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Assessment of Batteries' Contribution for Optimal Self-Sufficiency in Large Building Complexes

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Abstract: The EU has set ambitious targets to combat climate change. Incorporating renewable energy technologies to reduce greenhouse gas emissions is a critical aspect of achieving the European Union's (EU) 2030 climate goals. Similarly to all member countries of the EU, Greece shares the same climate goals. In order to achieve these goals, ensuring a consistent supply and the effective use of clean energy is pursued, as it has a significant impact on the sustainable development and growth of the country. As the Greek tourism sector is one of the most energy-consuming of the national economy and a major contributor to the country's GDP, opportunities are presented for innovation and investment in sustainable practices. Such investments must focus on buildings and facilities, where the energy consumption is concentrated. One of the most popular holiday destinations in Greece is the island of Crete. Visitation patterns are seasonal, which means during the summer months, Crete is exceptionally popular and more demanding energy-wise. One of the highest energy-demanding types of tourism-based businesses is the hospitality industry. Energy demands in hotels are driven by factors such as heating, cooling, lighting, and hot water. Thus, such activities require thermal and electrical energy to function. Electrical energy is one of the most essential forms of energy for hotels, as it powers a wide range of critical systems and services throughout the establishment. Therefore, the hotels are highly susceptible to fluctuations in energy prices which can significantly impact the operational costs of hotels. This paper presents an analysis of the annual consumption for the year of 2022 of five hotels located in Crete. An algorithm is also implemented which strives to minimize the capital expenditure (CAPEX), while ensuring a sufficient percentage of self-sufficiency.

Keywords: buildings' energy consumption; self-sufficiency; energy storage; photovoltaics; hotels

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1. Introduction

Achieving sustainability is the way to achieve the energy transition. Climate change objectively requires the attainment of sustainability. Thus, reducing too many negative impacts such as CO_2 emissions and greenhouse gas (GHG) emissions from the atmosphere by 2050 is paramount [1]. The EU has set a central goal to limit global warming below two (2) degrees Celsius above pre-industrial levels in response to the Paris Agreement (Paris Agreement Goal). The European Green Deal's implementation set an aim of reducing CO_2 by 55% [2–4]. Furthermore, the EU has developed a broad range of policies to advance its goal of transforming its economy to achieve climate neutrality by 2050 [5,6]. In the context of these specific goals, the EU is promoting, through various policies, the development and implementation of various types of clean energy sources, such as solar power, wind power, hydropower, biomass energy, geothermal energy, etc. A crucial step toward this goal is the decarbonization of the building sector [7]. The International Energy Agency (IEA) stressed the importance of clean energy technologies for achieving net-zero emissions, and one key aspect of this effort involves decarbonizing buildings by supplying them with renewable energy [8,9]. The primary goal of the Energy Performance of Buildings Directive (EPBD) is to improve the energy efficiency of buildings and reduce their carbon emissions by transforming them into highly energy-efficient and decarbonized structures, with a particular focus on achieving nearly zero-energy buildings (NZEBs) [10,11].

Greece, like all EU country members, must conform to the Union's goals and guidelines. These goals are achieved by pursuing the production of clean energy, a catalyst for energy security and lower energy costs. Clean energy technologies should also try to maintain environmental protection and social well-being and preserve the alignment of the principles of sustainable development for a stronger, more resilient economy [12]. These goals are difficult to accomplish under the specified conditions, due to certain difficulties regarding economic feasibility, technological prowess, and logistical issues. Currently, various efforts are underway to address these issues [13].

Both the public and private sector are currently facing these issues. In the private sector, where economic growth is a key decision-making factor, the measures to be taken should meet the highest clean energy standards while also satisfying logistical constraints and ensuring economic prosperity to the maximum extent. In Greece, tourism stands out as the primary driver of the national economy and energy consumption among all the sectors within the private service provision industry [14]. A requirement for sustainable tourism is the utilization of renewable energy technologies applied to building infrastructure, since the highest energy consumption is noted in buildings [15].

Such patterns of consumption call for a holistic approach to sustainable building operation. It is particularly essential to emphasize the integration of renewable energy technologies into buildings to minimize their energy (thermal and electrical energy) consumption. Photovoltaic (PV) technology is considered one of the most promising technologies to decarbonize buildings [9]. The significant growth of photovoltaic (PV) installations in recent years can be attributed to several key factors, including increased electricity costs and the decreasing price of PV modules [16]. The widespread installation of rooftop photovoltaic (PV) systems on buildings can potentially create challenges and stress on distribution networks, particularly if not managed effectively [17]. Coupling photovoltaic (PV) systems with battery energy storage systems (BESSs) can effectively address many of the technical challenges [18]. While renewable energy holds promise, its intermittent and unpredictable nature makes it unreliable for both power grids and consumers. Batteries offer a viable solution to address the variability in renewable generation and lower energy costs [19]. They are primarily employed for energy scheduling, enabling the shifting of energy consumption over time [20]. On a grid level, batteries are utilized to stabilize renewable energy fluctuations and enhance overall reliability. Conversely, at the consumer level, efficient energy storage and load scheduling play a crucial role in managing energy consumption and minimizing costs [21,22]. This approach, which actively involves consumers and utilities in the energy market, leads to the development of self-sufficiency designs [23–25].

As Greece is a popular tourist destination, particularly the island of Crete, which was the second most popular destination globally for the year 2023, the influx of tourists is extraordinary [26]. There is a seasonal periodicity in visitation, the peak of which is noted during the summer months, when Crete is exceptionally popular and more demanding energy-wise. There are several key energy-consuming activities and practices that need to be addressed to reduce its environmental impact and contribute to sustainability. Addressing the seasonal energy demands associated with tourism is crucial for sustainable development, while also balancing the objectives of energy sustainability and cost-effectiveness regarding tourist buildings and facilities, the prevalence of which is covering a significant portion of Crete's landscape.

One of the highest energy-demanding types of tourism-based businesses is the hospitality industry [27]. Energy demands in hotels are driven by factors such as the use of energy required for heating, cooling, lighting, and other hotel operations; water heating; outdoor lighting, etc. [28,29]. Thus, such activities require thermal and electrical energy. Over time, most of these needs are increasingly being met by electrical energy rather than thermal, due to the emergence of innovative appliances with both cost-effective and energy-efficient advantages [30]. Thus, electrical energy stands as a critical energy form for hotels, as it fuels a diverse array of crucial systems and services across an establishment [31].

