# Microgrids with Energy Storage Systems as a Means to Increase Power Resilience: An Application to Office Buildings

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## Abstract

This work describes a methodology to quantify the benefits from both a business-related and energy resilience perspectives provided by a microgrid based on photovoltaic solar energy and electrochemical energy storage integrated in large buildings, such as office buildings not open to the general public, which is presented as case study. First it has been identified how, by using distributed renewable energy sources (in particular, photovoltaic solar energy) and electrochemical energy storage systems, the life-cycle cost of the energy in a microgrid connected to the electrical network can be reduced significantly. As novel approach, it has been evaluated how this microgrid design can increase the resilience of a power customer supply, quantified as the time period the microgrid is able to feed an electrical consumer at an outage, which it results of great importance for large office buildings that are used to have several critical loads, such as data servers and data processing centers. It was found that, by adding photovoltaic solar energy and electrochemical storage, it is possible to extend the power resilience of this sort of power customers achieving an average survival time to a power cut of four hours thanks to the proposed solar photovoltaic and energy storage system. Then, the microgrid could save $ 112,410 in energy over the 20-year life cycle of the facility, while increasing the amount of time it can survive a power outage. The proposed methodology presented in this paper provides a model that can be applied to other case studies and scenarios where an alternative to the classic diesel-based emergency supply systems are needed.

*Keywords*: power resilience; distributed renewable energy sources; solar photovolatic energy; electrochemical storage; microgrids.

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**Nomenclature**

| | |
|---|---|
| AC | Alternating current. |
| AS | Ancillary services. |
| BDG | Backup diesel generator. |
| DC | Direct current. |
| DR | Discount rate. |
| EB | Energy balance. |
| ED | Energy demand. |
| ECRC | Energy capacity replacement cost. |
| ECRY | Energy capacity replacement year. |
| EIA | Energy International Agency. |
| FCI | Federal Corporate Income. |
| FS&L | Federal state and local. |
| IE | Inverter efficiency. |
| IM | Islanded mode. |
| INOCT | Installed normal operating cell temperature. |
| GCM | Grid connected mode. |
| HETR | Host effective tax rate. |
| LCC | Life cycle cost. |
| LCOE | Levelized Cost of Energy. |
| MACRS | Modified accelerated cost-recovery system. |
| MSoC | Minimum state of charge. |
| NERC | North American Electric Reliability Corporation. |
| nZEB | Nearly Zero Energy Building. |
| PCRC | Power capacity replacement cost. |
| PCRY | Power capacity replacement year. |
| PICM | Power interruption cost model. |
| PPR | Peak power requirement. |
| RE | Rectifier efficiency. |
| RP | Reactive power. |
| RTE | Round trip efficiency. |
| SoC | State of charge. |
| SL | System losses. |

## 1. Introduction

Although policy makers have focused on the decarbonization of electricity generation for many years, some recent extreme weather events have led to an increase in attention to the resilience of the electricity sector [1]. Failures in the power grid related with strong weather conditions affecting renewable energy generation, out of bounds power loads and safety breaches, have conducted to test with caution the ability of the power grid to operate with safety under stated conditions [1]. Therefore, it is imperative to increase the availability of electricity supply in order to provide an adequate service during power outages and other emergencies [1].

In an electrical power system, resilience is characterized by four key elements, namely: i) prevention of interruption of the power supply; ii) mitigation of the consequences of the interruption of the power supply; iii) reduction of the response times needed to restore the electricity, and iv) recovery of the electricity supply [2].

Backup diesel generators (BDGs) are currently the most widely accepted option to provide energy when an outage occurs, sometimes combined with energy storage systems [3], although other technologies have arisen, as fuel cells [4]. On the other hand, BDGs, which are nearly inactive all the year, have proven to have a lower reliability than other technologies that can be used in normal conditions, such as solar photovoltaic generators [5]. This circumstance has, in the case of large office buildings, important economic effects [5]. Then, renewable energies are progressively acquiring greater strategic importance in energy resilience [6], mainly due to the following reasons:

a) Given the changing environmental conditions, the current approaches and regulations for existing and future energy infrastructures may no longer be sufficient [7]. In the particular case of the United States of America (USA), seven out of the ten most costly disasters that occurred during the 1980-2018 period have taken place in the last 13 years [8].
b) Fuel supply interruptions are not only a theoretical vulnerability [9]. According to the *"State of Reliability 2017"* report [10] (from NERC), the lack of fuel was the second most important cause of forced outages of the generators; being the fourth most important cause by 2015 [11].
c) The significant costs reduction of the solar photovoltaic technology in the recent years has been *"impressive"* according to experts [12]. With regard to new and emerging electricity storage technologies, their potential cost reduction is equally significant [10].
d) As shown in [13], forming an electric island to sustain power loads considered critical and increase the resilience of the installation is possible today by using standard equipment.

As a consequence of the above, the ability to maintain electrical service during a blackout; the maximization of the economic benefit of the facilities; and the integration of distributed resources that allow the system to effectively use the energy, improve its stability (frequency and voltage), and meet the requirements of the power demand, is something that must necessarily get considered with the use of renewable energies [14].

