Sustainable Microgrids with Energy Storage as a Means to Increase Power Resilience in Critical Facilities: An Application to a Hospital

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Abstract

This manuscript proposes to study different cases that require the use of renewable energies in addition to diesel generators and energy storage systems with the aim of increasing the resilience of a microgrid feeding critical facilities. The aim of the work here presented is to quantify the benefits provided by an improvement of the energy resilience that could be achieved by installing a microgrid in a hospital fed by renewable energy sources. The microgrid will use a scheme based on solar PV in addition to diesel generators and an energy storage system based on electrochemical batteries. First, it has been evaluated how the implant of the microgrid increases the resilience of the power supply when a power failure occurs, considering that the main application in a hospital, even in the event of breakdowns, is to ensure the continuity of the surgical procedures and safely store drug stocks. Thus, these have been defined as the critical loads of the system. The components sizes have been optimized by considering both economic profitability but also the resilience capacity, observing that, by installing solar photovoltaic modules, Li-ion batteries and diesel generators, according to simulations performed in *REopt*® software, the microgrid could save approximately $ 440,191 on average over a 20-year life cycle of the facility (both considering the mitigation of energy provide by the power grid and the avoided losses during probable power services interruptions), while increasing the minimum resilience of the installation more than 34 hours.

Keywords: energy resilience; hospital; solar photovoltaics; microgrids; batteries

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1. Introduction

Microgrids can be defined as small grids with the ability to operate autonomously, independently of the conventional power grid [1]. Because of its autonomy, it can be found in a number of end-uses such as military bases, hospitals or university campuses. Microgrids have the ability to isolate themselves from the power grid when a power outage occurs. Then, they continue to supply their critical loads without interruption, which is of great importance for critical facilities. This paper concerns in particular with the implantation of microgrids in hospitals, which are considered critical facilities that must guarantee electrical energy services for certain critical processes, such as surgery procedures or drugs storage.

Energy resilience has become vital in recent years as a result of many successive natural disasters. In the US, it has been found that power cuts due to the absence of an effective energy resilience policy have caused substantial economic losses in the last times. In particular, since 1980, on average, six disasters have exceeded $1 billion dollars per year [2]. The consequences are much more dramatic and add to this heavy toll: loss of production in industries and safety in critical facilities. One solution to this problem might be to set up a REHS (Renewable Energy Hybrid System) microgrid comprising photovoltaic panels, batteries and diesel generators. It has been shown that, in some cases, the use of diesel generators might not be appropriate because they have not worked during periods of major disasters (when test phases showed the opposite). This was the case, for example, during Hurricane Sandy at Coney Island Hospital, where patients had to be evacuated due to the lack of functioning diesel generators [3]. But the failure of diesel generators has another cause: refills of fossil fuels add an uncertainty to the facility [2].

In other countries, such Kuwait or Egypt, the installation of photovoltaic panels has been proved as a means to reduce the pressure on power plants and meet the growing demand for electricity [4,5]. The solution would avoid, on the one hand, the increase in the use of fossil fuels and, on the other hand, crises in electricity production. The consequences are also catastrophic for the country's industrial, social and economic sectors. As a result, the main international challenge will be to design green electrical systems that will not harm the environment [6]. However, there are a number of barriers that hamper the installation of microgrids [5]. In this case, energy support policies to reduce the investment costs and promote a faster implementation has been proved to be successful in some regions, such as in Sicily (Italy) [7].

Nowadays, in the US, hospitals' energy consumption represents nearly 5.5% of the total consumption of the country [1]. A potential hospital microgrid could assess electricity prices from the grid, and possibly *"buy"* electricity when its cost is low [1], and conversely, re-sell electricity when its cost would be high. In this case, intraday *"electrical hours"* have a great deal of influence on electricity. In the scientific literature, it has been shown that the establishment of microgrids has been promoted by favorable aid policies [8-11]. Other analyses also reveal the physical aspect to be considered because of the existing weaknesses in the system: the presence of a transitional regime of the generators might, in some circumstances, lead to the complete collapse of the microgrid [12]. In addition, the various strategies that can be implemented to increase and boost resilience were investigated. According to [13-16], it will be necessary to set up self-sufficient microgrids by implementing the appropriate number of renewable energy sources (this design is a result of an *"electrical point of view"* of electrical systems adapted to extreme disasters). Many successful efforts have been done in order to optimize the economic dispatch of energy storage systems in microgrids with high penetration of renewable energy sources, demonstrating that installing energy storage systems (ESS) in microgrids reduce operating costs and that it is necessary to have an efficient operation strategy to allow the maximization use of the ESS [17]. However, very few works nowadays consider both the economic approach and the resilience capacity. Lastly, the fight against cyber-attacks should neither be overlooked [18,19]. Main opportunities and challenges of microgrids focusing on applications in enhancing grid performance can be found summarized in the review conducted in [20]. The islanded operation of the microgrids is one of the main challenges these facilities may face in the near future.

The majority of designs considering energy storage systems for resilience enhancement are focused mainly on the maximization of the survival probability to an outage, which usually conducts to not optimal economic sizing of generators and energy storage systems. This approach is mandatory for those facilities connected to not trustable or weak power grids, typical from undeveloped countries. However, the deployment of microgrids, especially those which account with renewable energy generators, in developed power grids in order to help the transition to a decarbonized power grid, forces new approaches. Under this new scenario, although the need to satisfy a critical load is still present, it must be considered with more relevance the normal operation conditions. Thus, in this paper, the sizing of power supply for critical loads has been approached mainly from the economical point of view, trying to minimize costs (or even maximize benefits for surplus energy selling to the grid), while valuating the resilience capacity considering both the outage probability and duration in a modern power grid from a developed country, which results much more realistic to real life scenarios. Moreover, this approach also differs from the business as usual sizing which depreciates the resilience capacity, which is highly valuated in critical facilities such as hospitals or military bases, among others.

This manuscript consists of three other sections. The following section brings together all the elements for analyzing the economic benefits and advantages of resilience with renewable energies. In this section the parameters to be entered during the simulation will be presented. The third section will be based on a series of simulations on a real case study. Finally, the last section will summarize the obtained results and the main authors’ conclusions.

2. Materials and Methods

This section explains the approaches addressed by *REopt®* [21] and the comparison between other software tools that can conduct a number of simulations related to the topic here addressed. The last part details the different families of inputs offered by the aforementioned software.

2.1. REopt® model as a modeling approach

With *REopt®* [21], the economic viability of the joint use of solar PV, Li-ion batteries and diesel generators will be evaluated. The simulation system can also calculate the length of time that the system provides power to the site in the event of a power outage [22]. It should be noted that the model only provides technical and economic estimates of the various installations. As a consequence, it will be necessary to refer to decision-making strategies for investments at a later stage [22].

At this stage, these assumptions are sufficient for a first estimation. It should be noted that *REopt®* helps the facilities’ owners to find the *“optimal”* size for the microgrid facilities considering a scenario that minimizes the Life Cycle Cost (*LCC*) of the project, considering capital costs, operating expenses, operating revenues, incentives and tax benefits [22]. A general flowchart of the followed procedure can be seen in Figure 1.

The optimization model solves a mixed-integer linear program (MILP), which objective function is the LCC, over the analysis period subject to a variety of integer and non-integer constraints to ensure that thermal and electrical loads are met at every time step by some combination of candidate technologies. The full model implemented in *REopt®*, including parameters, variables and equations is described in [23]. Generators, loads and storage technologies equations are also fully described in [23]. It must be highlighted that the *REopt®* model has been developed by the National Renewable Energy Laboratory (NREL) and, since 2007, different versions of this model have been evaluated at over 10,000 sites, resulting in over 260 MW of renewable energy fed facilities deployed, which guarantees its validity. The model is intended to deliver a cost-optimal solution for meeting a customer's energy requirements while observing all location-specific goals and constraints.