As a result, hotels are particularly vulnerable to changes in energy prices, and the rise in energy costs can have a substantial effect on the operational expenditures of these establishments [32]. Increasing energy costs can have a notable impact on their operational expenses, affecting their profitability, competitive positioning, and ability to invest in sustainable practices; so, independence from the electrical grid and detachment from the fluctuating energy market prices constitute self-sufficiency, which is a pivotal goal for hotels.

This paper presents an analysis of the annual consumption for the year 2022 in five hotels located in Crete. Crete's significant sun exposure throughout the year, combined with the financial feasibility of photovoltaic systems, dictates the selection of this specific technology as an optimal energy source, coupled with a storage system compensating for the lack of production on cloudy days and at nighttime. The coupling is introduced as a suggestive renewable energy technology, and an algorithm is also implemented which strives to minimize the capital expenditure of the system installation while ensuring a sufficient percentage of self-sufficiency. Finally, a correlation between the facilities' characteristics and their respective optimal solution is explored.

2. Materials and Methods

Studying and comparing five hotels based on the hourly consumption of one year, and specifically for the year 2022, a common characteristic of all five hotel units is found to be the significant increase in demand during the months from April to October, as the specific hotels are located in the island of Crete, where the influx of tourists is higher. From the collected data, the total consumption of each hotel is extracted, as well as the maximum hourly demand of the year, and organized in Table 1.

Table 1. Total energy consumption and power peaks for all hotels.

	Hotel 1	Hotel 2	Hotel 3	Hotel 4	Hotel 5
Yearly Consumption (kWh)	5,394,446.9	904,831.9	973,294.2	2,142,032.8	3,827,135.5
Hourly Max Consumption (kWh)	1598.6	372.3	285.2	628.8	1187.7

Figure 1 below shows the annual consumption and maximum value, constructed based on the values in Table 1.

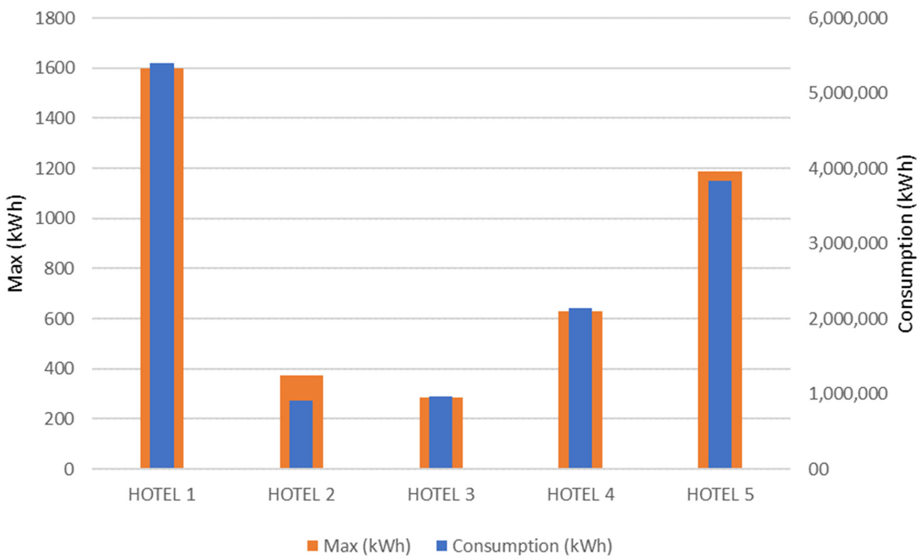

Figure 1. Annual and maximum hourly consumption for all hotels in 2022.

By acquiring the data of the plot's surface area occupied by each hotel, as well as the available rooms (see Table 2), a comparison can be made in relation to the area and the consumption of these 5 hotels.

Table 2. Characteristics of all hotels.

	Hotel 1	Hotel 2	Hotel 3	Hotel 4	Hotel 5
Rooms	411	402	410	260	650
Surface Area (m^2)	384,451.4	283,279.9	28,327.99	465,388.5	607,028.5

The consumption of each hotel depends not only on the size of the plot and the number of rooms but mainly on the facilities where the highest portion of consumption is concentrated. Hotel 1, which requires the highest amount of energy, has very large facilities in terms of area and quality. Therefore, the consumption of a hotel depends on various factors, such as the area, the number of customers it serves, and the comfort and luxury it offers. In Table 3, the number of stars is shown next to each hotel's name, and the type of facility along with the corresponding number for each hotel is catalogued.

Table 3. Facilities of all hotels.

	Hotel 1 ****	Hotel 2 ****	Hotel 3 ****	Hotel 4 *****	Hotel 5 *****
Waterpark	1	1	0	0	0
Pool	5	3	3	5	5
Bars	6	3	3	3	6
Restaurant	3	2	2	6	5
Gym	1	1	1	1	1
Spa	1	0	1	1	1
Jacuzzi	1	0	0	1	1
Sauna	1	0	0	1	0
Hammam	1	0	0	0	1
Football field	1	1	0	0	0
Tennis court	2	0	0	1	1

In a further analysis of the data of each hotel, Table 4 is drawn to depict the percentage of energy occupied by the rooms per year as well as the average consumption per room.

Table 4. Total room consumption rate and consumption per room.

	Hotel 1	Hotel 2	Hotel 3	Hotel 4	Hotel 5
Room occupancy rate	13%	30%	32%	15%	21%
Consumption Per Room (kWh)	1706	675	760	1236	1236

This specific profiling conducted for the hotels leads to the conclusion that the average consumption of the rooms does not indicate a large deviation for hotels with the same number of stars. The differences between the hotels are caused by the offer of different facilities in each hotel and the dependency on the quality and stars. The former is the most impactful on the total consumption, as can be concluded by analyzing the overall profile of Hotel 1. This specific hotel has fewer stars than Hotels 4 and 5, yet surpasses them in its total number of available facilities, making it the most energy-demanding hotel. This is usually unlikely, since the reason behind the smaller consumption rate of the hotels with lower stars is the limited availability in facilities they provide compared to hotels with more stars, meaning that the annual consumption is also lower, with a textbook example being the comparison between Hotels 3 and 4. In Figure 2, the annual consumption per room is presented, reinforcing the previous argument.

