Multiobjective optimization of the energy storage systems (CHP and batteries) for small and new buildings

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October 2019

Abstract

Environmental concerns about global warming and resource depletion are leading to new and more efficient energy systems, where the consumption of electricity is mainly satisfied with self-production units. Both the residential sector and the commercial sector started to integrate self-generation units in order to achieve cost-savings in electricity bills or to spread environmental awareness. The first off-grid and entirely self-sustainable houses also started to be built in the residential market. These houses have a production system based on renewable energies. However, this is more difficult to design for buildings. The work developed in this thesis, analyzed a previously built model that considered the energy system of a residential building. Moreover, it aims to improve and provide deeper knowledge on off-grid residential buildings with the development of a new model. Photovoltaic and cogeneration (as an emergency source) technologies were integrated and the production and consumption profiles were analyzed. Finally, an economic assessment of the work was performed, as well as a sensitivity analysis. It was concluded that the photovoltaic system could not operate on its own, requiring the use of cogeneration. The system with both technologies was more expensive than the utility companies' electricity price. The lower price obtained in the sensitivity analysis was not enough to be competitive with the utility companies' price. Solutions for future developments and deeper research consideration were discussed in order to improve the results of this work.
Keywords: Photovoltaic, Off-grid, Energy storage, Self-sustainable, Cogeneration

1. Introduction

In 2016, 19.1 % of the total energy use for heating and cooling in the EU-28, was renewable energy. What contributed to this growth was the increase use in the industrial, services and residential sectors [1].

The construction activity is the second highest contribution to the gross value added of the environmental economy [1].

In Portugal, the residential sector has the third highest share of final energy consumption, with a share of 17%, after the transport sector with 37 % the industry sector with 31 % [2].

In 2016, the building sector led the electricity consumption with a share of 60.3 %, where the residential sector had a weight of 27.7 %. In this sector, the electric energy consumption represented 43.6 % followed by a renewable energy consumption with a share of 31.2 % [2].

The renewable energy produced within the EU-28 increased by 64 % between 2007 and 2017. Solar energy, although remaining with relatively low production, had a rapid expansion and represented a 6.4 % share of the renewable energy produced in 2017. The electricity generated from renewable sources increased during the period of 2007 to 2017, this growth "*reflects an expansion in three renewable energy sources acros the EU, principally wind power, but also solar power and solid biofuels*" [3].

The scope of this thesis aims to build and analyze a model for the energy system of an off-grid building that generates electricity with renewable energies. The focal point is to assess a previously built energy system and provide improvements and deeper understanding on the energetic performance and consumption behavior of such building.

In chapter 2 the background will be discussed then, in chapter 3.1 some considerations will be discussed. Chapter 3 discusses adjustments to the computation algorithm, inverter system and power cables and the importance of its losses will be assessed. The consumption profile will be analyzed and adjusted in chapter 4. In chapter 5 the system will be re-designed with batteries for the new consumption profile and all new devices and the system's performance will be discussed. A micro combined heat and power plant will be implemented as an emergency source of energy in chapter 6 and finally, in chapter 7 an economic assessment of the entire energy system will be performed.

2. Background: PV systems

A Photovoltaic (PV) system is basically composed by the following elements: a set of PV modules, batteries, a regulator (or charge controller), an inverter and the load [4].

2.1. PV panel: working principle

The power output of a PV cell depends on the cell's temperature, T_c, and on solar irradiance, G, given in W/m^2, this is described in equation 1, combining with equation 2, that show the efficiency variation with cell's temperature. The efficiency of a cell decreases with an increase in temperature [5] [6].

$$P_{PV} = \eta(T) * A_{PV} * G \quad (1)$$

$$\eta(T) = \eta(STC)[1 + \gamma(T_c - 25^oC)] \quad (2)$$

Where, γ is defined as the relative decrease in module efficiency per degree centigrade of cell temperature increase [6].

The cell's temperature depend on the ambient temperature and on solar irradiance. Equation 3 specifies the cell's temperature, using the normal operating condition's temperature, $NOCT$, in °C, of the PV cell [6].

$$T_c = T_a + \frac{NOCT - 20}{800} \cdot G \quad (3)$$

Where T_a is the ambient temperature, $NOCT$ is the normal operation condition's temperature and G is the solar irradiance.

2.2. Inverter

Any isolated PV system , should have an off-grid inverter as this is an essential electronic device that converts low voltage DC electricity to 100 V - 120 V or 220 V - 240 V AC signal depending upon the need of the load. Some requirements are indispensable for an off-grid inverter [4].

- Auto starting and adequate protection warning signs;
- Peak power capacity – it should support more than two times its nominal power;
- Low stand-by power; High efficiency; Voltage stability – between the range of 230 V ± 10
- Possibility to connect other inverters in parallel.

Some inverters and Maximum Power Point Trackers (MPPTs) have charge controller functions integrated, these devices can operate as a regulator.

2.3. Battery

An electric battery is a device that converts stored chemical energy into electrical energy in accordance to the chemical reactions of reduction and oxidation [4].