The benefits of using distributed resources and electrochemical storage in microgrids include, among others, (i) the improvement of the reliability of the system; (ii) the improvement of the quality of energy; (iii) the procurement of ancillary services (AS); (iv) a reduction of peak power requirements (PPR) thanks to on-site generation; (v) the procurement of reactive power (RP) for voltage control; and (vi) the provision of an electricity supply available in emergency situations [15].

This paper focuses on the role of renewable energies in reducing energy consumption; energy costs; and dependence with respect to the electrical grid of large office buildings not open to the public, which usually concentrate important power loads due to intensive penetration of electronic equipment. Part of this equipment can be considered a critical power load, such as data servers and data processing centers, so this approach results of great importance for them. About 50 publications were reviewed for this work and, despite being a substantial and representative sample of the state-of-the-art, this number is not absolute. Some researchers have focused on investigating the design, implementation, and simulation of a hybrid microgrid testing facility, outlining different elements within it required to make a functional microgrid test system [16]; on proposing a power balancing strategy with smart grid interaction, aiming at reducing grid peak consumption [17]; on proposing a comprehensive approach for evaluating the performance of various Smart and nearly Zero Energy Buildings (nZEBs) [18]; or on develop, test and apply an optimization model to evaluate on-site renewable energy technologies including energy storage in buildings and assess optimal configurations for nZEBs [19].

According to [20-22], the definition of microgrid is: *“a cluster of loads and microsources operating as a single controllable system that provides both power and heat to its local area.”* If one analyses this definition, it readly follows that the electric power system that feeds the power demand of a large building, which includes several loads, when integrates energy generators (such a PV system) and energy storage devices, agrees with it, even more, if it accounts with a control system for a smart energy dispatching of the energy.

From a deep survey of grey literature and updated literature related to the addressed topic, it was found that – even though there are plenty deal of different approaches – few methods quantify the benefits from both a business-related and energy resilience perspectives provided by a microgrid including photovoltaic solar energy and electrochemical storage. Thus, this paper undoubtedly contributes to the pool of existing knowledge and provides a reference application considering specifically large office buildings not open to the public. By performing this thorough literature review, we ensure the originality of the idea and method here presented. From this line of analysis, a much clearer insight of solar photovoltaic and electrochemical storage systems' benefits on the resilience of similar office buildings not open to the public is gained (so far not explicitly included in already published scientific contributions). Furthermore, the proposed method here presented improves the analysis in the sense that it is a systematic and easy approach that allows to make comparisons among different office buildings regardless of their sizes and locations.

In many countries, and specially in the United States, are under progressively increasing electricity consumption rates and, thus, new paradigms of delivering electricity are required in order to meet the power demand [23]. Despite the efficiency gains possible, regulators and utilities have been reluctant to implement distributed generation, but certain governments, most notable California, are making concerted efforts to overcome these barriers [23]. Usually, microgrids design is intended to provide a feasible solution to remote areas with difficulties to access the utilities [24]. Several studies have demonstrated that polygeneration microgrids with optimized combination of hybrid capacitors can operate with great success [21-25].

Energy management systems are essential and indispensable for the secure and optimal operation of Polygeneration microgrids which include distributed energy technologies, in particular if they can operate connected to the power grid, isolated or at transitional modes [26]. Several control approaches can be applied including the latest Game Theory applications [26]. Some authors, like in [27], even propose multi-objective control strategies to optimize the behavior of microgrids with renewable energy sources, including several generation technologies, such as micro-turbines, fuel cells, and batteries as energy storage systems.

The deployment of microgrids is being favored by the technological improvements, falling costs, proven track records and growing recognition of their benefits [28]. Nevertheless, several challenges, such as legal and regulatory uncertainty, interconnection policies, utilities regulations and opposition still must be faced [29]. One of the main barriers to identify the microgrids and smart grids benefits is the assessment of the overall project success [29], although several demonstration projects have enabled to learn for further develop and application of commercial, sustainable and renewable technologies [30].

It has been demonstrated that the arrival of small-scale decentralized energy installations can contribute to the minimization of the levelized cost of energy (LCOE) both for PV and wind generators allowing even grid parity under certain scenarios [31]. Moreover, it is expected that the future deployment of electrochemical energy storage systems both in static devices or thanks to electric vehicles, will contribute to reduce the energy costs and guarantee power supply even considering the batteries capacity degradation [32].

The manuscript is organized in three more sections. Section 2 describes the proposed methodology to quantify the economic and resilience benefits provided by the penetration of renewable energy sources in microgrids, and summarizes the assumptions and key inputs for the carried-out analysis. In the next section, ill different technologies to minimize the life-cycle cost of the energy (LCC) are evaluated for normal operation conditions, connected to the electricity grid; Then, once the best renewable resources are selected and optimally evaluated, a series of stochastic simulations that analyze the performance of the microgrid of a representative large office building are run, considering interruptions of random durations. Finally, Section 4 explores the significance of the results and introduces the major outcomes of the research.

## 2. Material and methods

This section describes the methodology used to quantify the economic and resilience benefits provided by renewable energy resources in microgrids, while summarizing assumptions and key inputs for the analysis.