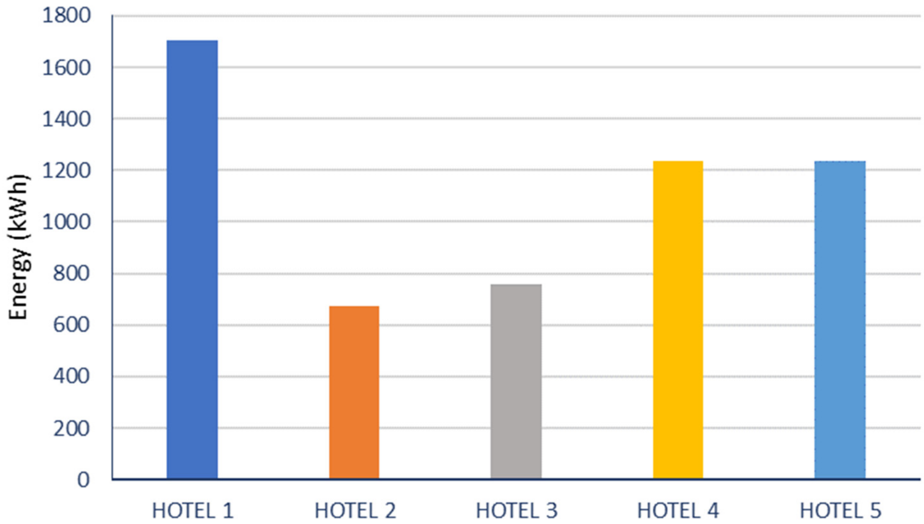

Figure 2. Yearly consumption per room.

Exploring their monthly consumption within a year as well as their hourly maximum value, these hotels can be further compared and studied.

Observing Figures 3 and 4 and comparing the area and the rooms of each hotel presented in Table 2, it is easy to conclude that the area and the number of rooms are not appropriate criteria for the consumption of each hotel. Taking into account the area and consumption as well as the maximum hourly value for each hotel, it is noticeable that it is not proportional to the area, but it depends on the facilities.

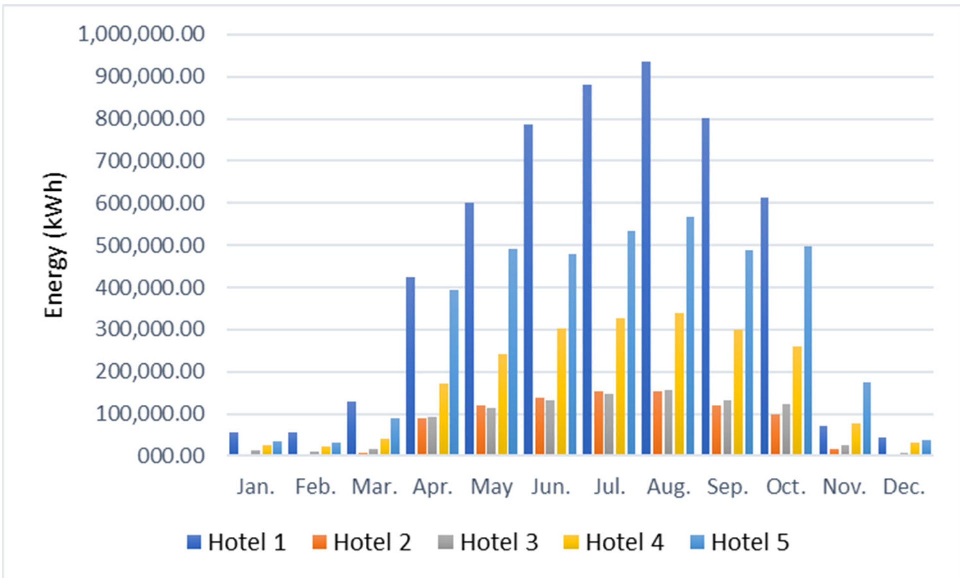

Figure 3. Total energy consumption of the 5 hotels for each month of 2022.

Focusing on a smaller scale, the consumption is studied in a random week in August and presented in Figure 5.

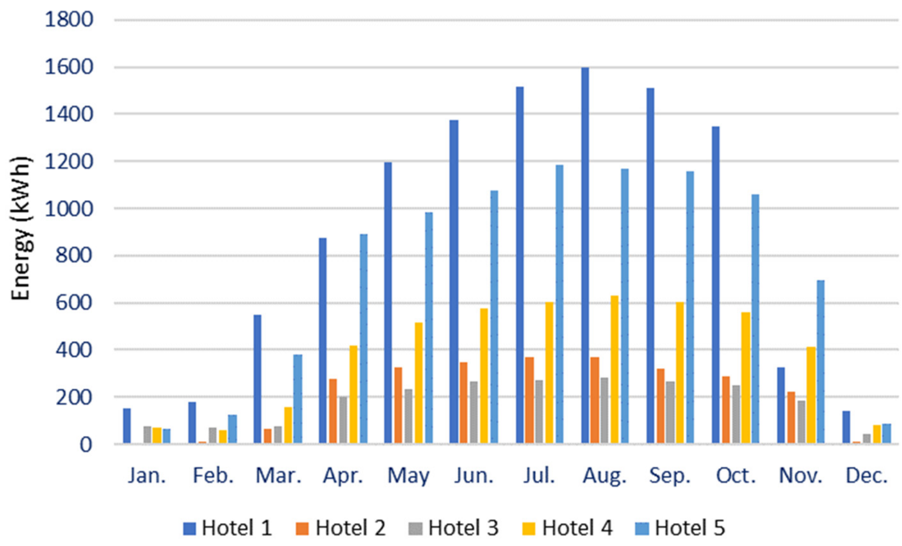

Figure 4. Hourly maximum consumption for the 5 hotels in 2022.

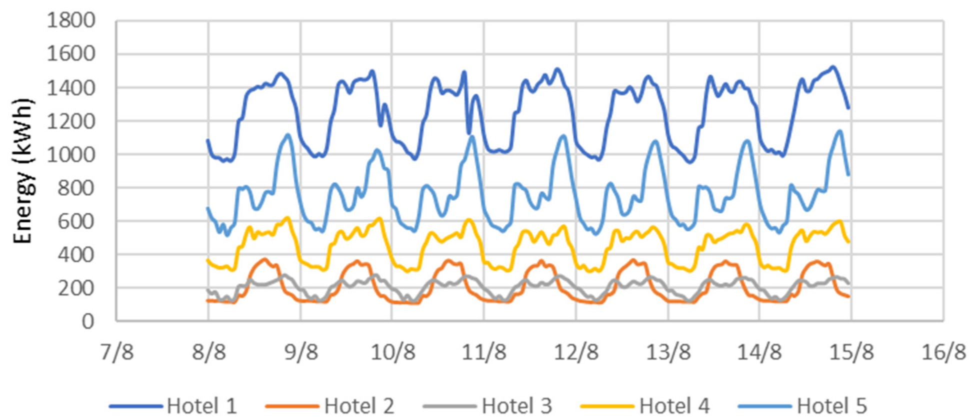

Figure 5. Consumption curve of a week (8–14 August 2022) for the 5 hotels.