The batteries integrated in autonomous PV systems must have the following characteristics:

- Reduced maintenance requirements;
- Long service time;
- Reduced self-discharge and high energy efficiency;
- High storage capacity and power density;
- Good performance/price relation;
- Protection against the occurrence of hazards to the environment and health.

3. Improvements in the PV system model

3.1. Initial system and considerations

The starting point for this thesis is based on a previous thesis developed by Ricardo Ladeira [7]. In his work, he studied and analyzed the energy needs in a small 9-apartment building, with 3 floors, that would be built in Lisbon.

The energy system of this building was composed by a PV system, battery energy storage and a diesel generator. In the PV system, the number of panels in series and in parallel was not addressed. Panel's slope was 35 ^{o}, consideration used as well in this thesis. The number of inverters and the number of strings were not addressed. With these considerations, no current or voltage changes were assessed. The power generated by the PV system was computed based on weather data in Lisbon (the incident radiation and ambient temperature) and PV panel data (change of cell's efficiency with temperature). However, cell's temperature was considered as the same as ambient temperature. The values measured for the ambient temperature in the Lisbon area are between -0.9 °C and 40.48 °C. In this methodology, no power losses were considered.

The data used for this thesis such as weather data and building's specifications are the same used by Ladeira [7] in his work, as well as some components of the energy system such as PV panels.

Ladeira considered the battery pack to be a hypothetical giant reservoir of energy installed in the building.

The micro combined heat and power plant that Ladeira considered had a nominal power of 20 kW, it was a XRGI 20, from EC Power and was fueled by natural gas. This unit had enough power to support this buildings needs [7]. The generator operation set by Ladeira was, if the battery's State of Charge (SOC) reached 10%, the generator was turned ON, and it would produce electric energy until the SOC reached 90%. While operating, the generator prioritizes the consumption of the building, leaving the excess energy for charging the battery.

3.2. Temperature effects

The temperature effect on the efficiency of a PV cell was considered using equation 3 and the $NOCT$ given in the manufacturer datasheet, the cell's temperature was computed. It varies between -0.9 °C and +70.29 °C while the ambient temperature is the same as in section 3.1. Note the almost 30 °C of temperature difference during the summer. This 30 °C of temperature difference, reflect a difference in efficiency of 2.2 %.

3.3. Operation and topology of the photovoltaic system

Ladeira developed a case considering full roof coverage (around 60 % of the roof area covered with panels) with around 36 kWp of peak power, this case was used as a base to obtain the operational design of the system. As a starting point, no charge controllers or batteries will be considered. The weight of power losses in cables was assessed only with modules, inverters and the load. The operational design obtained is described in figure 1.

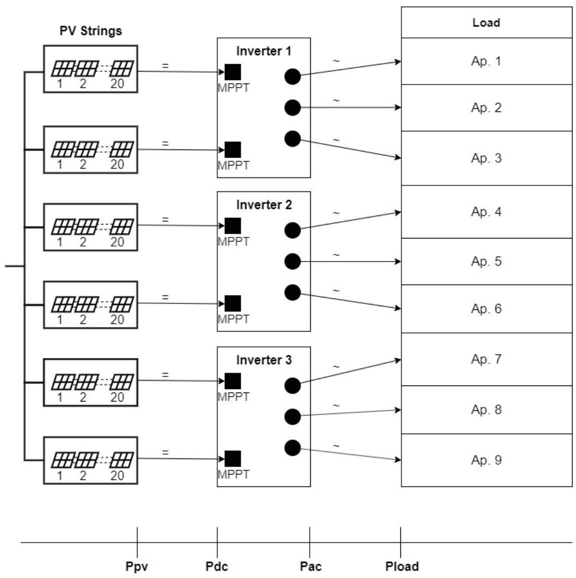

Figure 1: Electricity flow from generation to load

The compatibility of the PV system with the inverter was analyzed and assured.

To estimate the power cables' losses, one needs to size the power cables that transport energy from the PV system to the grid.

3.4. Sizing the power cables

The design and placement of the system and the power cables is described in figure 2.

Using figure 2 to identify the cables, the length estimated for each cable is given in table 1

The obtained area for the cross-section is 1.5 mm^2 for the Direct Current (DC) cables.

To estimate the section of the power cables in the Alternating Current (AC) side, it's necessary

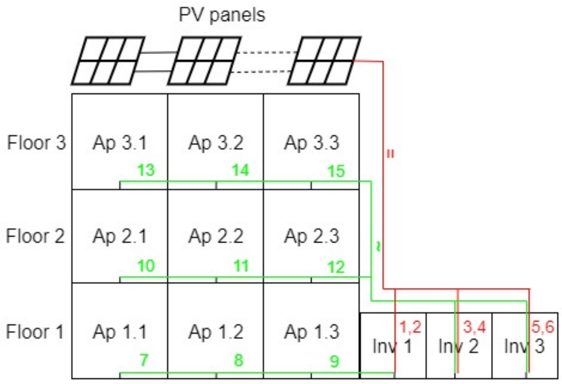

Figure 2: Scheme of the power cables connections in the building

DC side		AC side	
Cable number	Estimated length [m]	Cable number	Estimated length [m]
1 and 2	102	7	131
3 and 4	103	8	81
5 and 6	104	9	31
		10	139
		11	89
		12	39
		13	147
		14	97
		15	47

Table 1: Length estimation for the power cables

to compute the Root Mean Square (RMS) value of the current. The computational method described in section 3.5, shows how the RMS value for the current is obtained and estimates the cable's power losses.