In contrast with other multiperiod optimization algorithms for sizing and dispatching renewable energy fed generators, the *REopt®* model allows the specification of additional resilience requirements to design a system that would sustain a critical load for a specified outage period [24]. The outage is defined by its duration (in hours) and the starting date and time. Moreover, the outage event can be simulated as a single outage occurring the first year of the analysis or, on the other hand, it can be assumed to be an average outage event that occurs every year of the analysis period. In this case, the avoided outage costs for one year are escalated and discounted to account for an annually recurring outage [24], but it will not impact the optimization results or the net present value calculation for the project.

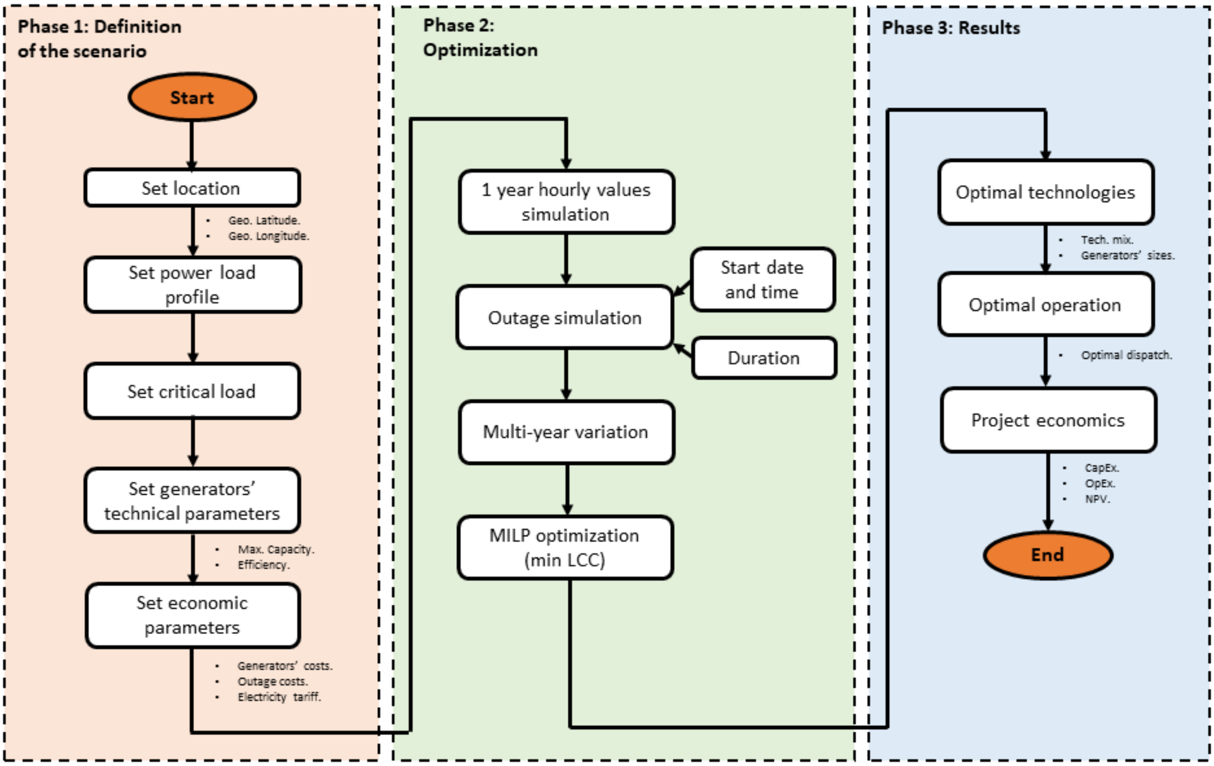

Figure 1. *Flow chart of the followed procedure. Own elaboration.*

2.2. Comparisons between different models

Depending on the software to be used, a number of simulations at different scales to assess the resilience of systems (residential, regional and/or district modelling) can be conducted. As shown in Table 1, *REopt®* is able to conduct simulations at all of the aforementioned levels.

Performance models simulate energy efficiency with system configurations entered by the user. These different models can help to plan system sizes to meet energy objectives, reduce *LCOE*, and minimize carbon emissions.

It can be seen from Table 1, that *REopt*® has a large number of possibilities that other software could not accomplish. Green cells represent the features that can be used [25]. On the other hand, the red cells represent the features that cannot be used by the different software tools [25]. In our case, resilience can be optimized. The other simulations, on the whole, cannot achieve this objective.

As far as renewable energies are concerned, *REopt*® allows simulations to be carried out on a photovoltaic system, wind generators (currently with a beta version), and energy storage through batteries. From all the above, it is clear that *REopt*® will allow us to model the behavior of the system thus formed. It is now necessary to detail the different inputs that make up the simulation software to be used. Even though other software could have been used to conduct similar simulations and extend the assessments conducted to other locations different to the US, it has as a counterpart the fact that it is not an open-source software such as *REopt*® is.

Table 1. *Evaluation of a number of simulation models implemented on different software tools. Green cells mean that the software provides de corresponding feature in the column, while the red color means the opposite. Adapted from [21].*

	Simulation	Optimization	Photovoltaics	Wind Energy	Biomass Energy	Battery Storage	Residential Modelling	District Modelling	Regional Modelling	Consecutive Technology Modelling	Finance	Performance	Free?	Capability of modelling large plants	Beginner Tool	Advanced Tool
SAM	Green	Red	Green	Green	Green	Green	Green	Green	Red	Red	Green	Green	Green	Green	Green	Green
CREST	Green	Red	Green	Green	Green	Red	Green	Green	Red	Red	Green	Red	Green	Red	Green	Red
PVWatts	Green	Red	Green	Red	Red	Red	Green	Red	Red	Red	Green	Red	Green	Red	Green	Red
Pvsyst	Green	Red	Green	Red	Red	Red	Green	Green	Red	Red	Green	Green	Red	Red	Green	Green
Windographer	Green	Red	Red	Green	Red	Red	Green	Red	Red	Red	Red	Green	Red	Red	Green	Green
WindPro	Green	Red	Red	Green	Red	Red	Red	Green	Red	Red	Red	Green	Red	Green	Red	Green
RETScreen	Green	Red	Green	Green	Green	Red	Green	Red	Red	Red	Green	Green	Green	Red	Green	Green
Helioscope	Green	Red	Green	Red	Red	Green	Green	Green	Red	Red	Green	Green	Red	Red	Green	Green
REopt	Green	Green	Green	Green	Red	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Red
HOMER	Green	Green	Green	Green	Green	Green	Red	Green	Red	Green	Green	Green	Red	Green	Red	Green
Gatecycle	Green	Red	Red	Red	Green	Red	Red	Green	Red	Red	Red	Green	Red	Green	Red	Green
ReEDS	Green	Red	Green	Green	Green	Red	Red	Red	Green	Green	Green	Green	Green	Green	Red	Green
EnergyPlan	Green	Red	Green	Green	Green	Green	Red	Red	Green	Green	Green	Green	Green	Green	Red	Green
KomMod	Green	Red	Green	Green	Green	Green	Red	Red	Green	Green	Green	Green	Green	Green	Red	Green

2.3. *Description of the case study*

As case study, a hospital facility has been selected as it is one of the civil facilities where resilience may result critical at the time they can benefit from renewable energy sources integration. In this case, the Palmdale Regional Medical Center has been analyzed. It is a private hospital located in Palmdale, California and it is the only hospital in Palmdale, the largest city in California without a hospital prior to opening in December 2010. The hospital is 320,000 square feet (or 30,000 square meters) and it accounts with 171 beds, although the hospital is able to expand up to

239 beds at maximum development. Moreover, this facility has a 35 beds emergency department, which is the largest in the Antelope Valley area, and it also features a heliport. The hospital complex also includes (although they have not been included in this study) with a 60,000 square foot (5,600 square meters) medical office tower and an apartment housing for those who need assisted living, covering a total area of 13.86 ha. Real data provided by official sources have been used in this study.