At this point, an algorithm is deployed to investigate a proposal scheme of photovoltaic system–battery storage coupling as a solution towards self-sufficiency for each hotel. The first step of the algorithm represents the compilation of different types of data, the hourly energy demand of each hotel for the year 2022, and the hourly production of a photovoltaic (PV) system located on the island of Crete. The use of these data yields the state of the storage system after each hour, along with the energy flows caused by the PV installation and the network's imports that contribute to load satisfaction. The next step is the calculation of annual quantities describing the system's efficiency, which are used to detect a possible correlation between the characteristics of each hotel (such as number of rooms, size), along with the capital expenditure needed for such an investment, and the decision variables of the model (the installed PV power and the storage capacity).

The array of hourly demand contains elements that are symbolized as Load[i], with i being the number of hours since installation, and the normalized PV output as PV[i], meaning that for hour i, the PV output $PV_{out}[i]$ is calculated using Equation (1):

$$PV_{out}[i] = PV_{power} \times PV[i] \quad (1)$$

with PV_{power} symbolizing the installed nominal power of the photovoltaic system.

At the start of the algorithm's implementation, the storage system in each hotel is describing the behavior of the system for each hotel separately, for a time step of one hour, are calculated.

Initially, the discharge of the storage system installed to the system for each hour, $Storage_{out}[i]$, is calculated as described in Figure 6.

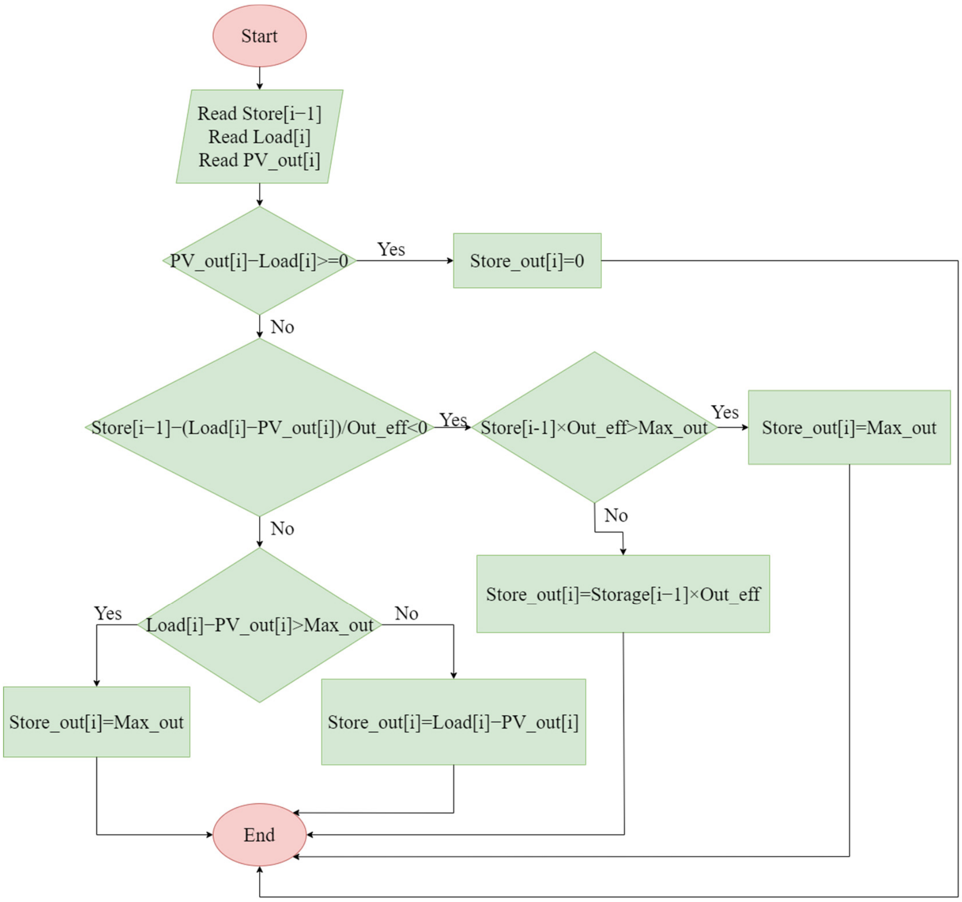

Figure 6. Computation of storage output after each hour.

Afterwards, the total amount stored after each hour is computed (Figure 7).

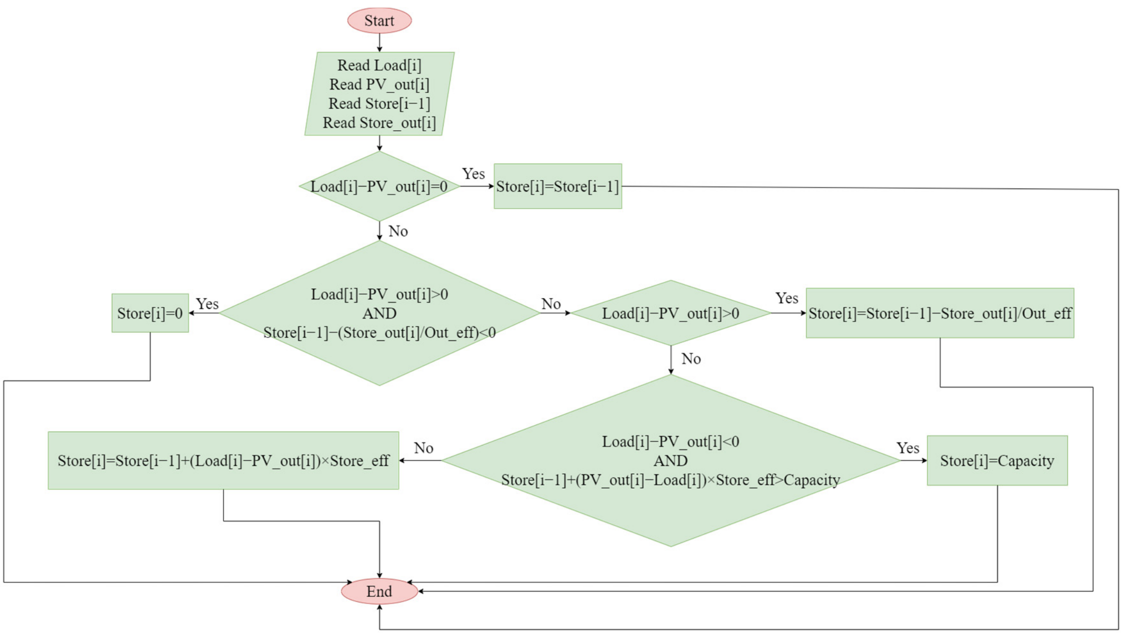

Figure 7. Computation of system storage for each hour.