3.5. Estimating power cable's losses

To compute the power losses in cables, one considered the cables as an equivalent resistance, R_{eq}, with equation 4 and computed the total Joule power losses, $P_{J_{cables}}$ with equation 7. The Joule losses in the DC side were computed with equation 5 and on the AC side with equation 6.

$$R_{eq} = \frac{\rho \cdot l}{S} \tag{4}$$

$$P_{J_{DC}} = R_{eq} \cdot I^2 \tag{5}$$

$$P_{J_{AC}} = R_{eq} \cdot I_{rms}^2 \tag{6}$$

$$P_{J_{cables}} = P_{J_{DC}} + P_{J_{AC}} \tag{7}$$

Where ρ is the resistivity for copper, l the length of the cable, S the cross-sectional area and I is the current that flows in that cable. Note that $P_{J_{DC}}$ represent the DC Joule power losses in cables connecting the PV strings and the inverter, and that $P_{J_{AC}}$ represent the AC power losses in cables connecting the inverter and the load (see figure 1). The current must be computed using equation 8.

$$P = U \cdot I \tag{8}$$

Where P represents the power, U the operating voltage and I the current. Thus, the current for the PV strings, I_{PV} is computed with equation 9.

$$I_{PV} = \frac{P_{PV}}{U_{PV}} \tag{9}$$

Then, the DC power losses were calculated using equation 5, where $I = I_{PV}$ and R_{eq} is the electric resistance of each cable. The sum of the losses in each cable results in the DC power losses. Afterwards, using equation 10, the DC power was computed.

$$P_{DC} = P_{PV} - P_{J_{DC}} \tag{10}$$

Considering the inverter's efficiency, the AC power at its output was computed using equation 11.

$$P_{AC} = P_{DC} \cdot \eta_{inv} \tag{11}$$

The AC current, I_{rms}, was obtained with equation 12 to compute the AC power losses and to obtain the section of the power cables in the AC side. $cos\varphi$ represents the power factor.

$$I_{rms} = \frac{P_{AC}}{3 \cdot U_{phase} \cdot cos\varphi} \tag{12}$$

The AC power losses were computed using equation 6 and then, the sum of the losses in each cable resulted in the total AC power losses.

The net power that the load receives becomes established using equation 13.

$$P_{load} = P_{AC} - P_{J_{AC}} \tag{13}$$

In figure 1 the different stages of power computations along the electricity flow can be observed.

3.5.1. Results and discussion

The methodology described in section 3.5 was used for the coldest day of the year. During this day it is expected that the consumption of electricity increase to ensure that there is thermal comfort in all apartments. The power losses in cables were computed to evaluate it's importance in the energy system. Note that the PV power used to assess such losses is the hourly average power during production hours of the coldest day. For the coldest day, production started at 10:00 and ended at 19:00, the average production of power during this period was 12240.9 W.

The results for power computed in several stages of the system are given by:

$P_{PV} = 12240.9$ W ; $P_{DC} = 12172.6$ W
$P_{AC} = 11929.2$ W ; $I_{rms} = 7.2$ A
$P_{load} = 11394.0$ W

The section of the power cables in the AC side was obtained, since $I_{rms} = 7.2$ A the cable's section is 1.5 mm^2.

The total power losses in the cables have a value of $P_{J_{cables}} = 603.5$ W which can be related to the generation as a percentage lost: $P_{\%losses}= 4.9\%$.

The power losses obtained were evaluated specifically for the system described in section 3.3, if the system's design change, the influence of cable losses may change as well.

4. Residential sector: energy consumption profile

Data on the energy consumption profile for the residential sector was obtained from the Update of the Consumption, Production and Self-consumption for the Year of 2019: Methodological Document, of EDP: Distribuição [8]. In this document, the profiles are obtained considering an average of the population that are inserted in a certain consuming group. The residential sector's consumption is well represented by the normal low voltage, or in Portuguese, Baixa Tensão Normal (BTN), class C profile, with an installed power lower than 13.8 kVA and an annual consumption lower than 1681 kWh. The average annual consumption of the BTN C profile in 2017 was 1681 kWh. Consumption profile BTN class C is similar for different days of the week and during the weekend. However, it has a large variation depending on the seasons. Figure 3 is used as an example to describe the average consumption for the BTN C profile, during different days and for different months of the year. In such figure, it is possible to observe that for winter months the consumption of energy is higher.

4.1. Week and weekend analysis

In figure 3, for a typical week day, the lowest consumption is achieved between 04:00 and 06:00. The consumption then increases until 08:00 and follows a stable trend to increase slowly between 08:00 and 13:00. At 13:00 the consumption reaches a local maximum and decreases slowly until around 16:00/17:00. Afterwards, the consumption increases until around 21:00 where it reaches its' daily maximum, a higher consumption of energy occur around dinner time between 20:00 and 22:00. Finally, the energy consumption decreases until mid night. For the weekends the profile is very similar.