## 2.1 Modeling approach

### 2.1.1 The *REopt*® model

In this paper, the *REopt*® modeling platform [33] has been used in order to evaluate the renewable energy resources and storage technologies that minimize energy costs and increase the resilience of a microgrid. Formulated as a linear program of mixed integers (MILP), the implemented algorithm considers no randomness for the development of future system states and then, it provides the most favorable technology to be used, its size, as well as the optimal dispatching approach considering a minimum LCC [34]. The LCC value includes the costs of the energy demand (ED), capital costs, profits and tax incentives, and the operation and maintenance costs [34]. The installation associated economic parameters are calculated for a *N* years analysis period, optimizing only the energy dispatch or energy balance (EB) for the first 365 days[†]. The rest *N-1* years are used to evaluate the economic impact of the facilities degradation and performance worthening. It is supposed that all projects are built immediately and that they begin to be operational in the first year[‡] [35]. *REopt*® also provides the optimum delivery strategy based on a business-related perspective to operate the recommended technologies at maximum economic efficiency [36].

### 2.1.2 Assessment of the economic benefits of renewable energies and electrochemical storage

Solar energy systems are an option increasingly widely used by those electricity consumers (customers) who want to reduce their monthly bill and generate electricity on-site [37]. When combined with storage in the form of batteries, the benefits of solar energy are even higher [37]. A scheme that includes solar energy and electrochemical storage can provide a variety of services, from benefits in the form of resilience, such as emergency electric power, to economic benefits, such as savings in electricity bills [37]. The design of a hybrid scheme of solar energy and electrochemical storage will depend on the expected function (or functions) of the system [37]. In general terms, schemes based on photovoltaic solar energy and electrochemical storage can be grouped into those designed to provide energy isolated from the electricity grid and those designed to operate connected to the electricity grid [37]. Solar energy and electrochemical storage facilities can potentially provide high benefits from both a business-related and an electrical resilience perspective [37]. *REopt*® model was used to simulate a case in which the office building not open to the public continues to acquire its electricity from the electricity grid. *REopt*® was also used to optimize a scheme based on renewable energies with electrochemical storage, where the size and operation of the system are optimized through the model. In this case, it will be evaluated if the renewable energy systems are advantageous supposing they operate on a grid connected mode (GCM), and if they are also capable of feeding electrical loads during power grid failures or blackouts.

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[†] According to [35], the model achieves an energy balance between consumption and generation during each period of time by creating and dispatching an optimal combination of renewable generation and energy storage. Although the *REopt*® economic model considers an analysis period of *N* years, it is assumed that the energy consumption and production are constant for all years in such a way that the optimal balance of energy achieved for year 1 remains valid for the subsequent years in the analysis period. In making this assumption, the present value of the total energy costs for the next *N* years can be determined by increasing the current energy costs (using an increase rate for electricity) and then discounting those costs at present by using an appropriate discount rate.

[‡] Following [36], *REopt*® assumes a perfect prediction of all future events, including weather conditions and charges.

### 2.1.3 Assessment of the increase in resilience due to renewable energies and electrochemical storage

Apart from the economic benefits, another important aspect when evaluating microgrids that have to feed critical loads is the quantitative evaluation of the additional resilience obtained through the proposed scheme [38]. In this section, a methodology will be described to quantify the increase in the capacity to supply energy to the loads of an office building not open to the public through the introduction of renewable distributed energy resources. Through the use of *REopt®*, the scheme based on renewable energies is evaluated to obtain the greatest economic benefit for a microgrid connected to the main power grid, in which the renewable energy system can reduce the expenses related to the purchase of electricity, reduce demand peaks, and carry out an energy arbitration.

As a measure for resilience we will use the term *"survivability"*, which is defined as the probability of having electricity continuously available during a power outage until it is reestablished within *t* units of time after the interruption of the power grid supply has taken place [39]. It should be considered the fact that the likeliness of happening an outage depends on the variation in the electrical load versus time, the electrochemical storage SoC when the interruption of the supply occurs; as well as on its duration, and the battery management strategy [39].

By using a conventional BDGs and a constant quantity of on-site combustible, the survivability changes depending on the power interruption duration. For example, for a critical facility such as a hospital or an airport, the survivability would typically be 100% for the first 24 hours of a power outage (assuming a sufficient amount of fuel is available), falling rapidly as the supply runs out of fuel. For a hybrid system based on renewable energies, the survivability of the aforementioned hospital or airport due to power cuts of longer durations would be greater due to their ability to satisfy the electricity requirements of the loads that were previously exclusively powered by backup diesel generators. However, for those facilities considered as *"non-critical"* (such as office buildings not open to the public) maintaining backup generators which are idle most of the time of the year might not be advantageous from a business-related perspective.

To assess the increase in terms of electrical resilience provided to a scheme based exclusively on renewable energies (such as the office building evaluated in this research), the survivability is calculated solely considering renewable energies and electrochemical storage. By default, it is normally assumed that the electricity grid is 100% reliable, which means that it is capable of providing an infinite amount of electricity at any time [40]. However, in an electrical resilience analysis, what is usually done is to inject a random number of failures in the model to evaluate the ability of the scheme to sustain interruptions in the electrical grid [40]. A model that can evaluate the cost of a random interruption of the electricity supply from the available statistics, called power interruption cost model (PICM) is necessary to carry out an adequate cost-benefit analysis, as described in [41] and [42]. The most widely used PICM is the *"customer damage function"* [43], which models an average interruption cost for each type of customer as a function of the outage duration. However, there are other factors besides the duration that also may affect the cost of the interruption of the power supply, such as the time and day of the week in which the power outage occurs, or the season of the year, as it has been demonstrated in [42]. Moreover, in [42] the smart grid capabilities, such as smart switching the distribution topology or renewable energy sources integration in microgrids are evaluated to minimize the impact of widespread blackouts of the bulk power grid system. *REopt®* takes these circumstances into account when carrying out the optimization of the scheme, as described in the user manual [34] and software description documents [34,36].