Although it can result a particular case study, its characteristics and representativity allows the extrapolation of the results to other similar critical facilities worldwide and, specially, in the US.

2.4. Model inputs

All model inputs have been summarized in Table A.1 from Appendix A. Nevertheless, the following paragraphs provide further details.

2.4.1. Location and electricity distributor

As case study to run the simulations, it has been selected a representative facility in California (US). The actual area of the site is 320,000 square feet which corresponds to 30,000 square meters [26].

With regard to the electricity distributor, the *"net metering"* is, in fact, an agreement between the electricity distributor and the consumer. In this case, when surplus electricity is produced, credits are granted and transferred to the consumer who will only pay the net amount. Renewable installations may be affected by this pricing method. Currently in California the only limits imposed are that the maximum capacity must not exceed 1 MW; and that the share of renewable energy must be 5% of the use of electricity from the conventional electricity grid. In our simulation, we will assume that the studied installation will not be affected by net metering. It should be noted that this depends on the legislation that is adopted in each country or state [27].

2.4.2. Simulated workload profile

The simulated building will be evaluated over a complete year with an estimated consumption of 4,900 MWh/year, according to statistic values for the US and this sort of buildings. The critical load factor, which in this case has been considered of 50%, has been estimated in order to include the store drugs devices, average surgical procedures electricity demand, other non-interruptible loads (life support systems) and part of lighting and power supplies.

2.4.3. Financial criteria

The analysis period will be conducted for a time length of 20 years. This period analysis shall also consider, the equipment lifetime. Table 2 summarizes the increase in operation and maintenance costs over the last three years between 2017 and 2019, respectively. This corresponds to the so-called operation and maintenance (*O&M)* cost escalation rate and these values are expressed in %. In the last column (*Avg*) it can be observed that costs increased by 2.5% on average in this period. Then, a 2.5% yearly *O&M* cost increment will be considered in the performed simulations.

Table 2. *Percentage increase in inflation of operating and maintenance costs. Source: [28].*

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVG
2017	+2.5	+2.7	+2.4	+2.2	+1.9	+1.6	+1.7	+1.9	+2.2	+2.0	+2.2	+2.1	+2.1
2018	+2.1	+2.2	+2.4	+2.5	+2.8	+2.9	+2.9	+2.7	+2.3	+2.5	+2.2	+1.9	+2.4
2019	+1.6	+1.5	+1.9										

2.4.4. Resilience

For resilience, three separate assumptions will be made about the duration of the interruption of electricity distribution: 8, 16 and 24 hours. These times are designed for hospitals to size the generators to feed their critical loads for a minimum of 8 hours—and, at best, 24 hours of assistance [29].

With regard to the day and time of the outage, June 21st and December 21st, days of summer solstice and winter solstice respectively, will be selected as critical days for the evaluation, as they represent both extremes of sunlight duration and thus, photovoltaic production. Second, two possible outage times will be considered in the analysis: at 2 a.m. and at 5 p.m.

The type of interruption chosen is considered to be severe, occurring only once during the life time of the project. This allows us to simulate and quantify the behavior of the microgrid in the event of a major disaster.

REopt® will include the presence of three diesel generators. For the conducted simulations, it has been assumed that each diesel generator had a nominal power of 400 kW—so, the total of the nominal power would be 1,200 kW. It will also be assumed that the amount of fuel available will be 680 gallons or 2,575 liters [30]. In this case, and as a safety measure, emergency supply by diesel generators have been designed into three independent units to guarantee a minimum of 400 kW in case of failure of two units.

On the other hand, a value of $ 100 per unserved kWh price has been considered as the cost of the unserved energy. This value depends on many factors that must be considered with care, including the power grid topology (radial or meshed), the supplied energy loads, the effects of a blackout in the feeded process, etc. Very little work has been done to incorporate the Value of Lost Load (VoLL) in the design of microgrids, although some approaches can be seen for sizing resilient microgrids to survive a design-outage [31]. In this case, the methodologies presented in [32-34] have been considered to approximate the VoLL as a function of the energy not served by the microgrid. It should be noticed that the unavailability of medical services is very costly and the toll then increases for public services that depend on hospitals and have to reimburse the affected sectors. In addition, health and safety effects are visible such as looting and vandalism [33], but in our study these side effects have been neglected as first approach.

2.4.5. Photovoltaic system

For the conducted evaluations a number of entries have considered, including different losses sources for the photovoltaic production: (i) dust that may accumulate over the life of the project, (ii) shadows that may form on solar panels, (iii) losses in diodes and connections, (iv) general ageing of the system, and (v) losses induced by light. Total losses have been estimated to be 14%.

2.4.6. Energy storage by batteries

Battery system design and dispatch strategies differ depending on the use-case and the value streams that are being tapped [35]. A value of 20% will be recorded for *MSoC* (Minimum State of Charge). When the battery, especially for Li-ion batteries, reaches this value, the voltage at its terminals decreases so rapidly that the efficiency is significantly affected [36]. In this case, it has been considered that the power grid can, in some cases, charge the batteries system if necessary.

3. Results

The work which follows takes up a series of simulations carried out with the *REopt*® software. The objective is to evaluate the performance of the microgrid through twelve scenarios (two extreme daylight duration times, two starting times and three outage durations for each case), presented in the Materials and Methods section, with the aim to study the share from PV to feed the loads, the energy used to charge the batteries and the energy exported to the power grid. For the readers' help, Table 3 shows the relations of the eight most representative simulations with their corresponding figures.

Please bear in mind that, both to reduce redundancy and improve readability and to conform to usual research papers' page limits and format, only significant results have been included and discussed. As a consequence, only eight (out of the twelve possible combinations) have been included in the body of the manuscript.

Table 3. *Simulation results related figures and tables. Source: Own elaboration.*

Outage start time	Outage duration	June 21st	December 21st
2 a.m.	8 h	6	2
	16 h	8	4
	24 h	9	5
5 p.m.	8 h	7	3

Before the analysis, it must be noticed that the power load profiles changed for the same day scenario according to the time (2 a.m. and 5 p.m.) and duration of the tested outages (8, 16 and 24 hours) as, during the outage, the power load may change according to the critical load. Thus, some power demand profiles cannot be compared between directly. On the other hand, due to the numerical approach used by *REopt*®, some slight differences can be found in some cases for the same power load demand, (differences of up to 100.3 kW at 7 a.m. and 18.4 kW at 10 a.m. at maximum), but they can be neglected when analyzing the overall performance of the microgrid.

Most part of the time, when operating under normal conditions, the power dispatch algorithm prioritizes the direct consumption from the PV production over the energy storage, as PV peak production matches with the highest electricity tariff prices. Thus, batteries are usually charged from the power grid when the electricity cost is minimal. In this case, the electricity price gets a minimum value in the period comprised between midnight and 1:00 a.m. In general, batteries are charged when the *SoC* (State of Charge) falls to 20% (this value has been considered the minimum possible *SoC* in order to enlarge the useful lifespan of the batteries system). Only under extreme circumstances, when PV surplus electricity is produced, batteries are charged when the *SoC* is about 60 or 80%. Energy stored in batteries is required during normal conditions operation when the PV production ends and energy from the external power grid is still costly.

Depending on the outages start time and duration the behavior of the power dispatch changes significantly. During the winter solstice, which corresponds with the period with the lowest number of daylight hours, it can be observed that diesel generators have a principal role in the energy management. Figures 2, 3, 4 and 5 show the effect of power outage in the simulated facility for different durations and starting times but in both three figures this effect can be observed. In Figure 2, when the outage starts at night and lasts only 8 hours, PV support is not provided until the fifth hour. Moreover, when the PV production starts it is still not sufficient to feed all the load and, as the diesel generators are still necessary and they are conditioned by a technical minimum, PV energy is used to charge the batteries.