5. PV system

With the change of the consumption profile to a residential sector specific profile, the system must be reviewed. Since the decrease in consumption was around 60%, the system will have a decrease in peak power but not lower than 60% and the balance of the system will be ensured.

5.1. Re-sizing the PV system

The new operation of the PV system will consider the use of batteries. With this, devices with

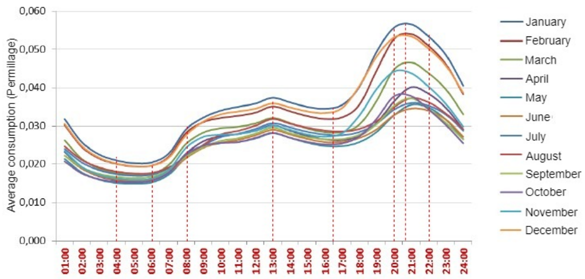

Figure 3: Average consumption profile for a typical week day per month (January to December) of BTN class C [8]

charge controller functions such as inverter chargers and MPPT charge controllers will be implemented. While choosing the new configuration, compatibility between the modules, inverter, MPPT and battery was ensured. The final design of the system is equal for every floor and is described in figure 4.

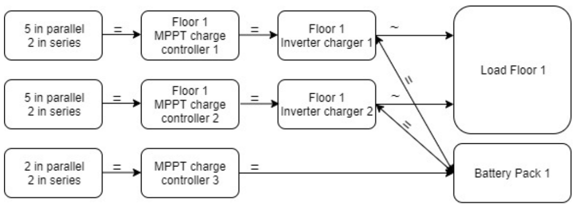

Figure 4: Representation of the assembly scheme of the PV system for floor 1

The total number of PV panels is 72 with a peak power of 21.6 kWp and occupies 34.8 % of the roof area. The total number of MPPTs is 9, where 6 of them connected to 6 inverters and the number of battery packs is 3 with a total of 9 batteries.

Choosing each specific model of inverter and MPPT, one had to consider the electrical properties of all the devices and ensure their compatibility with each other. The inverter and the MPPT are ready to be connected to a battery with a nominal voltage of 48 V.

5.2. Re-sizing the power cables

In this new operational design of the PV system, it is necessary to re-size the power cables. The new design for cables is described in figure 5. The losses in the power cables that transport energy between the MPPTs and inverters, MPPTs and battery packs and between inverters and batteries will be neglected, since the devices are considered to be placed together in each floor. The power cables are small, thus they have a negligible electric resistance.

Using figure 5 to identify the cables, the length estimated for each cable is given in table 2.

The cross-sectional area chosen for the power cables connected to the MPPTs which then will connect to an inverter, has 16 mm^2. The cross-sectional area chosen for the power cables connected to the MPPTs that will connect to a battery pack has an area of 4 mm^2.

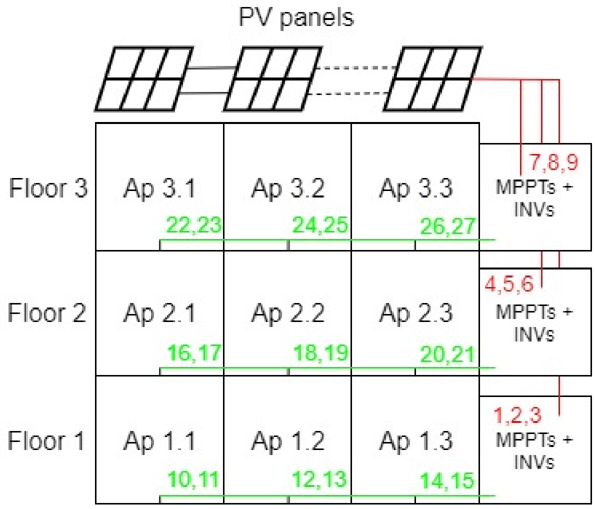

Figure 5: Scheme of the power cables connections in the building for the new system

DC side		AC side	
Cable number	Estimated length [m]	Cable number	Estimated length [m]
1,2 and 3	102	10, 11, 16, 17, 22 and 23	25
4, 5 and 6	95	12, 13, 18, 19, 24 and 25	75
7, 8 and 9	88	14, 15, 20, 21, 26 and 27	125

Table 2: Length estimation for the power cables in the new system

To estimate the section of the power cables in the AC side, it's necessary to compute the RMS value of the current, obtained in section 5.3.

All of the different cross-sections must be reviewed to ensure that they are in accordance with the European Cable Fire Safety Regulations.