## 2.2 Inputs of the model

As case study, it has been chosen a representative scenario consisting on an office building not open to the public, located in the city of Palmdale (California), with a total area of 60,000 ft$^2$ (about 5,575 m$^2$). In a realistic way, it has been considered that the building requires having a reliable energy to avoid (or at least mitigate) the potential losses in the event that there is a blackout. Considering McKenney et al. [44], the average load has been assumed to be approximately 110 kW, varying from a minimum of 85 kW to a maximum of 180 kW in summer. The total annual energy consumption has been estimated in 1,000,000 kWh, according to [40-42].

### 2.2.1 Electricity tariff

In the Californian city of Palmdale are used to be under an unregulated market, in this case provided by the Southern California Edison Company. According to the building characteristics, the TOU-8 CPP rate (2 kV-50kV) has been chosen for supply [45]. It has been assumed that, for the analyzed year, the costs related to electricity amounted to $ 178,500. This tariff is available to customers with demands not exceeding annual peak demands of 4 MW and who install, own, or operate solar, wind, fuel cells, or other eligible onsite renewable distributed generation technologies as defined by the California Solar Initiative (CSI) or the Self-Generation Incentive Program (SGIP). Eligible systems must have a net renewable generating capacity equal to or greater than 15 percent of the customer's annual peak demand, as recorded over the previous 12-months. Participation on this rate option is limited to a cumulative installed distributed generation output capacity of 400 MW for all eligible rate groups [46]. More details regarding this tariff are shown in Table 1.

Table 1. Applied electric tariff. Source: [47].

| **Time-Of-Use - General Service - Large: TOU-8 CPP (2kV-50kV)** | | |
|---|---|---|
| Fixed Charge (First Meter) [$/month] | 319.47 | Fixed Charges |
| Seasonal/Monthly Demand Charge Structure [$/kW] | 14.88 | Demand |
| Time of Use Demand Charge Structure | | |
| Period 1 (Tier 1) [$/kW] | 0 | Demand |
| Period 2 (Tier 1) [$/kW] | 6.41 | Demand |
| Period 3 (Tier 1) [$/kW] | 23.24 | Demand |
| Demand Reactive Power Charge [$/kVAr] | 0.51 | Demand |
| Tiered Energy Usage Charge Structure | | |
| Period 1 (Tier 1) [$/kWh] | 0.06426 | Energy |
| Period 2 (Tier 1) [$/kWh] | 0.08397 | Energy |
| Period 3 (Tier 1) [$/kWh] | 0.05902 | Energy |
| Period 4 (Tier 1) [$/kWh] | 0.08222 | Energy |
| Period 5 (Tier 1) [$/kWh] | 0.1351 | Energy |

This tariff is favorable for photovoltaic solar energy because most of the charges related to electricity occur during the generation power peaks. However, it results less favorable to electrochemical storage because there are no charges related to *"Time-of-Use demand"*.

### 2.2.2 Microgrid configuration

The microgrid which constitutes the building is based on the power grid interconnection, a solar photovoltaic field, and an electrochemical storage system. Although other technologies could also play an important role in the near future, today they are, among the most respectful with the environment, the most widespread and which provide the best business model.

a) **External power grid**. It has been assumed that the national power grid can provide an unlimited amount of electricity although it can suffer from blackouts of random duration [48]. It has been supposed that the utility has not capital nor operation and management costs and that the only related expenditures are the energy flows from the grid [49]. A retail electricity rate for the chosen rate type based on the state has been considered and estimated in $ 0.16/kWh, according to the Energy Information Agency (EIA) [50].

b) **Solar photovoltaic field**. The *REopt*® model evaluates the renewable technology generation potential by hourly capacity factors [47]. In the case of solar photovoltaic energy, the hourly capacity factors are obtained by *REopt*® from the *PVWatts*® database and solar model, also developed by NREL [50] for the specified location and assuming a typical orientation and efficiency for the photovoltaic modules [51]. The electric energy produced by the solar photovoltaic modules is proportional to the capacity factor of each site [36]. Due to the power production tends to decrease throughout their useful life, *REopt*® calculates an annual generation profile considering a degradation rate of 0.5% per year [52]. Moreover, following [34], roof mounting has been considered as it is a typical for residential and administrative installations where modules are attached to the roof surface with standoffs that provide limited air flow between the module back and the roof surface. For roof mount systems, the installed normal operating cell temperature (INOCT) is 50 ºC, which corresponds roughly to a three or four inches standoff height. The installation capital costs, used for the PV field size optimization, have been estimated in $ 2,000 per installed kW peak power [53]. The considered assumptions are shown in detail in Table 2.