If both the PV output and available storage discharge do not cover the hourly amount needed, the facility relies on the network to satisfy the difference. The difference is calculated in Figure 8.

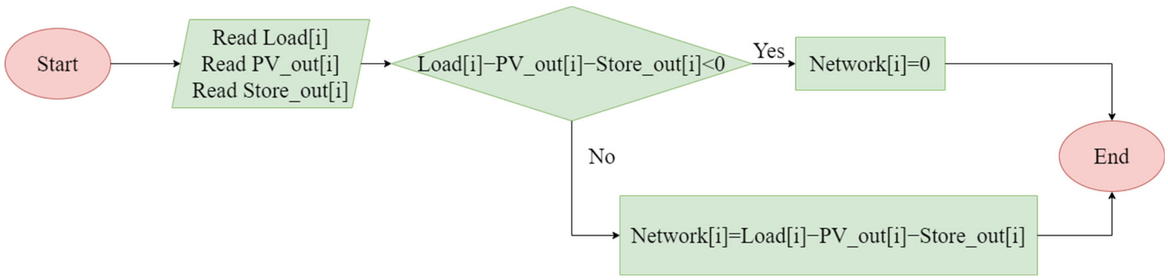

Figure 8. Computation of network imports in each hour.

Considering the limitations of the storage system's capacity and charge/discharge efficiency, the surplus of energy, after losses, originating from the photovoltaic system cannot be successfully stored at all times; thus, system rejections are introduced and computed as dictated in Figure 9.

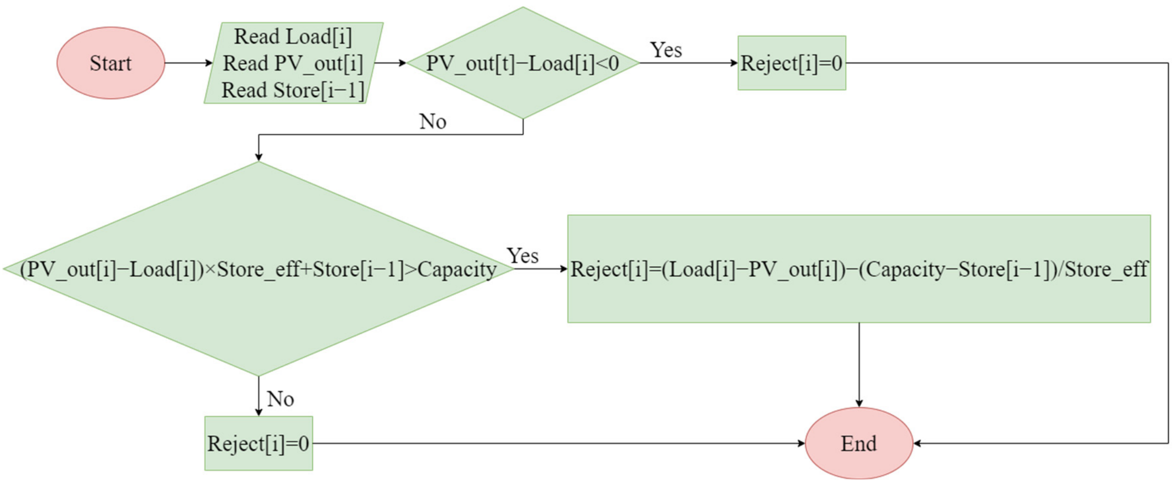

Figure 9. Computation of system rejections after each hour.

The losses caused after each bidirectional power flow from the storage system are computed in Figure 10.

Computing the values described in Figures 6–10, the percentages of annual rejections, annual network imports, and the self-sufficiency of each hotel's system are calculated.

The percentage of the imports originating from the grid is the sum of annual energy imported over the sum of annual demand:

$$\text{Network}_{\text{perc}} = \frac{\sum_{i=1}^{8760} \text{Network}[i]}{\sum_{i=1}^{8760} \text{Load}[i]} \tag{2}$$

The percentage of annual rejections is the summed amount of rejected energy over the total PV system's production, excluding the amount that was either discarded due to the storage system's inefficiency or the amount safely stored after the year's end:

$$\text{Reject}_{\text{perc}} = \frac{\sum_{i=1}^{8760} \text{Rej}[i]}{\sum_{i=1}^{8760} \text{PV}_{\text{out}}[i](\text{Store }[8760]\text{-Cap})} \tag{3}$$