5.3. Assessment of the power losses in the new system

Since the design of the system was changed, the power losses must be re-assessed. Note that, as in section 3.5, the PV power used to assess the power losses is the hourly average of energy generated during production hours of the coldest day (P_{pv} = 7344.5 W). The methodology used for this computations is the same as in section 3.5. However, a slight change must be considered. In this system, the energy will be stored, thus on the AC side, the power transported will be limited by the load needs, thus, P_{load} is equal to the energy needs of the building (P_{load} = 3375.3 W), I_{rms} must be computed using equation 14. The value used for P_{load} is the maximum load value for the coldest day.

$$I_{rms} = \frac{P_{load}}{3 \cdot U_{phase} \cdot cos\varphi} \quad (14)$$

As results, I_{rms}, in each AC cable is equal to

1.02 A thus, the section of these cables is equal to $1.5mm^2$; $P_{J_{cables}}$= 136 W, $P_{\%losses}$ = 2%. The energy that is lost in the power cables is lower than 10%, the losses transporting energy in the power cables do not have significance for the formulation of the problem, thus, they were neglected.

5.4. System's performance without energy storage

In a first approach the viability of the system was tested without storage devices. The peak of production and peak of consumption are not during the same hour of the day, it is expected that the consumption will not be fully satisfied. This raw test of the system is mainly used to compare the total surplus of energy produced after the demand is met and the total deficit of energy when the demand is not met. The load of each apartment is considered equal to the hourly average one, thus, each floor has the same characteristics for energy consumption.

The energy that reaches the load was compared with the energy needs of the building. The surplus and deficit of energy were computed. The time spam for computations was 2 years and 3 months starting in January 1^{st}, 2018. However, for this analysis it was reduced to one year, starting in the second Winter (December 21^{st}, 2018). This restriction was chosen in order to analyze the PV system in a near-stationary condition, where the battery does not start fully charged. From figure 6 ,the total surplus of energy was 28205 kWh and the total deficit of energy was 7216.9 kWh.

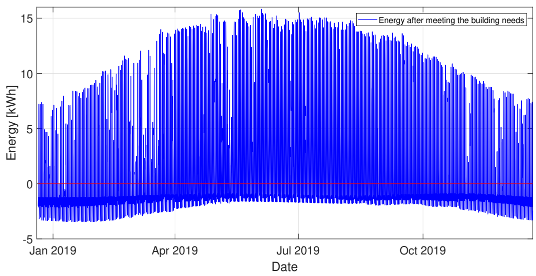

Figure 6: Surplus and deficit of energy for the second year

This is a representative value that show that the production, if stored, is enough to cover all the building needs.

5.5. Integrating batteries as energy storage devices

The use of batteries to store energy is a solution that aims to ensure that the building has energy being delivered 24 hours a day. Each floor of the building have a pack of 3 batteries, with a total of 30.18 kWh capacity per floor. The system was designed with this capacity to ensure that if the PV system was off during the coldest day, each battery pack would sustain the needs of each floor for the entire day.

Battery's compatibility with the inverter and MPPTs was ensured.With batteries implemented, the energy produced by the PV system had the priority to feed the building, the exceed would charge the batteries. The system was now tested for the same weather and load conditions as in section 5.4. A seasonal analysis was performed to assess the different behavior and response of the system under different weather conditions. Remember that this analysis starts in the second winter of the data computed, this allows to evaluate the system in a near-steady state condition. The Depth of discharge (DOD) of the battery is 80%, the battery could not be discharged under 20 % and this resulted in a lack of energy being delivered to the building when the battery reached this lower capacity.

5.5.1. Seasonal analysis

The production of energy in a PV system depends on weather factors, the three most important are irradiance, temperature and cloud cover of the sky. The irradiance that reaches a panel is influenced by the cloud cover, and the panel efficiency depends on the cell's temperature and this depend on irradiance and ambient temperature, as explained before in equation 3.

It was observed that the most critical season was winter.

In the Winter season, figure 7, shows the relation between cloud cover, useful irradiance (which is the irradiance that is felt by a solar panel) and production. It is possible to note that when the cloud cover is at 100% or near, the useful irradiance decreases and the production decreases with it. For instance, in the end of February, the cloud cover is at 0% and the useful irradiance is very high, so is the production. However, in the beginning of March, when it is observer a sky cloud cover of 100%, the useful irradiance decreases and does the production.

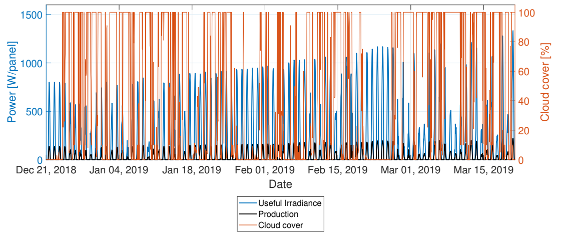

Figure 7: Hourly irradiance, production and cloud cover for the Winter of 2019

Figure 7 also describes a slight increase trend of the irradiance thus, the production.

The battery's SOC will suffer change depending on the needs of the building. The battery's capacity is limited to never decrease below 20%. Figure 8 shows that the SOC of the battery reaches 20% in the end of December, beginning of January and again in the beginning of March, when this happens, the system has a deficit of energy, and the building's needs are not met. For this season the battery cycle count increases around 35 cycles.