In Figure 3, when the power outage occurs at the end of the daylight time, the normal energy dispatch made the batteries useless during the outage as all stored energy is used when the PV production decreases and the electricity tariff is still high. It can be observed then that in both scenarios represented in Figures 2 and 3, the energy storage was useless if considering only resilience enhancement. On the other hand, it contributed to reduce the energy imported from the power grid even under low PV production conditions.

With larger outage durations, as shown in Figure 4 and 5, the power dispatch remains the energy storage in batteries still useless as they are not used in any case during the power outage. This is due to the optimized power dispatch strategy prioritized the economic value of the stored energy in batteries (and its limited lifetime) over the critical service they can provide during the power outage. For the system it results more beneficial to feed the critical loads with energy from diesel generators rather than from batteries. This situation becomes even more extreme when, during the outage and with a positive PV production, surplus is injected into the power grid, as it can be observed in Figures 4 and 5, and the *SoC* of the batteries only decrease once than the power outage has finished and there is no availability of PV production.

Figures 6, 7, 8 and 9 conduct a similar analysis but considering a major PV production as the considered critical day is the summer solstice. In these scenarios, batteries dispatches are similar than in the previous figures: they are never used during the power outage due to it can result not economically optimal. On the other hand, the higher PV production allows to reduce the need of diesel generators, but they result mandatory in the three outage scenarios. Moreover, it can be observed in the four figures that, during the power outage, the greater PV production capacity can be used to inject surplus electricity both to the external power grid or the energy storage system (if the *SoC* is below 100%). Thus, during the power outage, no significant differences between both cases study (winter and summer solstices) are observed. However, during normal operation conditions, the optimal power dispatch of the batteries makes them to be discharge at midday hours in order to reduce the amount of energy to buy from the power grid.

Finally, it must be observed that only in the summer solstice scenario, batteries are charged from the PV generator during normal operation conditions, while in the winter solstice scenario, batteries are only charged from the power grid when the electricity tariff provides the lowest prices. During the winter solstice, batteries are charged from the PV facility only during a power outage, when the reduction of the power load (from the typical profile to the critical profile) generates a surplus of energy that can be stored in the electrochemical system.

When the power outage occurs at night and has a relatively short duration, as it can be seen in Figures 2 and 6, the use of diesel generators is minimized to lessen their potential impact on the environment and partially address supply and distribution issues. In Figure 2, the dedicated use is 7 hours while in Figure 6 the corresponding duration is almost 6 hours. This saves 1 hour and 2 hours of operation in a row. In one hour, about 220 kWh energy from diesel generators are consumed for the first case; and 233 kWh for the second one. These savings will be important because diesel generators, after 8 a.m., have to power more loads (assuming that, in this case, photovoltaic modules would not be able to operate). The time of usage of diesel generators is reduced because solar resources are available at that time. Afterwards, these two scenarios should be put in context because one takes place in winter, according to Figure 2; whereas the other case (Figure 6) is in summer. The main reason for reducing, in this case, the use of diesel generators is that solar energy is available and it is able to supply the power loads. In winter, the fuel is used and consumed until 10 a.m., which marks the end of the power outage from the conventional grid. We are likewise in the case where the solar resources are insufficient compared to summer.

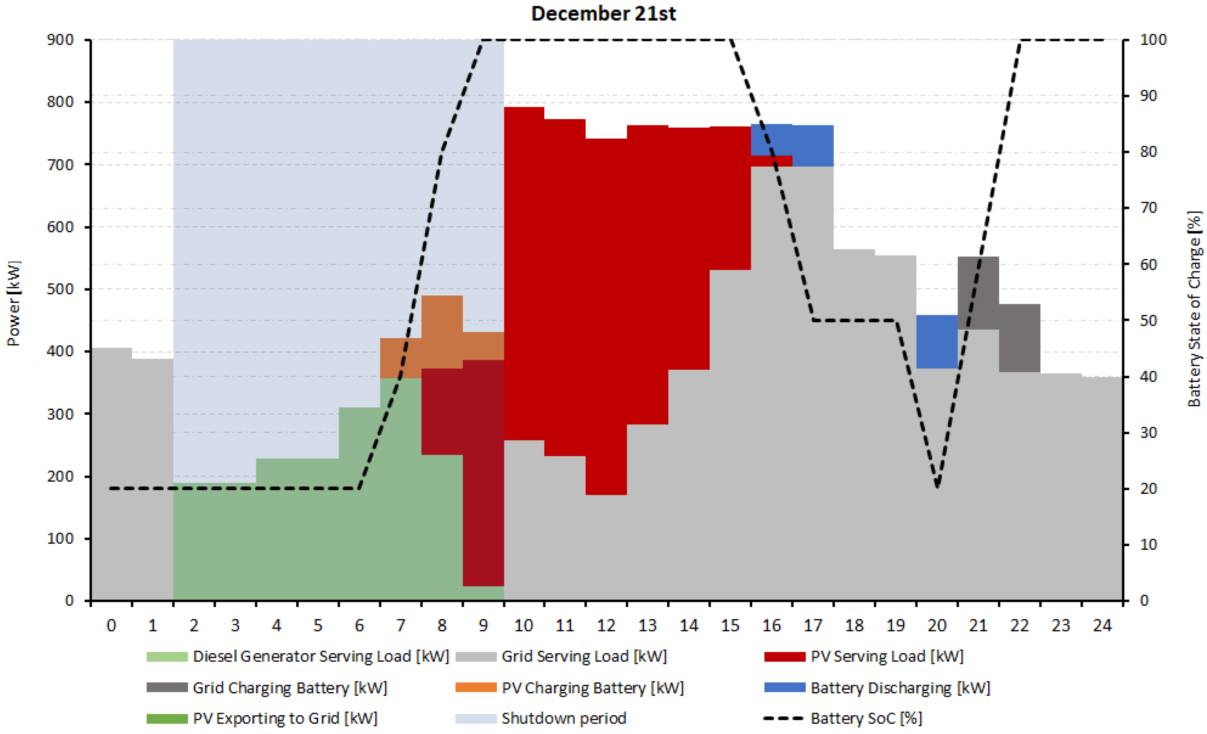

Figure 2. *Energy dispatch on December 21st with a shutdown at 2 a.m. for 8 hours. Source: Own elaboration.*