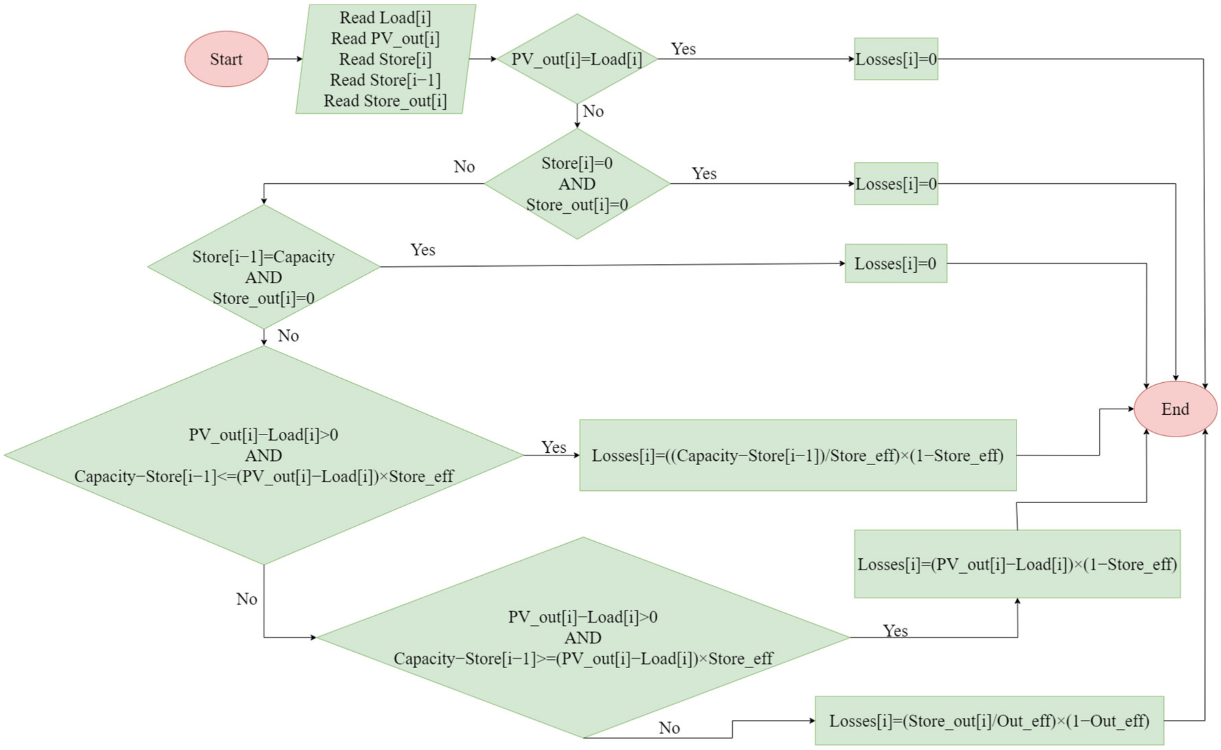

Figure 10. Computation of system losses after each hour.

Finally, the percentage of the annual energy that was both produced and consumed locally is the amount of PV production plus the initial full charge of the storage system minus the amount attributed to losses, rejections, and storage at the end of the year over the annual hotel's demand:

$$\text{Self-Suff}_{\text{perc}} = \frac{\sum_{i=1}^{8760} \text{PV}_{\text{out}}[i] + \text{Cap} - \sum_{i=1}^{8760} \text{Rej}[i] - \sum_{i=1}^{8760} \text{Loss}[i] - \text{Store}\ [8760]}{\sum_{i=1}^{8760} \text{Load}[i]} \quad (4)$$

3. Results

By following the methodology as previously explained, the dependency of each hotel's self-sufficiency to the PV production and storage capacity is studied, leading to the optimal solution of each individual model. Then, the average value of self-sufficiency is calculated and analyzed, concluding with the exploration of correlations between hotel attributes and capital expenditure.

To study the effect of PV power on the system's self-sufficiency, the impact of PV power on self-sufficiency without storage for each hotel is depicted in Figure 11.

Without a storage system, the self-sufficiency of all hotels converges to 70%. Such behavior is explained by being attributed to the variety in energy demand for the five hotels. The hotel that consumes the most energy is associated with the trendline having the shallowest incline since a certain rise in PV installation contributes less to the total annual self-sufficiency. This means that a storage system is required for all hotels that aspire to achieve nearly total independency with an economically viable PV installation. Applying the indicative value of 3000 kW PV power, the dependency of the self-sufficiency to the system's storage capacity is depicted in Figure 12.

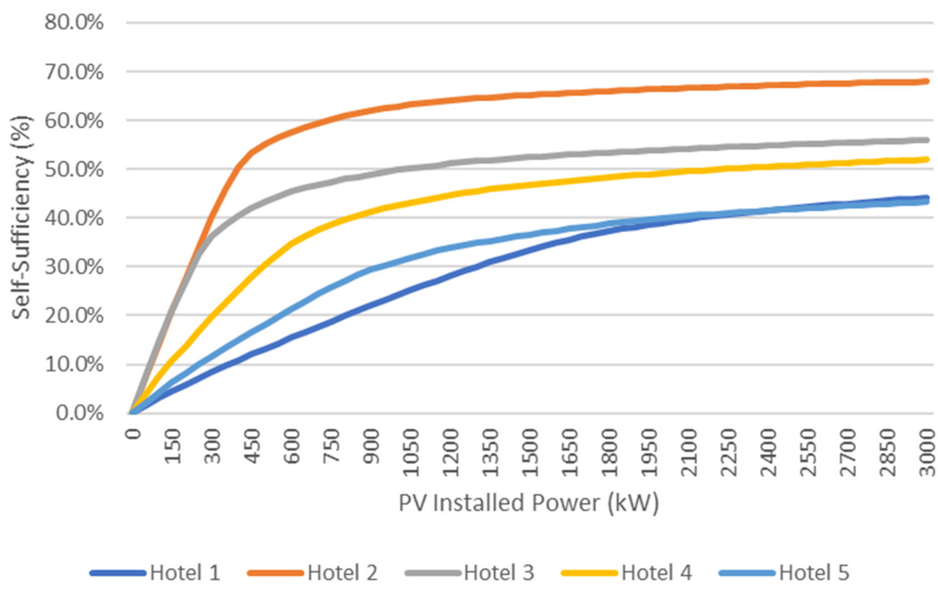

Figure 11. Dependency of self-sufficiency to PV power for the 5 hotels.

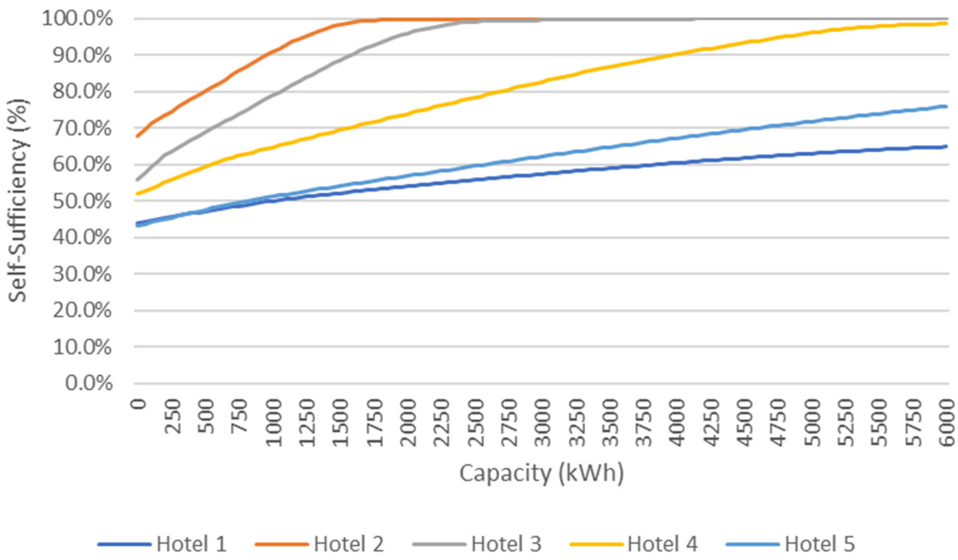

Figure 12. Dependency of self-sufficiency to storage capacity for a fixed PV power value.

