Hybrid Photovoltaic System Installation in a Stone Exploration and Transformation Company

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ABSTRACT: The present dissertation aims to perform the dimensioning of a photovoltaic system, in the stone industry company José Joaquim Amaro & Filhos.
The dimensioning in question is based on a proposal from the company SOLCOR. Whenever possible, similar parameters to those presented are used, to obtain a reliable comparison that allows us to verify if the obtained values are in accordance with the proposed ones or if this is done considering unrealistic scenarios that would be difficult to replicate daily. The energy needs of the company are taken into consideration, as well as the company's limitations. Despite its large area, the system can only be installed on one of the company's roofs. Since this is a stone transformation company, high amounts of energy are necessary for it to function, that results in very high monthly consumption values. So, it’s important that the system installation helps reducing these monthly values. An economic study is conducted to understand the feasibility of installing the sized system. In this study the time needed for the investment to be recovered is verified, considering the energy values that it allows to save, as well as the value that is recovered through the sale of energy to the public grid. The realization of this project allows us to verify that the project is in fact viable and that the values presented in the commercial proposal are indeed in line with those obtained. Despite representing a large investment, with a high initial value, this value can be recovered after 6 years of installation, from which we conclude that it is a financial effort that will present results in a short space of time, considering the lifetime of the same.

1. INTRODUCTION

1.1. Framing

Transitioning towards renewable energy is crucial to mitigate the significant environmental, economic, and societal impacts of unsustainable fossil fuels. Fossil fuels combustion is the primary cause of greenhouse gas emissions, resulting in alarming climate change phenomena and adverse effects on human health and ecosystems [1]. To address these challenges, countries, organizations, and individuals are recognizing the urgent need to adopt renewable energy sources for a sustainable future. This study investigates the feasibility of transitioning a small stone exploration and processing company towards a greener energy consumption model. Fossil fuel dependence poses economic instability risks due to scarcity and market volatility, as well as distribution chain disruptions caused by natural disasters or conflicts. The European Union (EU) has implemented various measures to combat climate change, including targets, financial incentives [2], quotas [3], and investments in renewable energy [4]. The EU aims to foster the production of renewable energy while reducing greenhouse gas emissions and promoting sustainable practices. By incentivizing clean energy production, setting targets and quotas, and funding research and development, the EU is working towards a greener energy system. The transition to renewable energy is essential to mitigate the detrimental effects of fossil fuel usage on the environment and ensure a sustainable future.

1.2. Objetives

This study examines and compares the proposed values for a hybrid photovoltaic system by SOLCOR [5] for installation at the company José Joaquim Amaro "e" Filhos [6]. The analysis focuses on the purchasing modality, where the company assumes 100% of the investment. Parameters such as solar orientation, tilt angle, and panel configuration are considered for evaluating the proposed values. The study aims to provide valuable insights into the feasibility and cost-effectiveness of implementing a photovoltaic system in the context of the company's energy needs. These findings contribute to the broader understanding of renewable energy adoption and sustainable practices within the industry.

2. RENEWABLE ENERGIES

Increasing efficiency, lower investment costs and minimal pollution are the advantages of photovoltaic systems that have led to a wide range of applications. In general, all photovoltaic installations can be distinguished according to their installed capacity and their connection to the grid.

2.1. Solar Energy

Solar energy is considered a key component for the future of energy and the planet due to several factors [7] :

- Sustainability;
- Cost-effectiveness;
- Scalability;
- Versatility.

These factors position solar energy as the future of "clean" energy production. Despite its lower contribution to renewable energy production compared to other sources, solar energy has experienced exponential growth in recent years. According to the International Energy Agency (IEA), solar energy has been the fastest-growing renewable energy source globally, with a relative increase of 2000% worldwide between 2010 and 2021 [8].
Portugal possesses favorable conditions for solar energy production, including high levels of radiation throughout the year, particularly in the southern and

central regions. The country also benefits from excellent weather conditions, characterized by a dry climate and abundant sunshine. Portugal's well-developed transmission and distribution network facilitates the integration of large-scale energy systems into the grid, and its geographic location allows for energy exports to neighboring countries like Spain.Portugal has witnessed a significant increase in installed photovoltaic capacity, resulting in a rise in electricity generation from solar energy. Between 2010 and 2021, solar energy's contribution to the country's electricity mix increased by approximately 4% [8].Overall, these findings highlight the favorable conditions, growth potential, and increasing significance of solar energy in Portugal's energy transition.