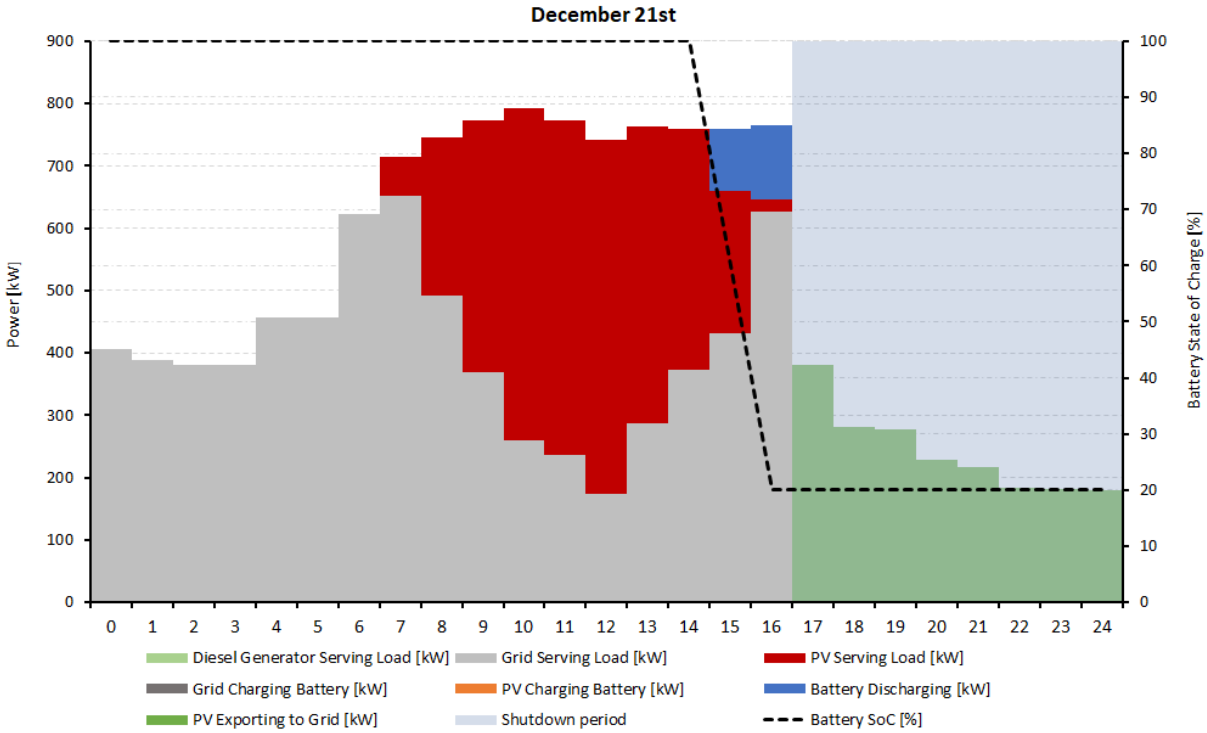

Figure 3. *Energy dispatch on December 21st with a shutdown at 5 p.m. for 8 hours. Source: Own elaboration.*

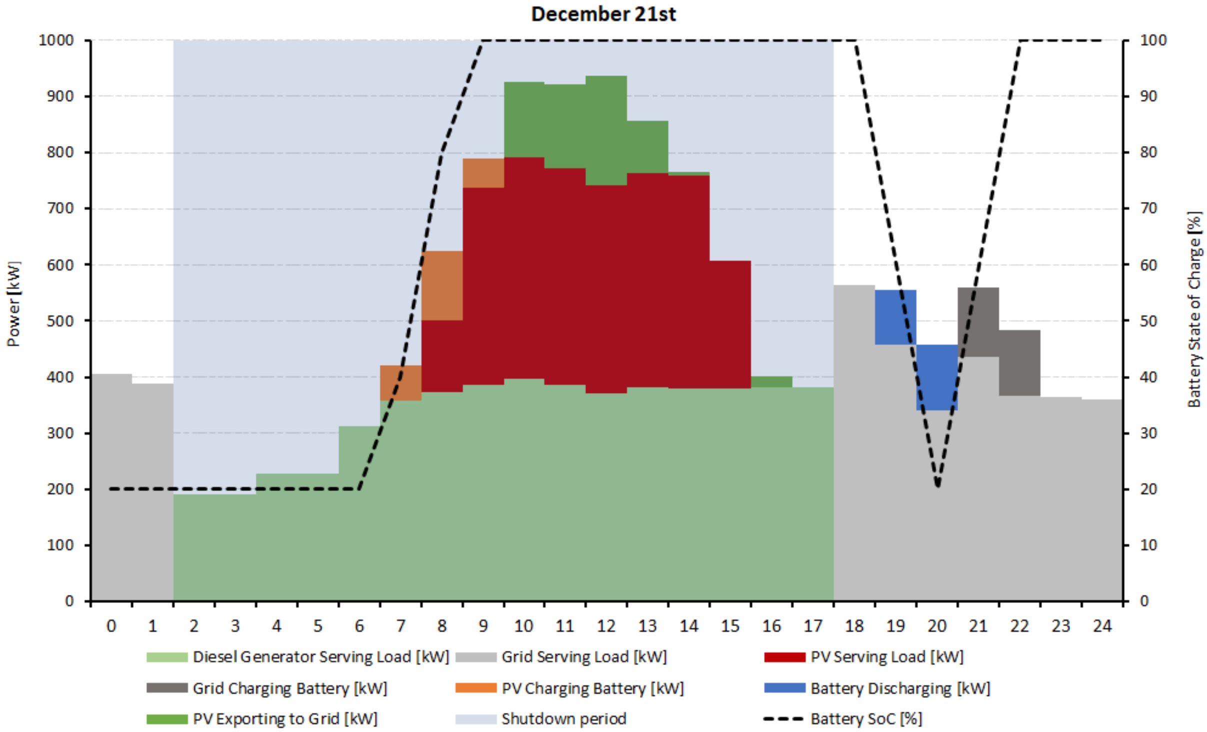

Figure 4. *Energy dispatch on December 21st with a shutdown at 2 a.m. for 16 hours. Source: Own elaboration.*

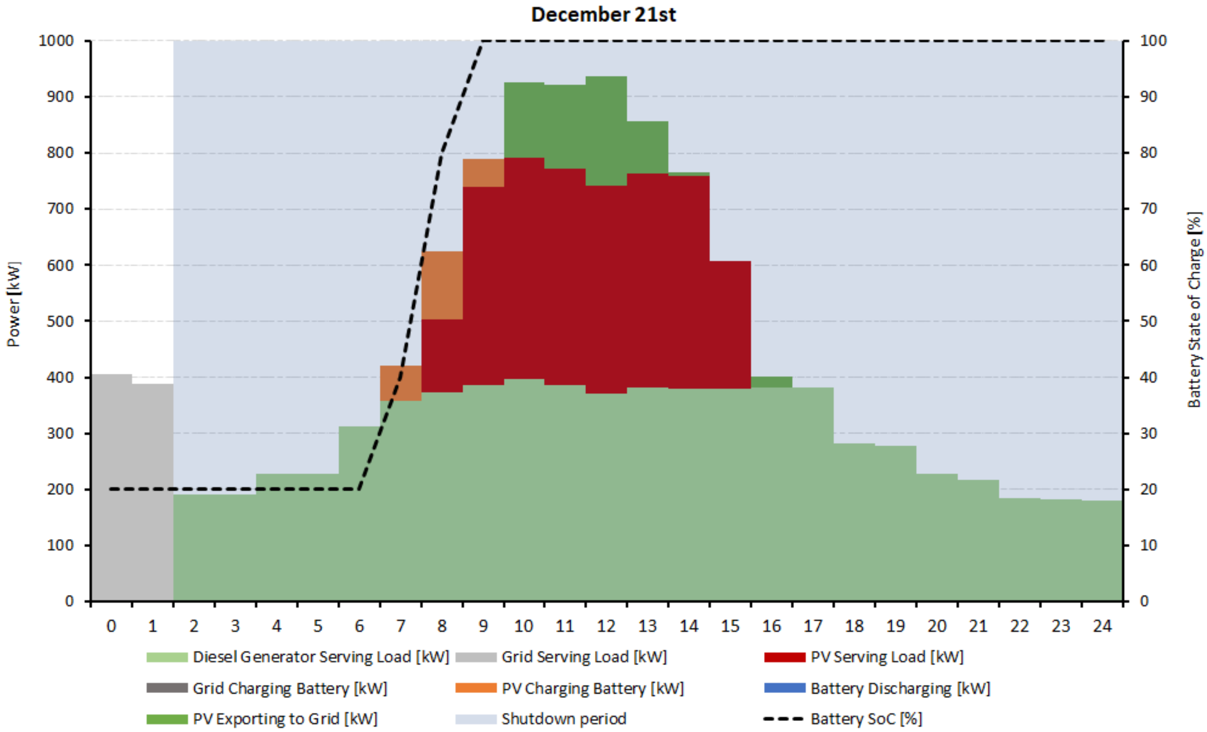

Figure 5. *Energy dispatch on December 21st with a shutdown at 2 a.m. for 24 hours. Source: Own elaboration.*