Table 2. Model assumptions for the PV field. Source: [50].

| Characteristic | Value |
|---|---|
| Module type | Standard |
| Cell material | Crystalline Silicon |
| Approximate nominal efficiency | 15% |
| Module cover | Glass |
| Temperature coefficient | -0.47%/ºC |
| Array type | Fixed (roof mount) |
| Latitude | 34.57 deg. |
| Longitude | -118.1 deg. |
| Tilting angle | 34.07 deg. |
| Azimuth angle | 180.00 deg. (South) |
| DC/AC ratio | 1.1 |
| Inverter efficiency | 96% |
| Ground Coverage Ratio (GCR) | 0.4 |
| Global system losses | 14.08% |
| Soiling losses | 2.00% |
| Shading losses | 3.00% |
| Snow losses | 0.00% |
| Mismatching losses | 2.00% |

| | |
|---|---|
| Wiring losses | 2.00% |
| Connection losses | 0.50% |
| Light-induced degradation | 1.50% |
| Nameplate rating | 1.00% |
| Age degradation | 0.00% |
| Availability | 3.00% |
| Annual performance degradation | 0.50%/yr |
| System capital costs | $ 2,000/kW |

**Electrochemical storage**. *REopt®* considers electrochemical batteries as a *"reservoir"*, in which the storage energy at a certain moment can be consumed in another, when the PV production is lower than the electric energy demand [36]. The chemistry of batteries is not considered directly by the model, but heuristic restrictions are imposed, that are designed to ensure that the battery operates within the manufacturer's specifications. These restrictions are based on limits for the minimum load status, the loading and unloading rates, and the number of cycles per day. The model is capable of selecting and dimensioning both the capacity of the battery and the power provided [36]. The characteristics of the simulated lithium-ion batteries are summarized in Table 3, based on the considerations stated in [33].

Table 3. Model assumptions for the simulated lithium-ion batteries. Source: [33].

| **Characteristic** | **Value** |
|---|---|
| Initial State of Charge (SoC) | 50% |
| Minimum State of Charge (MSoC) | 20% |
| Inverter efficiency (IE) | 96% |
| Round trip efficiency (RTE) | 97.5% |
| Rectifier efficiency (RE) | 96% |
| Total AC-AC RTE | 89.9% |
| Power Capacity Replacement Year (PCRY) | 10 |
| Energy Capacity Replacement Year (ECRY) | 10 |
| Power capacity costs | $ 1,000/kW |
| Energy capacity costs | $ 500/kWh |
| Power Capacity Replacement Cost (PCRC) | $ 460/kW |
| Energy Capacity Replacement Cost (ECRC) | $ 230/kWh |

### 2.2.3 Resilience assessment

For the resilience assessment modelling, the *REopt®* model has been applied considering the existence of blackouts along the whole year. The GCM is considered the normal operation mode. Then, the renewable energy generators can contribute to feed the electric power load in combination with the external power grid during the GCM and support critical electrical loads during a network outage, while conventional backup generators can only operate during an outage due to the legal requirements relating to air quality [34].

### 2.2.4 Economic assumptions

It has been assumed that the renewable energy generators and the energy storage system would be installed and fully operational since the first evaluated year. The useful life cycle, according to the *"2017 Annual Technology Baseline"* report from NREL [54], has been assumed to be of 20 years.

On the other hand, an increase rate of electricity costs[§] of 2.6% per year [55][**] [56][††], and 2.5% per year [54][‡‡] [56][§§] [57][***] for operation and maintenance costs has been assumed, considering that these costs escalate at inflation rate [34]. Based on guidance for regulatory benefit-cost analyses from FORTISBC ENERGY UTILITIES [58], all utility costs and operation and management costs incurred in the out-years are discounted to the present. Following the NREL 2017 Annual Technology Baseline and Standard Scenarios [54], the electric sector's historical nominal weighted average cost of capital (8.1%), has been used as nominal discount rate to evaluate the proposed scheme (it should be considered that distributed energy resources requirements might change considerably among promoters).

It should be considered that solar PV *stimulus* are accessible at the federal state and local (FS&L) level. Following [58], a federal 30% investment tax credit has been supposed[†††]. Solar projects are eligible for accelerated depreciation deductions over a five-years period [60][‡‡‡]. This circumstance has also been included in the model. A 40% host effective tax rate, or HETR (15 – 35% for Federal Corporate Income taxes (FCI) between 0 and 12%) [54,61,62] has been supposed. The energy components of the battery system are supposed to be replaced at the 10-th year of the project life cycle [63]. Model key inputs are summarized in Appendix B.

## 3 Results and Discussion

First, optimal sizes for the PV installation and the energy storage system are determined in such a way the LCC of the microgrid operating in GCM, were evaluated. Thus, the system is optimized to maximize the economic benefits under normal operation. Results show that the simulated office building is able to minimize its energy cost by installing a 282 kW peak power solar photovoltaic system, and an electrochemical storage of 29 kW of nominal power and a 55 kWh of rated capacity, considering a TOU-8 CPP tariff (2 kV-50kV). These recommended sizes minimize the LCC of energy at the site [34]. The battery power and capacity are optimized for economic performance [34]. However, it must be considered that the PV system performance predictions calculated by the *PVWatts®* model include many inherent assumptions and uncertainties and do not reflect

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[§] The nominal electricity cost escalation rate is provided explicitly in the EIA's Annual Energy Outlook and can also be calculated implicitly by combining the NIST Handbook's real electricity cost escalation rates with expected inflation rates [34].