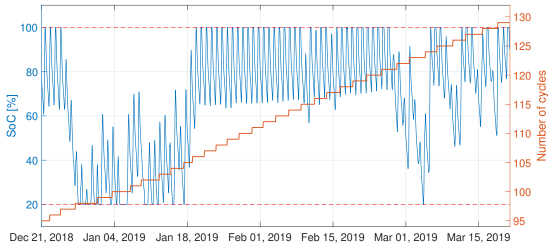

Figure 8: Hourly battery's SOC and cycle count for Winter 2019

Linking information from figures 7, and 8, it is possible to observe that cloudy days have a consequence resulting in low production of the entire PV system, since this happens, the system has to use the battery as an energy source, thus the battery's SOC decreases abruptly. In the end of December of 2018, beginning of January of 2019 and in March of 2019, such occurrence was observed.

During Spring and Summer seasons, the system did not have a deficit of energy. However for the Fall season, a decifit was experienced in the end of November and mid December as observed in figure 9, when the SOC reaches 20 %.

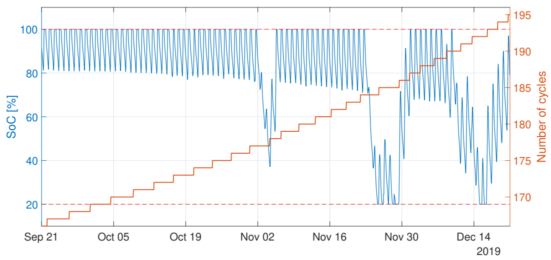

Figure 9: Battery's SOC and cycle count for Fall 2019

The season where it was noted a higher battery's cycle count was the Winter season.

The assembled system was not yet fully reliable to operate on its own has it was very sensible to irradiance variations during the Winter and Fall seasons. In order to complement the system, some emergency measure must be implemented to allow for this PV system to properly function without jeopardizing the energy consumption of the building's residents. At this stage, the system was not enough to ensure that all the energy needs were fully satisfied.

5.5.2. Critical day's analysis

The energy analysis of the battery was performed for critical days of the year. In this analysis the hourly production and consumption were assessed, as well as the battery SOC. Out of four critical days, the cloudiest day of Winter is important to assess because it is a day with very low production.

For the cloudiest day of the Winter, from figure 10, the production is smaller than the consumption for the entire day. The battery's SOC decreases during the entire day, even during production hours where the decrease is reduced. Around 10 p.m. the battery's SOC reached 20%, the lower limit, thus, there is a lack of energy in the system and the building's consumption was not satisfied.

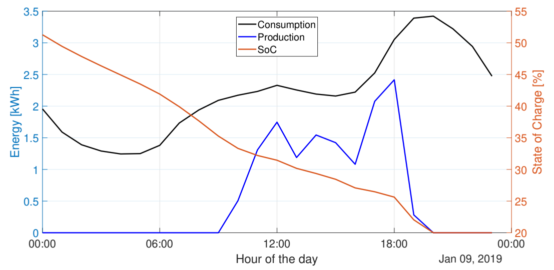

Figure 10: Hourly energy production, consumption and battery's SOC for the cloudiest day of Winter

6. Micro combined heat and power plant

The previous system could not supply the building for 185 hours and the total deficit of energy was 284 kWh, which represent around 2% of the hours and consumption of the year. In order to have a full steady supply of energy a new source of energy was installed in the building for emergency use, a micro Combined Heat and Power Plant (CHP) that works on the principle of cogeneration. When the battery reaches its lower limit of 20 % SOC and the PV production is not enough to satisfy the energy needs in the building, the micro CHP will be immediately turned on.

The maximum load for all the nine apartments was 3.441 kW, thus, the generator must have a higher power capacity, the model chosen for the generator was XRGI 6 from EC Power with an electrical output power of 6 kW.

6.1. Assembly of the device in the system

The priority for the energy generated is to satisfy the apartments needs, and any surplus will be fed into the batteries evenly. The physical links between the PV system and the micro CHP are the batteries and the load. The connection scheme for the generator is described in figure 11.

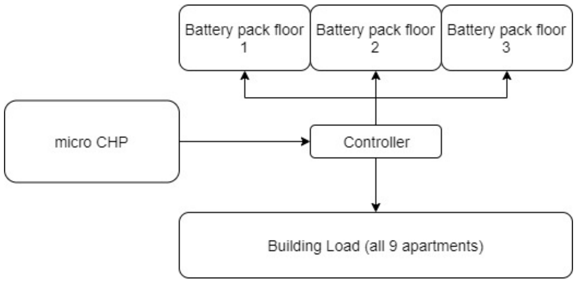

Figure 11: Representation of the electric connections for the micro CHP

6.2. Energetic analysis

Using the generator only in emergency conditions, it worked for 49 hours, during the period in analysis, and produced a total amount of energy equal to 294 kWh.

The system's performance was analyzed. The seasons where the system had deficit of energy were the Winter season and Fall season, those, will be discussed in section 6.2.1 and the critical days of the year will be discussed in section 6.2.2

6.2.1. Fall and Winter of 2019

During winter season, the generator was important to ensure that the building's energy needs were met. Figure 12, shows the total energy produced by the energy system in a hourly base, as well has the consumption and the energy produced by the generator. There were critical periods were the generator was very much needed to ensure a steady supply. The consumption was higher than production in several hours throughout the season and the emergency supply was used, since there was not enough energy stored to ensure such supply.