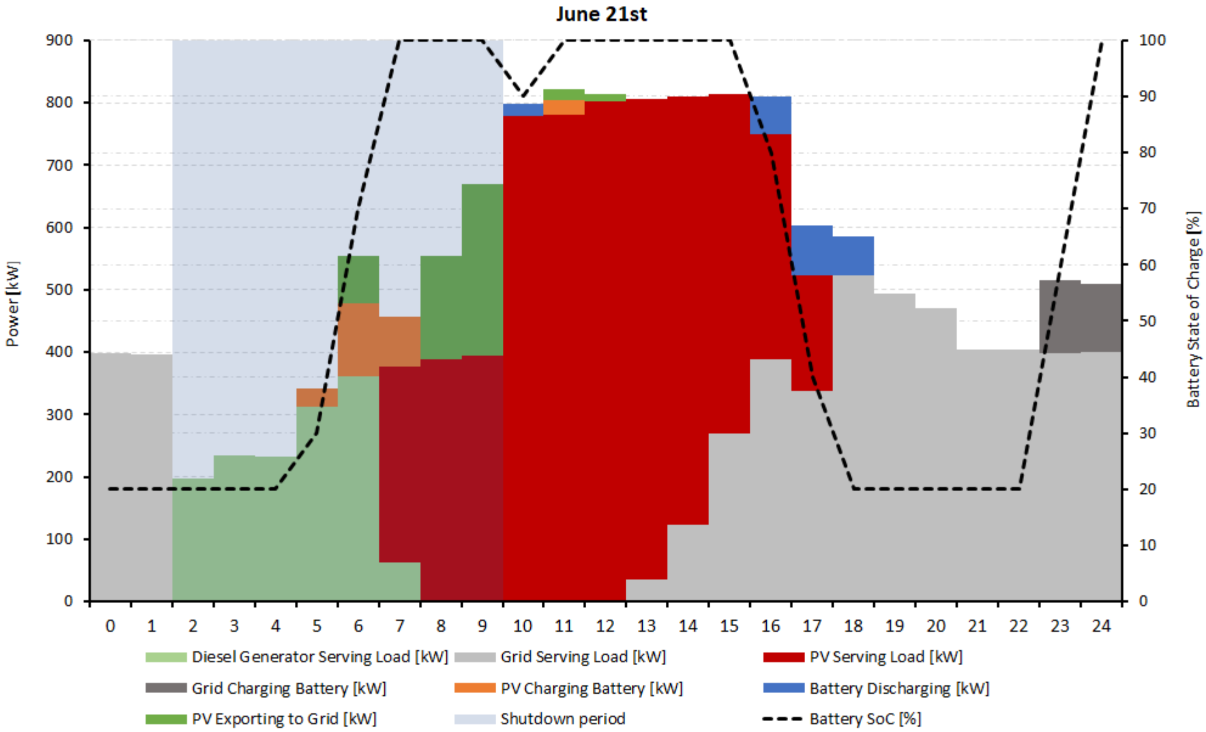

Figure 6. *Energy dispatch on June 21st with a shutdown at 2 a.m. for 8 hours. Source: Own elaboration.*

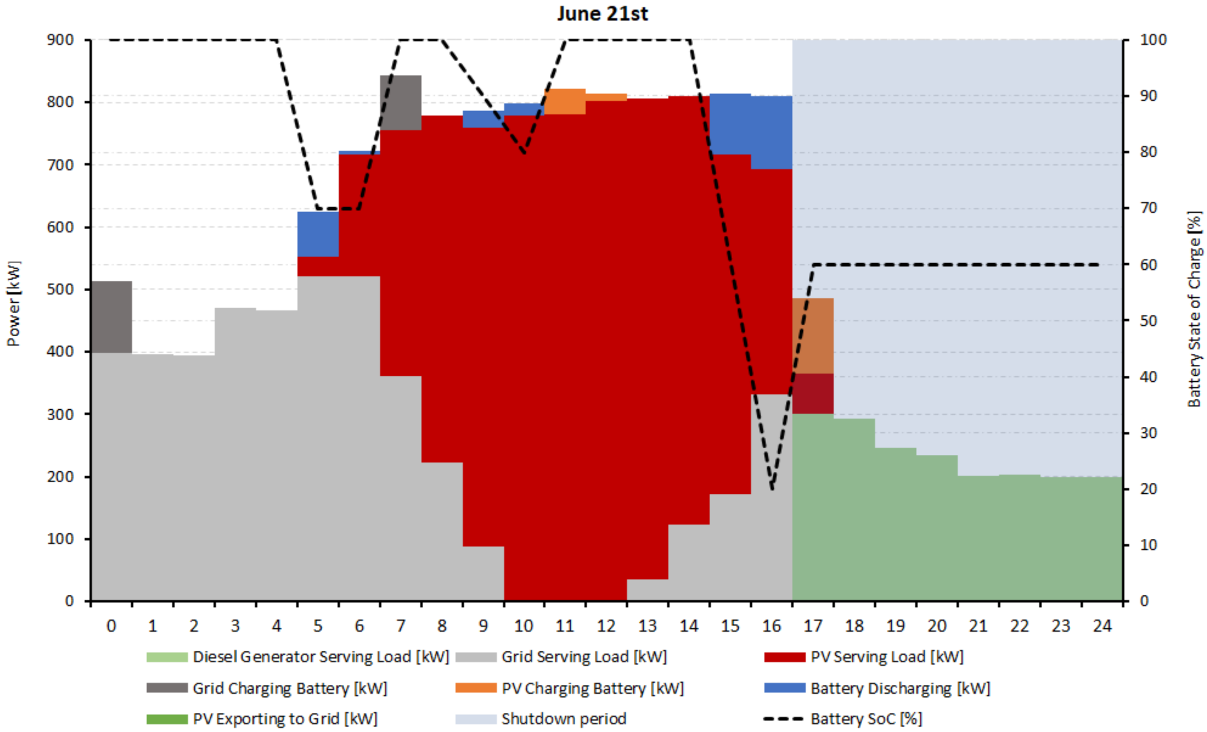

Figure 7. *Energy dispatch on June 21st with a shutdown at 5 p.m. for 8 hours. Source: Own elaboration.*