2.2. Solar Technology Evolution

The photovoltaic technology has experienced significant advancements since its invention. These developments have been crucial in increasing solar energy production, making it more efficient and cost-effective.Early photovoltaic cells were made of silicon and had relatively low efficiencies, ranging from 4% to 6%. Over time, with technological advancements, the efficiency of solar cells has reached approximately 22%.

Alongside technological developments, the cost of photovoltaic technology has also decreased due to economies of scale, making it more accessible to a wider range of users. The average price of photovoltaic modules decreased by around 88% between 2010 and 2021, from $2.15/W to $0.27/W [9].The evolution of technology not only led to a reduction in module prices but also in the cost of other components of a photovoltaic system. As a result, the global cost of these systems decreased from $4.81/W in 2010 to $0.86/W in 2021 [10]. This significant cost reduction has made solar energy increasingly competitive with fossil fuels. Consequently, global installed solar capacity has increased from 40.34 GW in 2010 to 843.09 GW in 2021 [11].To assess the cost-effectiveness of solar photovoltaic energy production, we compared the levelized cost of electricity (LCOE), which represents the average net present cost of electricity generation over the system's lifetime. The LCOE for solar photovoltaic energy decreased from $0.42/kWh in 2010, where it was the most expensive renewable technology, to $0.05/kWh in 2021. In 2021, only onshore wind energy had a lower production cost per kWh.The significant cost reduction in solar photovoltaic technology has had a profound impact on the energy landscape. Solar energy has experienced remarkable growth compared to other renewable technologies. The installed solar capacity in Portugal increased by 1284% from 2010 to 2021, from 0.13 GW to 1.80 GW. Similarly, on a global scale, solar capacity increased by approximately 1900%, from 40.34 GW in 2010 to 843.09 GW in 2021[16].These findings highlight the tremendous progress and potential of solar photovoltaic technology, as well as its increasing contribution to the global energy transition.

2.3. Photovoltaic System

Photovoltaic systems can be broadly categorized into three types: grid-connected, standalone/off-grid, and hybrid. Grid-connected systems are the most common and are connected to the electrical grid. They convert DC power into AC power using an inverter, allowing excess energy to be injected into the grid. These systems offer scalability and do not require batteries for energy storage. However, they cannot supply electricity during grid outages [12]. Standalone/off-grid systems operate independently and are not connected to the grid. They store energy in batteries for use when demand exceeds production. These systems provide energy independence and can continue operating during grid outages. However, they require regular maintenance and can be more expensive. Hybrid systems combine features of both grid-connected and standalone systems. They utilize stored energy from batteries when production capacity is insufficient and rely on the grid during adverse weather conditions [13]. Hybrid systems offer flexibility and reliability but are more complex and expensive than other types [14]. Proper system sizing considers factors such as size, capacity, regulations, cost, maintenance, efficiency, and scalability. Each system type has its advantages and limitations, catering to different energy needs and geographical considerations. In summary, grid-connected systems reduce dependence on the electrical network, standalone systems ensure continuous energy production in remote areas, and hybrid systems provide flexibility and reliability. Understanding these different system types helps stakeholders make informed decisions when implementing solar energy solutions.

2.4. Legal Framework

The proposed study focuses on grid-connected photovoltaic systems and the conditions for selling energy to the grid. Decree-Law No. 153/2014 regulates decentralized electrical energy production, including self-consumption with or without grid connection [15] Distinctions are made between UPAC (self-consumption units) and UPP (units for energy sale), with UPAC allowing local energy production for self-consumption and surplus energy sale. The project follows a self-consumption model with excess energy sold to the grid, complying with the legal framework stated in Decree-Law No. 162/2019 [16]. Different regimes apply based on the installed capacity, and registration fees are determined according to Decree-Law No. 153/2014.