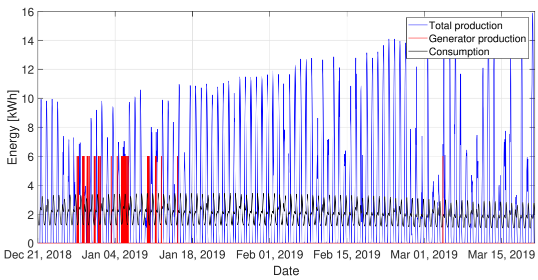

Figure 12: Hourly production and consumption for the Winter of 2019 with the micro CHP

During the hours that the generator was producing energy, it is possible to observe small oscillations in the battery's SOC. This can be observed in figure 13 and in more detail in figure 14, around January 5^{th} this happens because with the generator working at full capacity, supplying an output of 6 kWh per hour, after the building's energy needs were met, the surplus that was produced in that hour was used to feed the batteries.

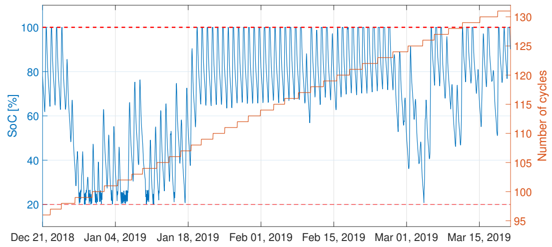

Figure 13: Hourly battery's SOC and cycle count for Winter 2019 with the micro CHP

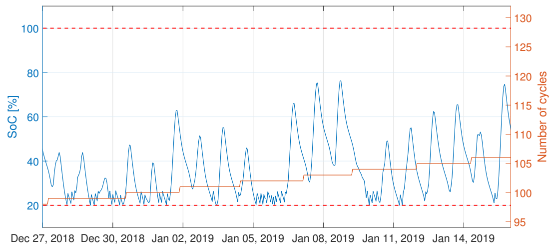

Figure 14: Hourly battery's SOC and cycle count for a period in the Winter of 2019 with the micro CHP

For the Fall season, as well as for Winter, the generator had an important role to ensure a steady supply where there was no deficit of energy.

Remembering data from figure 7, the periods where the generator was turned on, match with periods of low production, this is due to the occurrence of clouds in the sky, thus low irradiation, or due to night time. When there is the occurrence of a cloudy sky several days in a row, the system tends to require the use of an emergency source to satisfy the consumption of the building. In the end of this analysis the batteries count 197 cycles, instead of the 195 from section 5.5.1.

6.2.2. Critical days

The only critical day where a difference on the production profile is noted, is the cloudiest day of Winter, this happens because on this day, observed in figure 10, the batteries' SOC, reaches 20%, thus a deficit of energy occurs. Now it is possible to observe the alteration in production due to the emergency trigger of CHP. Note in figure 15 that when the SOC of the batteries reaches 20%, the production increases abruptly to 6 kWh at 21:00, this is because the generator was turned on during this hour.

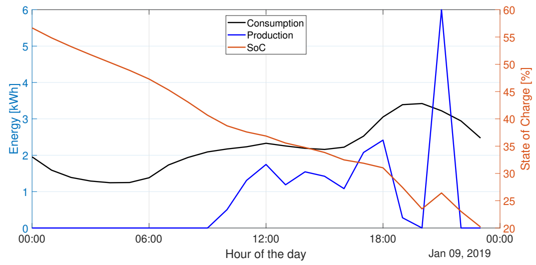

Figure 15: Hourly energy production, consumption and battery's SOC for the cloudiest day of Winter with the micro CHP

7. Economic assessment

Now that the energy system can fully satisfy the energy consumption of the building, an economic assessment of such system was performed. The investment costs of the energy system are described in table 3. The method used in this chapter will be focused on computing the Levelized Cost of Energy ($LCOE$) as a measure for comparison.

Investment Costs			
Devices	Price per unit [€/unit]	Units	Total [€]
PV panels	202.40	72	14 572.80
Inverter	2 020.00	6	12 120.00
MPPT	602.00	9	5 418.00
Batteries	4 686.00	9	42 174.00
XRGI	19 950.00	1	19 950.00
Storage vessel	1 100.00	1	1 100.00
Power correction factor	995.00	1	995.00
Total PV			74 284.80
Total CHP			22 045.00
Total			96 329.80

Table 3: Investment costs of the energy system

The $LCOE$ is the cost of energy in €/kWh, it represents the net present value of the unitary cost of electrical energy over the lifetime of a system. It is obtained by summing all the costs of a system during its lifetime, these costs include investment costs, operation and maintenance costs and fuel costs, then, this result is divided by the total electrical energy generated, this is described in equation 15,

$$LCOE = \frac{I_t + \sum_{j=1}^{n}[\frac{c_{om,j}}{(1+a)^j}] + \sum_{j=1}^{n}[\frac{c_{fuel,j}}{(1+a)^j}]}{\sum_{j=1}^{n}[\frac{E_j}{(1+a)^j}]} \quad (15)$$

Where I_t is the total investment cost, assumed to be invested, in full, in the beginning of the project (present moment), $c_{om,j}$ is the operation and maintenance costs of year j, $c_{fuel,j}$ is the fuel costs of year j, E_j is the total energy generated in year j, n is the lifetime of the energy system which is considered as equal to 5 years and a is the discount rate, which is assumed to be equal to the inflation rate for this sector (2.2% [9]).