[**] The EIA predicts a 2.6% average nominal annual commercial electricity escalation rate from 2017-2037 in their reference case scenario, assuming an inflation rate of 2.1%. Regional variation yields a range of annual electricity cost escalation rates from 1.7% to 3.5% [34].

[††] The average real commercial electricity cost escalation rate across the US over the period 2017-2037 was 0.52%, as described in table Cb-5 of the NIST Handbook 2017. More detailed projections for rates across the various regions of the US are available in the Handbook in tables Cb-1 through Cb-4. Five-years average electricity cost escalation rates over the period 2017-2037 for the different regions of the US range from -0.2% to 1% [34].

[‡‡] NREL analyses assume an inflation rate of 2.5% [34].

[§§] Federal projects use an inflation rate of -0.6% [34].

[***] Lists monthly US inflation rates from 1914-2017. Inflation rate in July 2017 listed as 1.7%. Since 2010, inflation rates have ranged from -0.2% to 3.9% [34].

[†††] Following [59] this investment tax credit is available to solar projects regardless of size, with no maximum incentive for solar technologies.

[‡‡‡] The Consolidated Appropriations Act, signed in December 2015, extended the *"placed in service"* deadline for bonus depreciation. Equipment placed in service before January 1, 2018 can qualify for 50% bonus depreciation. Equipment placed in service during 2018 can qualify for 40% bonus depreciation. And equipment placed in service during 2019 can qualify for 30% bonus depreciation [60].

variations between PV technologies nor site-specific characteristics except as represented by inputs. For example, PV modules with better performance are not differentiated within *PVWatts*® from lesser performing modules [34].

Then, stochastic simulations to analyze the performance of the resulting microgrid in the event of blackouts of random durations are carried out. This way, the resilience of the microgrid is quantified. It must be noticed that the increasing resilience is an added value, it has not been considered as an optimization.

In accordance with Table B.1 (Appendix B), the initial cost resulting from installing 282 kW of photovoltaic solar energy would be $ 564,000, while the cost of the electrochemical storage to be installed would be approximately $ 29,000[§§§]. According to Table A.1, solar photovoltaic energy would be able to generate 49% of the energy demanded by the office building. *REopt*® calculates the solar photovoltaic energy scheme in such a way that it is able to minimize the charges related to the consumed energy. Although it *"only"* generates the 49% of the energy consumed in the office building, a significant part of the generated energy is produced when the electricity is more expensive, so the microgrid is able to sell all the produced energy at a high price and to acquire it from the grid when the costs are lower (using the storage system). As a consequence of the microgrid scheme, utility energy costs would be reduced from $ 573,698 to $ 315,092. Current site life cycle energy cost would be of $ 1,112,221, whereas the proposed scheme would be $ 999,811. As a consequence, net present value (NPV) of the investment would be $ 112,410. This is also the NPV of the savings (or costs if negative) realized by the project based on the difference between the life cycle energy cost of doing business as usual compared to the optimal case [34]. All above values are summarized in Table A.1 from Appendix A.

These results assume perfect prediction of both solar irradiance and electrical load. In practice, actual savings may be lower based on the ability to accurately predict solar irradiance and load, and the battery control strategy used in the system [34].

The results include both expected energy and demand savings. However, the hourly model does not capture inter-hour variability of the PV resource. Because demand is typically determined based on the maximum 15-minute peak, the estimated savings from demand reduction may be exaggerated. The hourly simulation uses one year of load data and one year of solar resource data. Actual demand charges and savings will vary from year to year as load and resource vary [34].

Figs. 1 and 2 show the optimized energy dispatch for four typical days which characteristics are also shown in Table 4. Fig. 1(a) is an example of a typical day when the hourly power demand remains at low level the whole day and the solar resource is also low. Fig. 1(b) shows how the energy dispatch is performed when the power load is low but a high solar resource is available. Figs. 2(a) and 2(b) show the equivalent energy dispatch for high hourly power demand with low and high solar resource availability, respectively. In general terms, the PV system and the electrochemical storage work coordinated trying to supply the power demand minimizing the imported electric energy from the power grid. The microgrid uses electricity from the electricity grid during night hours, when electricity prices are usually lower and solar photovoltaic modules are not operative. During the daylight hours, the solar PV modules are able to satisfy all the demanded energy, and the surplus of the PV energy is used to charge the electrochemical storage system, or to export it to the grid if the batteries state of charge is high. It should be noted that, as the storage capacity is reduced in comparison with the building power load, its impact is relatively low. Thus, it is able to provide some savings through a limited peak power demand reduction (peak shavings strategy). Observe that the batteries SoC drops and rises very fast due to the batteries

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[§§§] Control costs associated with providing controls to the office building, including communications infrastructure, local and overall supervisory controls for synchronization, start-up and outputs of generators, as well as protection devices, are not included in the *REopt*® model [64].