3. STONE EXPLORATION AND TRANSFORMATION INDUSTRY

3.1. Stone industry in Portugal

The natural stone industry has a rich history in Portugal, with granite, marble, and limestone being the main types of stones extracted from quarries across the country [17]. These stones are used in construction for various purposes, such as countertops, flooring, and cladding. Granite is known for its durability [18], while marble offers versatility and elegance [19]. Limestone is prized for its variety of tones and resistance to mold and bacteria [20]. The industry is divided into industrial rocks used for construction and ornamental rocks used for decorative purposes.

3.2. Market Positioning

The stone sector in Portugal has witnessed significant growth in recent years, positioning the country among the top global exporters of natural stone [21]. Portuguese stone is renowned for its high quality and innovative products. About 70% of exports consist of processed stone, indicating a shift towards customized offerings [22]. The European Union is the primary market, with 53% of exports directed there. France and China are major importers, accounting for approximately 37% of export value [23]. Despite a 9% decline due to the pandemic, the sector has shown resilience, with a 6.3% increase in export value from 2013 to 2020 [24]. José Joaquim Amaro & Filhos exports primarily to Europe, with France, Germany, and Kuwait being key markets.

3.3. Transformation Process in José Joaquim Amaro & Filhos

José Joaquim Amaro & Filhos specializes in the processing of ornamental stones, primarily limestone. The company focuses on cladding (75%) and flooring (25%) projects. The stone transformation process involves receiving stone blocks, sawing them into slabs of varying thickness, and then cutting them precisely using CNC machines. The final step includes applying different finishes such as polished, honed, bush hammered, and flamed. José Joaquim Amaro & Filhos delivers high-quality stone products tailored to customer specifications.

3.4. Renewable energies in the industry

The stone exploration and processing industry has a significant environmental impact, including high carbon dioxide emissions from machinery and energy consumption. Quarrying operations result in habitat destruction, soil erosion, and water pollution due to sediment deposition [25]. Air pollution also affects nearby communities and biodiversity. To mitigate these effects, implementing renewable energy sources, such as solar panels, can reduce the industry's ecological footprint and dependence on the grid. The IAPMEI has introduced measures to support the industry's transition to a low-carbon and sustainable future [26].

4. SOLCOR COMERCIAL PROPOSAL

The SOLCOR proposal is divided into two modalities, with this analysis focusing on the turnkey modality. The estimated values are based on unknown parameters, such as the year chosen for power consumption curves. To ensure accurate comparisons, it is important to use the same time reference for both consumption and energy production curves.

4.1. Solar production and consuption

The company operates in a sector with high energy consumption, resulting in significant monthly electricity bills. According to the proposal, the annual energy consumption is estimated at approximately 389 MWh. The estimated energy production is around 183 MWh, representing about 47% of the consumed energy. However, the Energy Self-Sufficiency is 35% since not all the energy produced by the system is consumed. The self-consumption value is approximately 136 MWh, with a solar surplus of about 47 MWh. The solar surplus occurs during periods when more energy is produced than consumed, primarily during factory closures on Saturdays, Sundays, and vacation periods. The month of August, which includes the peak vacation period, has the highest solar surplus due to reduced energy consumption.

4.2. System componentes

4.2.1. PV module

Photovoltaic modules consist of different types of cells, distinguished by the semiconductor material used. Mono-crystalline cells offer high efficiency and durability but come at a higher cost. Poly-crystalline cells have lower efficiency but are more affordable. Thin-film cells are cheaper, lighter, and flexible but have significantly lower efficiency. The choice depends on specific system requirements and the trade-off between efficiency, cost, and flexibility.

4.2.2. PV module selected

The proposed photovoltaic system consists of 270 ZNSHINE solar panels, specifically the ZXM6-NH144-450W model [27]. These panels feature high-efficiency mono-crystalline cells and are known for their durability. ZNSHINE is a Chinese company that specializes in solar innovation and sustainability. The module parameters provided are based on Normal Operating Cell Temperature (NOCT), which better reflect real-world conditions.

4.2.3. Temperature effect on the PV module

Temperature has a significant impact on the electrical characteristics of photovoltaic modules. As temperature increases, voltage decreases while current increases. This is due to the energization of electrons and the narrowing of the bandgap. Consequently, the module's efficiency decreases. The temperature coefficient quantifies these effects.

