	600	600	2 700	2 500	6 000
Price (Euros)	695 €	753 €	1 156 €	2 117 €	5 590 €
Efficiency (%)	97%	97%	97%	92%	95%

The storage cost will be calculated with the levelized cost of storage (LCOS). The project analysis time will be 25 years. For this study, the following premises were considered:

- The maximum discharge rate for batteries (DOD) of lead acid technology is 50% and for lithium ion batteries is 80%. (Pawel, I., 2014)
- The project discount rate (a) will be 6% (Grant Thorton, 2019)
- The residual value of batteries (RT) at end of life is nil
- The cost of electricity will be 0.036 euros/kWh assuming that the system will only be powered by the photovoltaic system. Value corresponds to the average cost of production of photovoltaic energy in Portugal (Lugo-Laguna, D., *et al.*, 2021)
- The cost of operation and maintenance (O&M) will be 0.03 euros per kWh stored (Mongird, K., *et al.,* 2019).

The results can be seen in Table 11:

Table 11 - Batterie LCOS calculation

Data	Concord	Deka solar	Rolls	Victron	LG chem
Investment in the first year (Euros)	25 181 €	30 168 €	32 545 €	51 685 €	28 175 €
Battery number	36	40	28	24	5
Discharged energy (kWh)	8718	8674	8187	12653	13704
O&M costs (Euros)	1503	1503	1502	629	629
Pridodicity of change (years)	2	2	7	6	16
LCOS 25 years (Euros/kWh)	1,812	2,141	0,970	0,986	0,308

Based on the results, it was chosen the LG chem battery storage system, model Resu 13, which presents the lowest storage cost over the 25 years of the project, according to the considered premises.

The guideline for defining the battery bank size was to start with a combination and then progressively increase. The first hypothesis will have a voltage corresponding to 13 batteries in series, a voltage that fits the inverter limits. In the worst case scenario, the battery bank will have a voltage of 674 V (51,8 V x 13 batteries). The remaining hypotheses will be made with parallel combinations from this set. The hypotheses that can be seen in Table 12.

Table 12 - Storage banks to be tested

Hypothesis	Number of batteries (Serie x parallel)	Voltage (V)	Capacity (kWh)
1	13 (13 x 1)	674	142
2	26 (13 x 2)	674	284
3	39 (13 x 3)	674	426
4	542 (13 x 4)	674	555

An air conditioning system will be considered at the battery installation site in order to maintain the ideal temperature between 15 ºC and 35 ºC degrees, to ensure the proper functioning of lithium ion batteries according to Shuai

Ma (Ma, S., *et al*., 2018). In this way, its longevity is increased and the risk of fire is reduced.

3.4.6. PV Expansion Summary

Table 13 - YKK PV expansion main characteristics

Equipments	Characteristics
Module	Jinko solar Cheetah 72M 410 W
Slope	10º
Modules per string	17
Number od strings	8
Power per string	6,97 kWp
Installed power	223 kWp
Inverter module	SUN2000-50KTL
Number of inverters	4
Inverter power	46 kW
Batteries model	LG Chem Resu13
Bank capacity	To be defined

4. Methodology application

At this stage we have the conditions for the methodology application. There will be tested the 4 expansions hypothesis defined earlier (Table 12), all of them with the same characteristics (Table 13) regarding to installed capacity, energy conversion and slope, but with different storage capacities. Additionally, an expansion hypothesis without a storage system will also be considered.

The considered hypothesis can be seen in Table 14:

Table 14 - Considered hypothesis for methodology application

Hypothesis	A	B	C	D	E
Installed power (kWp)	223	223	223	223	223
Storage capacity (kWh)	0	142	284	426	555

To calculate the economic benefits of the system were considered the tariffs for energy sale (obtained through a market consultation) and self-consumption tariffs, obtained through the currently tariff practiced at YKK.