For this PV power value, some hotels successfully achieve a 100% self-sufficiency rate, meaning they can cover all their energy demands through a proper mixture of PV power and storage capacity. On the other hand, the rest of the hotels struggle to surpass an 80% self-sufficiency rate. This indicates that even with a significant storage capacity, they are unable to fully meet their energy requirements for the given PV power and need to supplement their power supply with electricity from the grid or other sources. To achieve the desired level of self-sufficiency for all hotels with optimal values of PV power and storage capacity, the average percentage of self-sufficiency for a significant range of the decision variables is computed and a three-dimensional scatter plot is designed, as shown in Figure 13.

Figure 13 highlights that for a specific range of PV power and capacity values, the self-sufficiency overpasses 99%, converging to 100%. A percentage of 99% is considered a satisfactory percentage of independency from the grid. Another important conclusion is that for 99% annual self-sufficiency, an average increase in PV power implies a decrease in average storage capacity. In Figure 14, the green curve consists of the set of points for which the annual self-sufficiency is equal to 99%, as can be seen from points A and B.

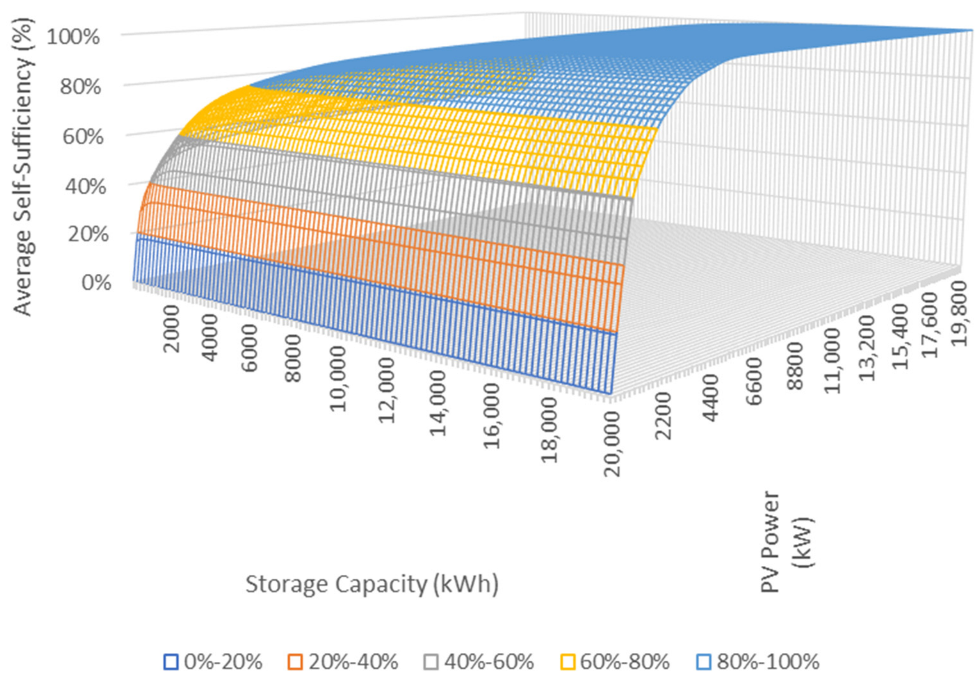

Figure 13. Three–dimensional scatter plot of the average annual self–sufficiency for a range of PV power and storage capacity values.

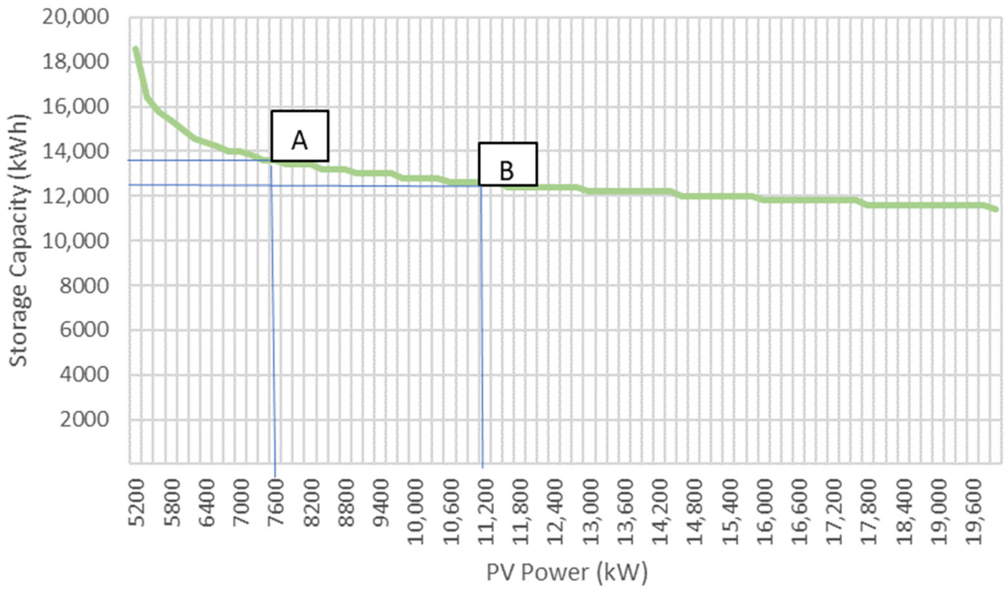

Figure 14. Approximation of the separating line between region where self-sufficiency < 99% and self-sufficiency > 99%.

In the same range, the optimal solution is the one that requires the minimum capital expenditure requested for the installation of the total system. The process described in Figure 13 was repeated for each separate hotel, isolating all sets of the decision variables yielding at least 99% of annual self-sufficiency. Since the total CAPEX is dependent on the PV power and storage capacity, with the former having the largest impact on CAPEX due to the greater value of EUR /kW, the optimal solution within the feasible range is determined by giving priority to finding the smallest PV power value within a specified range, while simultaneously seeking the lowest possible capacity value that meets the requirement of at least 99% self-sufficiency, in combination with the specific PV power value.