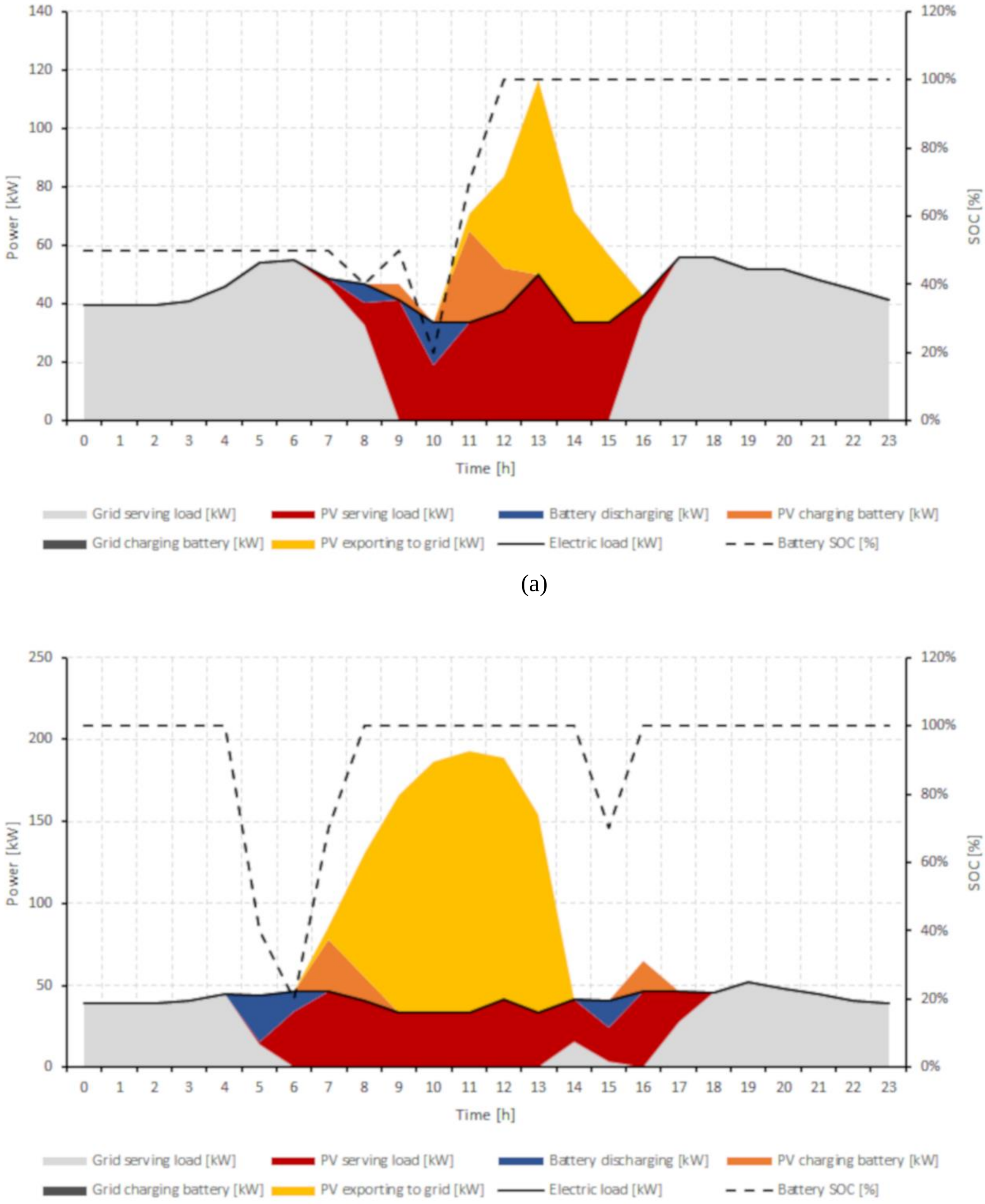
power, optimized at 29 kW. This means that they are able to discharge or charge approximately the half part of their rated capacity (55 kW) in just one single hour time.

Because inevitably there will be time periods when the PV generation is not able to satisfy all the power demand [65-70], the electrochemical storage will be responsible for satisfying the rest of the demand until the PV generation capacity can support the power demand by itself, or the batteries' SoC reaches the lower limit.

Fig. 3 shows the duration curves for the grid serving load, the PV serving load and the batteries discharging energy, referred to the power demand. Moreover, the duration curve for the energy storage SoC is also shown. It can be appreciated that the 50% of time, the power load is fed by the external grid in full, while the PV system supports completely the power demand just the 15% of time. On the other hand, the energy storage contributes only the 10% of the time and its contribution is less of 10% of the power demand, on average. The energy storage SoC remains at 100% more than 75% of the time.

Table 4. Typical days for energy dispatching. Source: Own elaboration.