4.1. Investment and O&M

The investment values of this project will be estimated based on the prices practiced in the construction of the existing system and on an online consultation. To calculate the investment of this project, the following statements were considered:

a) The PV system equipment: panels, batteries and inverters, including interconnection protections in accordance with DL162/2019;
b) The costs of installation, that in the case of panels, includes the purchase and installation of supports for the modules;
c) The creation of a climate-controlled place for the placement of batteries, in order to increase their efficiency and safety conditions.
d) Structural calculation to verify the roof's effort.

For the investments costs calculation, several assumptions were taken in account, 1) The considered project lifetime was 25 years 2) The present value of the investments was calculated considering a discount rate of 6% (Grant Thorton, 2019), 3) Inverters will be replaced in year 15 (Sangwongwanich, A., *et al.*, 2017), 4) The batteries will be replaced when their expected lifetime cycles are reached.

The O&M costs considered include:

a) Annual maintenance to PV and storage system
b) PV facility insurance

4.2. Results

Considering the economic parameters, the investment and the self-production rate graphically represented in Figure 9, we verify that the hypothesis that comes closest to the user's objectives while meeting the imposed requirements is hypothesis B, with a self-production rate of 58,31% .

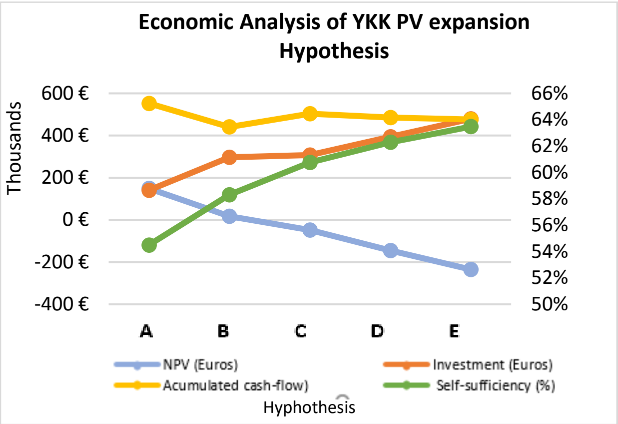

Figure 9 - Economic analysis of YKK PV expansion hypothesis

4.3. PV expansion impact on User grid energy consumption

Considering that the hypothesis B is implemented, the impact of the PV system in the YKK grid energy needs can be seen in Figure 10. A significant reduction in grid energy needs can be seen, with the lowest self-sufficiency rate of 35,8% in November.

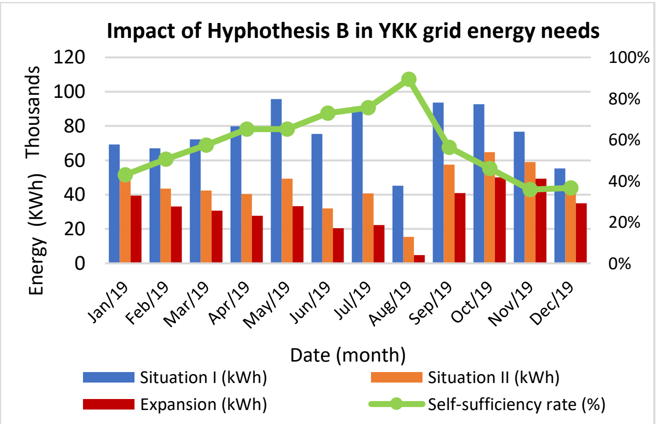

Figure 10 - Impact of Hypothesis B in YKK grid energy needs

The average hour grid power consumption over a year can be found in Figure 11, where we can see that the new grid energy consumption is mostly located in periods where there is no sun. With the existing system (situation II) this was already a reality, however, it is now more expressive. Considering the period of sunlight from 7:00 am to 6:00 pm, the average power consumed from the grid is 40,7 kW, which represents a reduction of 42% from the average value that was consumed only with the existing system, 71 kW.