4.2.4. Inversor

The proposed Huawei SUN2000-36KTL inverter is part of Huawei's solution for optimizing photovoltaic system performance. With a maximum power of 36 kW and MPPT technology, it aims to maximize efficiency. Although slightly undersized for the system's peak power of 121.5 kW, the chosen inverter offers high efficiency of 98.4% for European three-phase voltage. It includes advanced features like "anti-islanding" protection.

4.3. Monitoring

Monitoring devices, including the SmartLogger 3000 by Huawei and the Socomec Countis E43, are used to collect real-time data and analyze performance metrics of photovoltaic systems. The Itron SL7000 serves as a certified production meter, while the Litemeter LM2-485 PRO measures solar irradiation and electrical parameters. These devices enable accurate monitoring and optimization of system performance.

4.4. PV panel disposition

The proposed layout for 270 solar panels includes two groups with different tilt angles: 5 degrees and 10 degrees. The vertical distribution consists of three rows with 36 panels each, tilted at 10 degrees. The horizontal distribution comprises two groups: one with four rows of 18 panels (72 modules) and another with five rows of 18 panels (90 modules).

5. CLIMATIC PARAMETERS

The proposed installation area for the system, located in Pero Pinheiro, Sintra, offers favourable conditions for optimal performance.

5.1. Location

The proposed installation area in Pero Pinheiro offers favourable conditions for the solar energy system. The roof provides unobstructed sun exposure throughout the day, with south-facing orientation. However, certain areas of the roof are unsuitable due to shading and infrastructure limitations. Weather data confirms Pero Pinheiro's predominantly sunny climate, with minimal cloud cover, particularly in July and August, as shown in Figure 1[28].

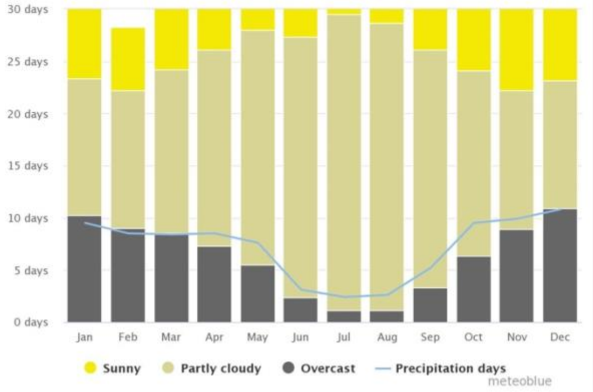

Figure 1: Days in the month it sunny, partly cloudy, overcast and precipitation days.

5.2. Temperature

Pero Pinheiro experiences favorable temperature conditions for solar panel efficiency. The average annual temperature is 16 degrees, with a maximum range of 21 degrees. The peak temperatures usually occur between 2 PM and 4 PM. These temperature patterns should be considered for optimal system performance.

5.3. Wind

Wind is an important factor in the design of a photovoltaic system. In Pero Pinheiro, the region experiences moderate winds primarily from the northwest and north-northwest directions. With wind speeds exceeding 38 km/h for only 115 hours per year, the impact on the panels and structure can be managed. Considering the panels face south, the structural design should account for wind effects on the back of the panels.

5.4. Irradiation

The study examined the optimal tilt angles (5 and 10 degrees) for photovoltaic panels and their impact on incident radiation. The analysis showed that both angles yielded similar results, with a maximum difference of approximately 70 W/m² and a mean deviation of 6 W/m², as it can be seen in Figure 2. It is important to consider the varying incident radiation values throughout the day and seasons. The study concluded that months with higher solar exposure and radiation values are ideal for solar energy production.

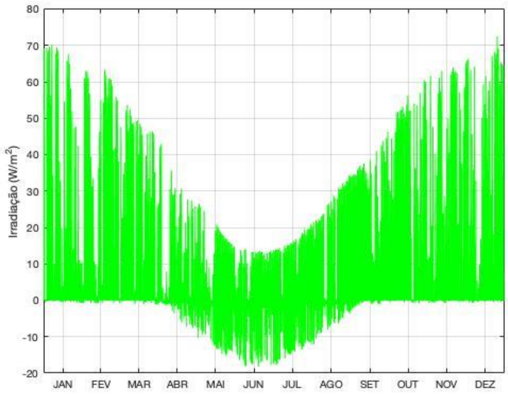

Figure 2: Irradiation difference between 10 and 5 degrees, in the pv inclination.