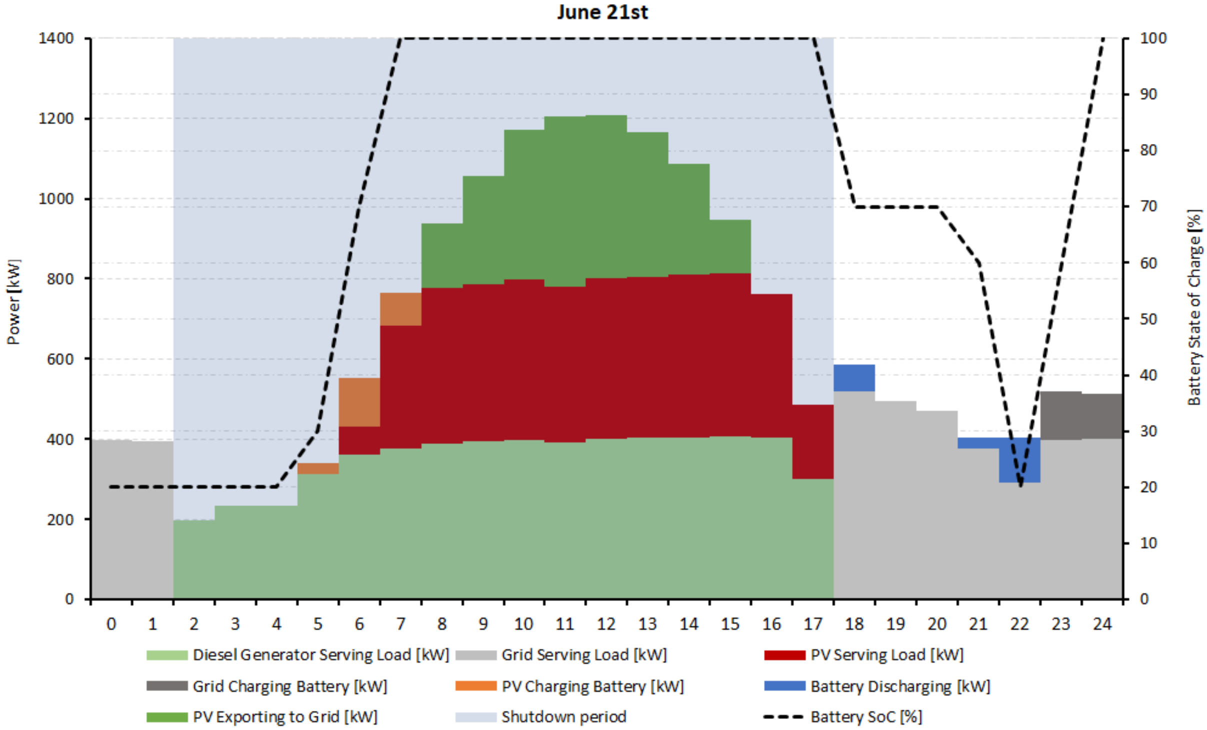

Figure 8. *Energy dispatch on June 21st with a shutdown at 2 a.m. for 16 hours. Source: Own elaboration.*

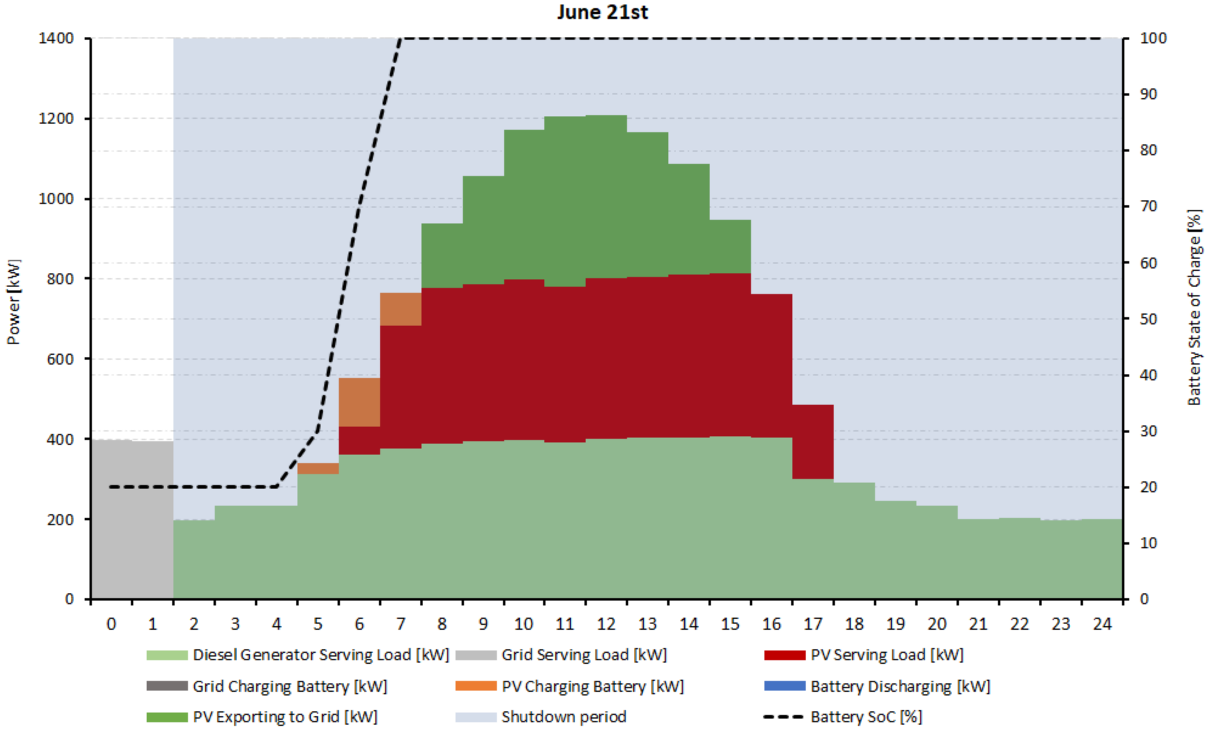

Figure 9. *Energy dispatch on June 21st with a shutdown at 2 a.m. for 24 hours. Source: Own elaboration.*

Figure 8 highlights a scenario where the solar resource is strongly present at the time the power outage has already occurred as it represents the summer solstice (June 21st) and, thus, it is observed that the system is able to provide the energy needed to charge the batteries system and, on the other hand, to export surplus energy to the power grid.

A thorough analysis of these different values shows that from 7 a.m. onwards, the battery stores the remaining energy to increase its *SoC* from 70 to 100%. The rest of the day, from 8 a.m. onwards, the power provided to the loads remains at around 400 kW. The remaining energy is exported to the power grid at a time when the profit of the resold energy would be maximum. Between 11 a.m. and 1 p.m., the share of exported power becomes greater than the share of energy consumed. *REopt*® considers that the best scenario in the event of power outages is to supply the majority of solar energy to the microgrid during the day. For the case studied, the solar energy that supplies the loads is kept constant from 8 a.m. to 3 p.m.

The battery will decrease its *SoC* until achieving a minimum of 20%, when the Sun is about to set. Figures 5 and 9 show the same type of reasoning, but with a much longer break time: 24 hours instead of 16 hours. However, it should be noted that Figure 8 contains an intermediate discharge level that is only understandable because of the compensation for the increase in energy required for hospital needs. It also exists because of the appearance of the Sun is about to set. At about 10 p.m., the batteries can no longer be used. This is present, in a smaller quantity in Figure 4. Figure 3 shows a situation where all solar resources are being exploited to supply the different loads. Even if this represents a winter scenario, Figures 4 and 5 can charge the batteries and resell the electricity thus recovered. The difference here comes from the fact that there is a high demand for electricity, which Figures 4 and 5 may reveal since the disconnection of the traditional grid is already underway.

Of all the above studies, the battery provides energy when solar resources are not operational. Figures 6 and 7 show the second alternative: in the event that energy demand becomes too high. It should be remarked that the proposed simulation, for diesel generators, are supposed to operate without malfunctions. As explained in the Introduction section, failures might occur during disasters. It should be considered that the use of a diesel generator requires increased supervision, especially when batteries and photovoltaic panels will not be able to supply the required energy [37].

In hospitals, loads are rather reactive in nature and it becomes necessary to have a stable transition, especially in voltage. It will be also necessary to consider, if necessary, the installation of capacitors that will increase the reactive reserve [35-40]. Due to this likely installation is not considered by the simulation, costs from this example may be higher than reality.

Finally, it is also necessary to consider in the most general way, the cost to which the project would be put in case of dysfunctions. This is shown in Figure 10, considering the example of batteries. The project assessed would cost $883,427. It can be seen on the aforementioned figure that the batteries would have a specific weight of 60% of the final cost of the project, which represents approximately $530,056. The Development/Software Costs and Hardware parts simultaneously represent the last third of the project cost. It should be reminded, however, that, for the project studied, the decision model provided by *REopt*® does not allow to approximate the cost of such an investment. It is therefore inevitable that investments of this type of technology are more expensive according to Figure 10.