Considering the hours of the day where there is no sunlight, it is also possible to graphically verify that there was a reduction in the grid energy consumption with the PV expansion due to the storage system. In situation II, the average consumption power in the periods between 18:00h and 07:00h is 50.2 kW, while with the proposed expansion they are situated at 47 kW, equivalent to a reduction of about 7%.

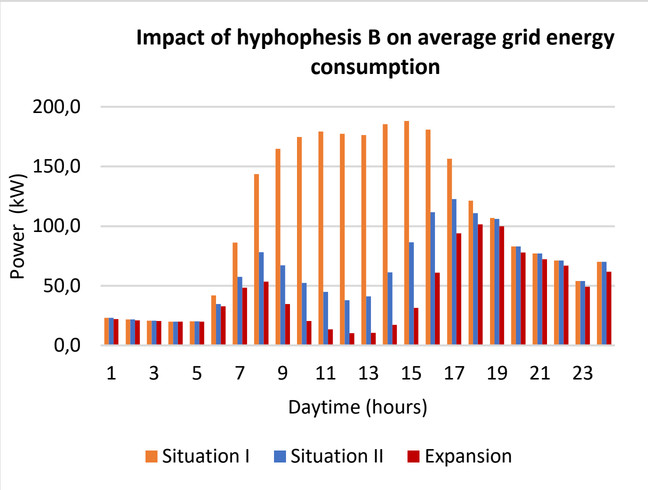

Figure 11 - Impact of hypothesis B on average grid energy consumption

In order to achieve an even greater rate of self-production, several storage system hypotheses were designed, which would serve as a complement to the increase of the installed power, and which would receive energy from both systems, the existing one and the expansion. Hypothesis A does not include a storage system, hypothesis B, C, D, E include a battery bank of 142, 284, 426 and 555 kWh, respectively. The battery model chosen were LG brand batteries, model LGChem of 13 kWh, which obtained an energy storage cost of 0,308 €/kWh considering a project lifetime of 25 years. The lowest value within the studied hypothesis.

The hypothesis B was selected since it obtains the highest self-production rate of the installation, of 58,31%, with an investment of less than 300 000 euros and a positive NPV. In this hypothesis, the energy cost over the life of the project is 0,077 €/kWh, an acceptable value according to the literature, which indicates that the LCOE of photovoltaic projects with a storage system is around 0,07 €/kWh (IRENA, 2020).

If hypothesis B is implemented, which is the best hypothesis in accordance with the user's requirements, YKK prospects of increasing the self-production rate with solar energy are limited once the connection power cannot be increased (DL162/2019) and there is no more space available. The desired self-production rate can be achieved complying with the restrictions by choosing a more economical storage systems or increasing the inverter overload ratio, by installing higher power panels. In this case the overload rate considered was 21%.

As 60% of YKK grid's energy consumption will be concentrated in the off sun periods, future projects should include new forms of energy production, like wind energy whose peak power production hours are in periods when there is no sun.

5. Conclusions

In this dissertation, a methodology was developed to calculate the economic benefit of expanding a photovoltaic system with storage. This methodology was later applied in a real case study, where several expansion hypotheses were projected with the help of the *PVsyst* simulation software. The case study concerns the expansion of the photovoltaic system of YKK, a company located in Carregado, which has currently a photovoltaic system with 240 kW of connection power and 288 kWp of installed power. The objective was to obtain the highest possible self-production rate, the minimum being a 60% rate, considering the user’s restrictions.

Regarding the sizing YKK's PV system expansion, the considered modules are from the renowned brand Jinko solar, model Cheetah 72M and their power was 410 Wp. The array configuration with the lowest conversion cost had a configuration of 8 strings of 17 modules each and had a conversion cost of 0,0057 euros/kWh in the project lifetime (25 years). The considered inverters had 46 kW. The new photovoltaic system was sized for the largest possible area and power, as the user's objective is to obtain the highest self-production rate. The final result of the sizing resulted in an increase of the installed capacity of 223 kWp and an increase in connection power of 184 kW.

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