6. PV MODULES CONFIGURATION

This study analyses the installation of 270 photovoltaic panels on a 1100 m^2 roof area. The panel layout consists of three rows of 36 vertically installed panels and nine rows of 18 horizontally arranged panels. An optimized organization strategy was developed to maximize power conversion while adhering to the panel layout and inverter limitations.

6.1. Distance between modules

The shadow effect caused by panels is important to consider. The minimum distances between rows are calculated based on panel length and inclination angles. For vertical panels with a 10-degree inclination, the minimum distance is 2.73m. For horizontal panels with a 5-degree inclination, it is 1.20m. The proposed layout allows for proper spacing between rows, accommodating both vertical and horizontal panels, like can be seen in Figure 3.

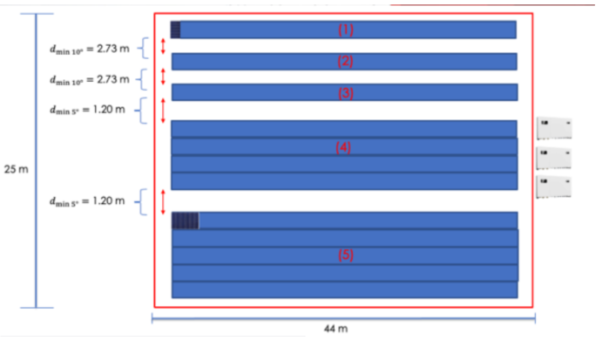

Figure 3: Modules configuration.

6.2. Module strings organization

The panel organization in strings is based on the characteristics of the inverter, MPPT, and photovoltaic module. The panel's electrical properties under NOCT conditions yield an output current of 8.70 A and voltage of 38.60 V. With three inverters, each connected to 90 modules, a total of 270 panels are utilized. The input current limits of the MPPTs allow a maximum of two strings connected in parallel. The distribution involves 15 strings of 18 modules each, ensuring system balance. The total power output of the system, calculated under NOCT conditions, is 90701.4 W.

7. RESULTS

7.1. Cell temperature

The impact of temperature on photovoltaic modules and energy production is explored in the previous section. The cell temperature is determined considering ambient temperature, incident irradiation, and the nominal operating temperature of the cell. Hourly data for ambient temperature and incident irradiation in 2020 were analysed to obtain precise cell temperature values. For module inclinations of 10 and 5 degrees, the cell temperature throughout the year was examined. Despite an average ambient temperature of 16 degrees, the cell temperature averages around 22 degrees, indicating the significance of this parameter in assessing module efficiency. The difference in cell temperature between the two inclinations is minimal, with a maximum difference of 2.5 degrees and an average difference of 0.2 degrees. These findings underscore the importance of accounting for cell temperature, influenced by ambient temperature and incident irradiation, when evaluating module performance and efficiency.

7.2. Temperature coefficent

The power output of the photovoltaic module decreases as the cell temperature rises. The temperature coefficient indicates a 0.36% reduction in power for each degree above 20ºC. Considering standard test conditions, where the ambient temperature is 20ºC, it is crucial to account for the temperature coefficient at that temperature for accurate power estimation. Hourly power reduction graphs were created based on the obtained data. The graphs show that for both 10-degree and 5-degree module inclinations, the maximum power reduction is around 12%, with an average reduction of approximately 2%. These results emphasize the importance of the temperature coefficient in evaluating module performance.

7.3. Voltage drop in the cables

The voltage drop in cables is a crucial factor for system design, as it can impact performance and efficiency. Cables in a series-connected string of photovoltaic modules create resistance, resulting in voltage decrease along the string. Excessive voltage drop affects system performance and poses a risk of overheating. In this study, 10 AWG copper cables were selected for their low resistance and suitability for photovoltaic systems. The voltage drop is calculated using the formula:

$$V_{Drop} = \frac{2 \times l_{cabo} \times I_{SC\ PV} \times \rho_{Material}}{Secção\ Transversal}$$

Hourly current values are determined based on incident irradiation, using current-voltage and power-voltage curves from the module datasheet. The calculated voltage drop accounts for both positive and negative conductors, considering the cable's length, resistivity, and cross-sectional area. The maximum voltage drop per string is 3.8 V for both inclinations, meeting the recommended maximum of 2%.