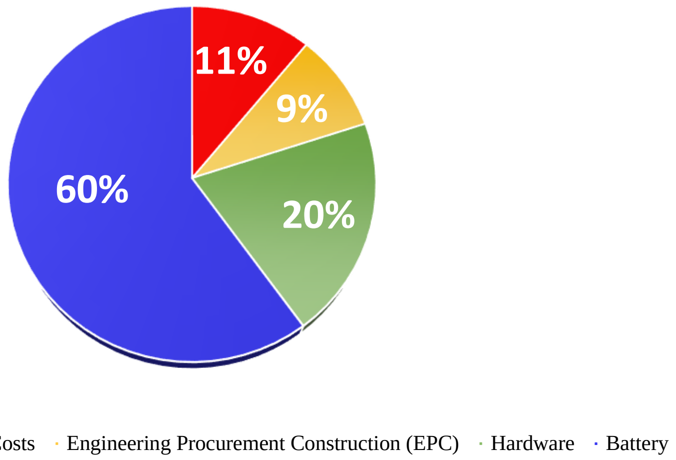

Figure 10. *Project costs breakdown when using Li-ion batteries. Source: [32].*

As reference of the differences between the business as usual approach and the optimal case, Table 4 summarizes obtained results for the June 21st with a shutdown at 2 a.m. for 16 hours scenario. Significant decrement (up to 1.8 GWh) of energy demanded from the power grid can be observed which conducts a Life Cycle Cost of the total system after tax to be reduced $ 435,268, which is approximately the same than the Net Present Value.

Table 4. *Comparison between the business as usual approach and the optimal case according to June 21st with a shutdown at 2 a.m. for 16 hours. Source: Own elaboration.*

	Business as Usual	**Optimal Case**	**Difference**
SYSTEM SIZE, ENERGY PRODUCTION AND SYSTEM COST			
PV Size	0 kW	1,134 kW	1,134 kW
Annualized PV Energy Production	0 kWh	1,836,030 kWh	1,836,030 kWh
Battery Power	0 kW	114 kW	114 kW
Battery Capacity	0 kWh	276 kWh	276 kWh
DG System Cost (Net CAPEX + O&M)	$ 0	$ 1,634,873	$ 1,634,873
Energy Supplied From Grid in Year 1	4,894,390 kWh	3,115,318 kWh	1,779,072 kWh
UTILITY COST (YEAR 1) – BEFORE TAX			
Utility Energy Cost	$ 377,442	$ 226,796	$ 150,646
Utility Demand Cost	$ 248,894	$ 168,147	$ 80,747
Utility Fixed Cost	$ 0	$ 0	$ 0
Utility Minimum Cost Adder	$ 0	$ 0	$ 0

	Business as Usual	Optimal Case	Difference
LIFE CYCLE UTILITY COST – AFTER TAX			
Utility Energy Cost	$ 3,376,765	$ 2,029,021	$ 1,347,744
Utility Demand Cost	$ 2,226,718	$ 1,504,321	$ 722,396
Utility Fixed Cost	$ 0	$ 0	$ 0
Utility Minimum Cost Adder	$ 0	$ 0	$ 0
TOTAL SYSTEM AND LIFE CYCLE UTILITY COST – AFTER TAX			
Life Cycle Energy Cost (LCC)	$ 5,603,483	$ 5,168,215	$ 435,268
Net Present Value (NPV)	$ 0	$ 435,268	$ 435,628

Conclusions

The research here presented estimates the savings that could be achieved over the lifecycle of a critical microgrid, in this case, considering a hospital as case study. Evaluations conducted in this research paper presented a breakdown among the different end-uses of the electricity produced by solar PV, i.e., battery charging, energy supplied to the microgrid loads, and energy resold to the electricity grid. For the proposed scheme, it was noted that most of the energy used by the loads of the hospital were obtained from solar PV. Batteries are used when the Sun is about to set or when the demand for electricity becomes high, but never during the power outage as expected, due to the valorization of the stored energy. The development carried out has made it possible to establish the schedules when electricity is the cheapest. On days when electricity demand is high, all photovoltaic energy will be used to power the loads. It can therefore be concluded that, with high solar resources and, for the electricity tariff studied, the addition of solar PV makes it possible to increase the resilience of a microgrid in the event of power outages. From a given load profile, it is therefore possible to determine how the microgrid will behave. All of this will reduce dependence on the use of diesel generators in a hospital. A further research might be to assess a microgrid based on the priorities between the different renewable energies mentioned above. Also, the analysis and comparison of special energy storage strategies, such those intended to maximize the resilience enhancement instead of the maximization of the economic benefit must be carried out in future research works. The results provided by the software used, *REopt®*, are relevant and allow to provide a number of scenarios giving a resilience capability, which is introduced as an input, while, at the same time, provides financial insights from a business perspective. By installing photovoltaic panels, Li-ion batteries and diesel generators, the microgrid could save approximately $440,191 over a 20-years life cycle of the facility.

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Appendix A. Summary of model inputs

Table A.1. Summary of the model inputs. Source: Own elaboration.

SITE AND UTILITY	
Site location	Palmdale, CA
Latitude	34.579434
Longitude	-118.116461
Land available (acres)	34.17
Roofspace available (sq ft)	320,000
Load profile	Simulated
Type of building	Hospital
Annual energy consumption (kWh)	4,900,000
URDB rate	Southern California Edison Co Time-Of-Use - General Service - Large: TOU-8 CPP (2kV-50kV)
FINANCIAL PARAMETERS	
Analysis period (years)	20
Host discount rate, nominal (%)	8.1%
Host effective tax rate (%)	26%

FINANCIAL PARAMETERS	
Electricity cost escalation rate, nominal (%)	2.6%
O&M cost escalation rate (%)	2.5%
SOLAR PHOTOVOLTAIC SYSTEM	
System capital cost ($/kW)	$ 2,000
O&M cost ($/kW per year)	$ 16
Minimum size desired (kW DC)	0
Maximum size desired (kW DC)	Unlimited
Module type	Standard
Array type	Rooftop, Fixed
Array azimuth (deg)	180
Array tilt (deg)	10.0
DC to AC size ratio	1.1
System losses (%)	14%
Net metering system size limit (kW)	0
Federal percentage-based incentive (%)	30%
Federal maximum incentive ($)	Unlimited
Federal rebate ($/kW)	$ 0
Federal maximum rebate ($)	Unlimited
State percentage-based incentive (%)	0%
State maximum incentive ($)	Unlimited
State rebate ($/kW)	$ 0
State maximum rebate ($)	Unlimited
Utility percentage-based incentive (%)	0%
Utility maximum incentive ($)	Unlimited
Utility rebate ($/kW)	$ 0
Utility maximum rebate ($)	Unlimited
Production incentive ($/kWh)	$ 0

SOLAR PHOTOVOLTAIC SYSTEM	
Incentive duration (years)	1
Maximum incentive ($)	Unlimited
System size limit (kW)	Unlimited
MACRS schedule	5
ENERGY STORAGE SYSTEM	
Energy capacity cost ($/kWh)	$ 500
Power capacity cost ($/kW)	$ 1,000
Energy capacity replacement cost ($/kWh)	$ 230
Energy capacity replacement year	10
Power capacity replacement cost ($/kW)	$ 460
Power capacity replacement year	10
Minimum energy capacity (kWh)	0
Maximum energy capacity (kWh)	Unlimited
Minimum power capacity (kW)	0
Maximum power capacity (kW)	Unlimited
Rectifier efficiency (%)	96%
Round trip efficiency (%)	97.5%
Inverter efficiency (%)	96%
Minimum state of charge (%)	20%
Initial state of charge (%)	50%
Allow grid to charge battery	yes
Total percentage-based incentive (%)	0%
Total rebate ($/kW)	$ 0
MACRS schedule	7
RESILIENCE	
Critical load factor	50%