For certain prices of 1000 EUR/kW and 250 EUR/kWh of PV power and storage capacity, the CAPEX is calculated and a correlation between it and the decision variables is sought within Figure 15.

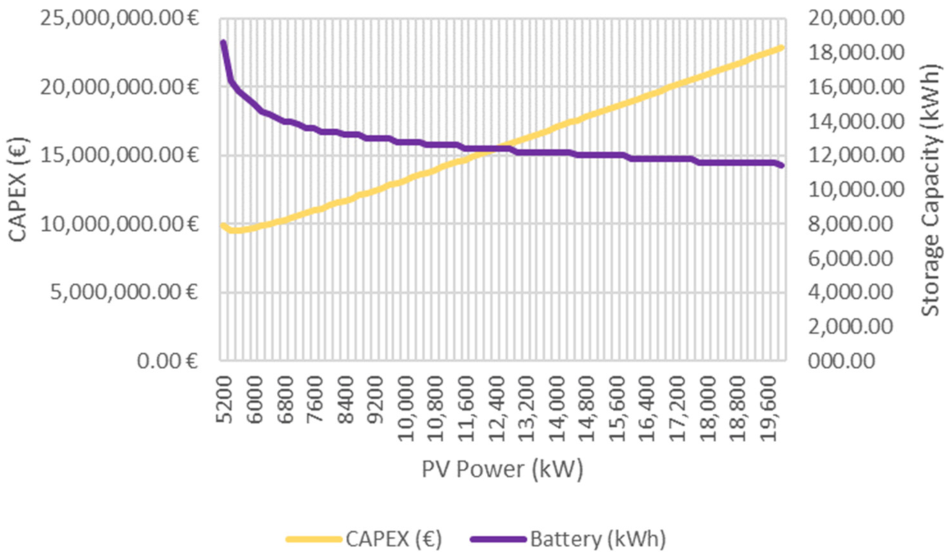

Figure 15. Trend line of CAPEX for a range of optimal decision variables.

It is apparent from Figure 15 that for the average values of self-sufficiency of all hotels, the optimal solution is 5400 kW of PVs with 16,400 kWh batteries' capacity, which yields 99.001% self-sufficiency and EUR 9,500,000 of CAPEX.

Repeating the same process for each hotel separately, optimal solutions that minimize the CAPEX are estimated, and correlations between hotel attributes and CAPEX are sought.

In Table 5, the number of hotel rooms and the corresponding optimal solution along with the outcome are presented.

Table 5. Number of rooms, surface area, and their respective optimal solutions.

	Rooms	Surface Area (m^2)	PV Power (kW)	Capacity (kWh)	CAPEX (EUR)
Hotel 1	411	384,451.4	7200	19,800	12,150,000
Hotel 2	402	283,279.9	1110	2650	1,772,500
Hotel 3	410	28,327.99	1400	3600	2,300,000
Hotel 4	260	465,388.5	2400	12,400	2,400,250
Hotel 5	650	607,028.5	6000	14,000	9,500,000

The observation made in Table 5 underscores an interesting finding. It is evident that the number of rooms and the overall surface area of each hotel do not exhibit any meaningful correlation with the decision variables or the value of the objective function. This intriguing outcome can be directly attributed to the distinctive energy consumption profile of these facilities. The majority of energy consumption within these hotels is concentrated within their buildings, with a particular emphasis on energy usage for various services rather than for the individual room needs. This means that the size or capacity of the hotels, as represented by the number of rooms or the total surface area, does not significantly impact the optimization of energy-related decisions, which, for the current study, is the investment in a photovoltaic backed by a storage system.

Table 6 illustrates the yearly energy requirements for each hotel, alongside the optimal PV power, storage capacity, and their corresponding capital expenditures. Additionally, it provides the calculated cost per kWh and a breakdown of this cost over a 10-year period.

Table 6. Optimal investment analyzed for a payback period of a decade.

	Annual Demand (kWh)	CAPEX (EUR)	EUR/kWh
Hotel 1	5,394,446.90	12,150,000	0.22
Hotel 2	904,832.08	1,772,500	0.19
Hotel 3	973,294.25	2,300,000	0.23
Hotel 4	2,142,032.80	2,400,250	0.11
Hotel 5	3,827,135.55	9,500,000	0.25
Average:			

4. Discussion

As it is shown in the current analysis, the average cost of electric energy is approximately 0.2 EUR/kWh in a representative group of hotels in the case of substantial PV with batteries' installation. In particular, comparing these results for each hotel to a benchmark value of electricity supply from grid at 0.15 EUR/kWh, it becomes evident that only Hotel 4 will achieve a profit over the course of 10 years, without any financial support scheme or subsidy. However, it is important to highlight that this investment not only enhances the hotels' energy self-sufficiency and potential for long-term cost reduction but also necessitates a significant initial capital investment. Furthermore, these types of investment offer a strong and robust energy source, enhancing the necessary resilience and mitigating the unwanted energy prices' volatility.

Given that both the Greek and European tourism sector is a major energy consumer within the national and European economy, and a significant contributor to the country's and EU's GDP, there exist opportunities for fostering innovation and sustainable investments. These investments should primarily target buildings and facilities, which account for the bulk of energy consumption. Respectively, Crete, a highly popular tourist destination in Greece, experiences seasonal visitation patterns during the energy-intensive summer months. Among the most energy-demanding sectors in the tourism industry is the hospitality sector, where energy needs encompass heating, cooling, lighting, and hot water supply, all reliant on thermal and electrical energy. Electrical energy, in particular, plays a crucial role in powering essential systems and services in hotels, rendering them highly vulnerable to fluctuations in energy prices that can significantly affect operational costs. This paper presents an analysis of the 2022 annual energy consumption of five hotels located on the island of Crete and introduces an algorithm aimed at minimizing capital expenditures (CAPEX), while ensuring a sufficient level of self-sufficiency.

To conclude, the hotels should assess their optimal solutions, taking into consideration their special needs and future perspectives, as a sustainable strategy against possible future energy crises and relative price instability that will influence their economic profitability. In parallel, an adequate financial support scheme or subsidy, which will keep the average cost of locally produced electricity significantly lower than 200 EUR/MWh, which is the average electricity price in the current energy market, will boost the energy transition of this specific sector. Regarding the region of Crete, a different type of local subsidy scheme could be implemented in order to minimize the CAPEX required for this kind of investment.

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