The value computed for the $LCOE$ of the PV system, $LCOE_{PV}$ was 0.42 €/kWh, with the use of the micro CHP only as an emergency source, the $LCOE$ for the total energy system, $LCOE_{System}$ is 0.58 €/kWh. The CHP used as a backup generator, operates for a small number of hours every year, thus, its $LCOE$, $LCOE_{CHP}$, is higher, 16.97 €/kWh. The value paid by an EDP client is around 0.20 €/kWh [10]. In comparison, $LCOE_{System}$ is very high, more than double. Thus, in this analysis an investment in an energy system, like the one in study, when constructing a building, is not a viable one.

7.1. Sensitivity analysis

The variation of the $LCOE_{System}$ is important to assess in order to obtain a more viable solution.

The largest portion of the investment costs in the PV system is the investment cost of the batteries. Thus, the value of the $LCOE_{PV}$ is expected to vary with the number of batteries. The $LCOE_{CHP}$ varies with the amount of energy generated, if the micro CHP generates more electric energy in the same time-span, the $LCOE_{CHP}$ decreases.

For the energy system obtained by combining the two technologies, it is important to understand that a reduction in the number of batteries reflect an increase in the amount of energy produced by the micro CHP. This happens because the micro CHP works only as an emergency source. An optimal value can be obtained by decreasing the number of batteries and, consequently, increasing the micro CHP generation. Figure 16 shows the variation of the $LCOE_{System}$ with the number of batteries, in this figure it is possible to observe that the $LCOE_{System}$ has a minimum, thus, optimal, value.

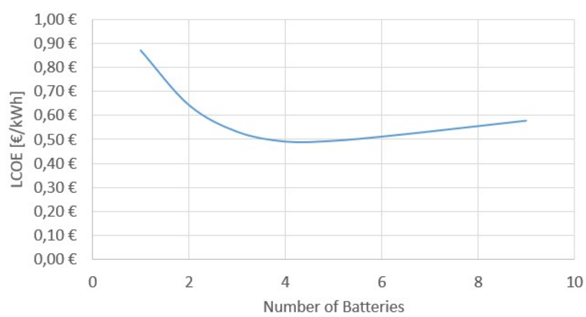

Figure 16: Variation of the $LCOE_{System}$ with the number of batteries

From figure 16, the optimal minimum value for the $LCOE_{System}$ is 0.49 €/kWh, and the system is considered to have 4 or 5 batteries. This price is still higher than the one used by EDP, thus, the investment is not viable.

8. Conclusions

The initial PV system was analyzed and its operation and topology were defined. The power cables of the system were considered in order to obtain the power losses in cables.

A new and more suitable consumption profile was obtained, and with this, the re-sizing of the PV system was required. The PV system was re-sized considering the use of batteries. The power losses were, once again, assessed in the new PV system and they proved to be small enough to neglect. Batteries were implemented in the system and the system's performance was analyzed. It was observed that the designed system was not yet enough to satisfy the energy consumption of the building for the entire year. Thus, a micro CHP was implemented to work as an emergency source of energy, as a result, the energy needs of the building were satisfied. An economical analysis for the final system was performed and the system proved to be an unreliable investment compared to utility prices. A sensitivity analysis was then performed to assess the possibility of a cheaper system with less batteries, but the reduction in costs was not enough to turn this investment viable.

The values of $LCOE$ obtained by Ladeira in his full roof coverage scenarios (around 120 panels), are 0.50 €/kWh and 0.34 €/kWh. These values were obtained because of several factors. The battery investment is very low compared with market prices, the investment costs do not consider the cost of auxiliary devices and the higher consumption profile has a consequence in $LCOE$ decrease. The values for $LCOE$ in the new designed system (0.58 €/kWh and 0.49 €/kWh) take in consideration a new consumption profile, auxiliary devices required and the market price for batteries.

8.1. Future Work

Energy systems for independent buildings are very important to study, the scope of this thesis is a very small beginning for what can be achieved in the energy sector in order to change the paradigm.

Regarding a topic development for this work, it should be considered a variety of consumption profiles. The apartments should not have the same load. The load can be varied as a percentage of the average consumption profile. In this situation, the batteries' SOC in each floor would not be the same. An optimization tool that analyzes the energy needs of each floor and balances the stored energy between the batteries can be developed. This proposal aims to analyze an environment as close as possible to a real and more practical situation.

Acknowledgements

I would like to express my appreciation for everyone that, somehow, played a role in the development of this thesis.

I would like to thank my supervisor, Prof. Paulo Branco for all the help and guidance in the developing process of this thesis. My appreciation to the institution of Técnico Lisboa for these wonderful year of education. And I would like to thank all my close ones for the incredible support.

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