7.4. Energy produced

The power and energy values of the designed system were obtained in accordance with the available data, considering factors such as cable losses, temperature losses, module and inverter efficiency. The power generation graph throughout the year was compared with the company's power consumption. Monthly energy production was analysed, with July producing the most energy (22.3 MWh) and December the least (6.4 MWh) as it can be seen in Figure 4. On average, the system generates around 14.0 MWh, mainly between May and August.

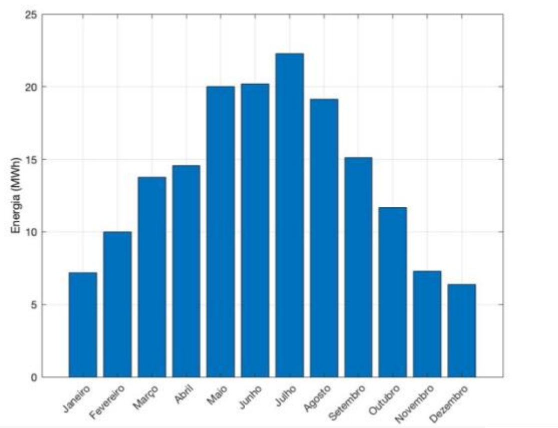

Figure 4: Energy produced by the system, each month.

However, due to the lack of batteries, not all the generated energy is consumed, with only 114.18 MWh being utilized. The system injects excess energy into the grid, averaging 4.45 MWh per month. A comparison with the proposal shows a slight difference in energy production (8.6%) but similar energy self-sufficiency levels. The study's self-consumption is approximately 68%, based on an atypical year due to the pandemic.

8. Investment calculation

To assess the economic viability of the project, we need to calculate the investment value and analyse its impact on the company's monthly and annual expenses. The estimated total investment cost is approximately €121,892, which includes the components and registration fees. By estimating the monthly energy savings from the solar system, we can calculate the potential savings. Additionally, the excess energy generated and sold back to the grid results in additional revenue. The total annual savings and revenue amount to approximately €21,968, as it can be shown in Table 1.

Table 1: Monthly values of saved energy and respective value.

Mês	Energia poupada (MWh)	€/MWh	valor poupado
janeiro	5,2527	179,74€	944,12€
fevereiro	8,27898	179,36€	1 484,92€
março	10,8372	163,27€	1 769,39€
abril	7,99597	245,59€	1 963,73€
maio	10,7974	219,67€	2 371,86€
Junho	12,6893	150,38€	1 908,22€
Julho	17,3879	170,02€	2 956,29€
agosto	7,72791	202,35€	1 563,74€
setembro	12,6068	178,12€	2 245,52€
outubro	19,1436	175,42€	3 358,17€
novembro	6,54954	133,99€	877,57€
dezembro	3,91368	134,09€	524,79€
Total	114,18	172,30€	21 968,32€

Considering the operation and maintenance costs, the project's viability is evaluated using metrics such as Net Present Value (NPV), Payback Period (PR), and Return on Investment (ROI). With an assumed yearly increase in electricity prices and O&M costs, the project shows a positive economic impact.

9. RESULTS AND FUTURE WORK

9.1. Conclusion

This master thesis analyses a proposal for installing a hybrid photovoltaic system at José Joaquim Amaro & Filhos company. The aim is to reduce high energy consumption and dependence on the grid. By dimensioning the system according to the proposal's parameters, the study verifies the accuracy of the values. The results closely align with the proposed values, with an annual energy production of 167.52 MWh, representing 68% direct usage. This leads to a 36% energy self-sufficiency, reducing electricity costs by approximately €22,000 annually. The installation requires an investment of €121,892, recovered in 6 years, resulting in a projected profit of €428,430 over 25 years. The proposal demonstrates credible values, making the hypothetical system a valuable and low-risk investment for the company.

9.2. Future work

This thesis examines a proposal for a hybrid photovoltaic system, focusing on potential variations in parameters and components. The study considers conservative estimates of electricity price evolution and compensation for surplus energy injected into the grid. Furthermore, the feasibility of incorporating a battery system to store excess energy is explored, acknowledging the current limitations of battery cost-effectiveness. Future advancements in battery technology may render this option more viable.

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