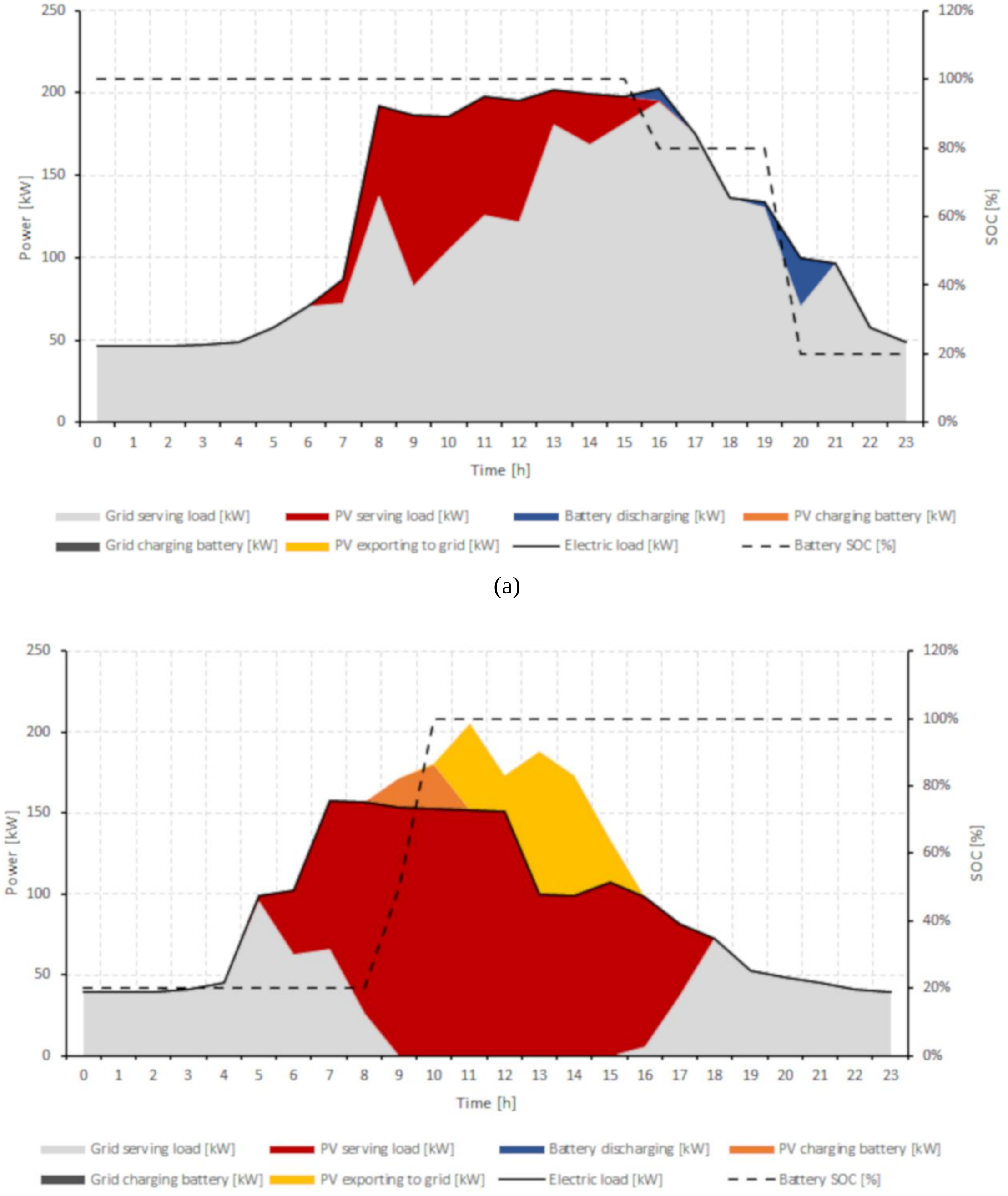
| **Parameter** | **Case A** | **Case B** | **Case C** | **Case D** |
|---|---|---|---|---|
| Power demand | Low | Low | High | High |
| PV potential | Low | High | Low | High |
| Figure | 1a | 1b | 1c | 1d |
| Example day | January, 1st | August, 6th | January, 6th | July, 22nd |
| Daily total electric load [kWh] | 1,067.40 | 1,006.20 | 2,961.50 | 2,110.90 |
| Daily total imported electric energy from grid [kWh] | 780.20 | 536.10 | 2,452.60 | 793.60 |
| Daily total grid serving load [kWh] | 780.20 | 536.10 | 2,452.60 | 793.60 |
| Daily total PV generation [kWh] | 483.40 | 1,273.60 | 468.10 | 1,629.00 |
| Daily total PV serving load [kWh] | 266.50 | 412.70 | 468.10 | 1,317.50 |
| Daily total Batteries discharging [kWh] | 20.60 | 57.50 | 41.10 | 0.00 |
| Daily total PV charging battery [kWh] | 51.60 | 64.10 | 0.00 | 45.70 |
| Daily total Grid charging battery [kWh] | 0.00 | 0.00 | 0.00 | 0.00 |
| Daily total PV exporting to grid [kWh] | 165.30 | 796.80 | 0.00 | 265.80 |
| Daily total Battery exporting to grid [kWh] | 0.00 | 0.00 | 0.00 | 0.00 |
| Daily total net metering [kWh] | -614.90 | 260.70 | -2,452.60 | -527.80 |
| Daily self-consumption | 26.90 | 46.73 | 17.19 | 62.41 |
| Daily PV surplus [%] | 34.20 | 62.56 | 0.00 | 16.32 |
| Daily average SoC [%] | 74.17 | 91.67 | 83.33 | 67.92 |



(a)

(b)

Fig 1. Energy dispatch for typical days for low power demand: (a) when low PV resource is available and (b) when high PV resource is available. Source: Own elaboration.



(a)

(b)

Fig 2. Energy dispatch for typical days for high power demand: (a) when low PV resource is available and (b) when high PV resource is available. Source: Own elaboration.

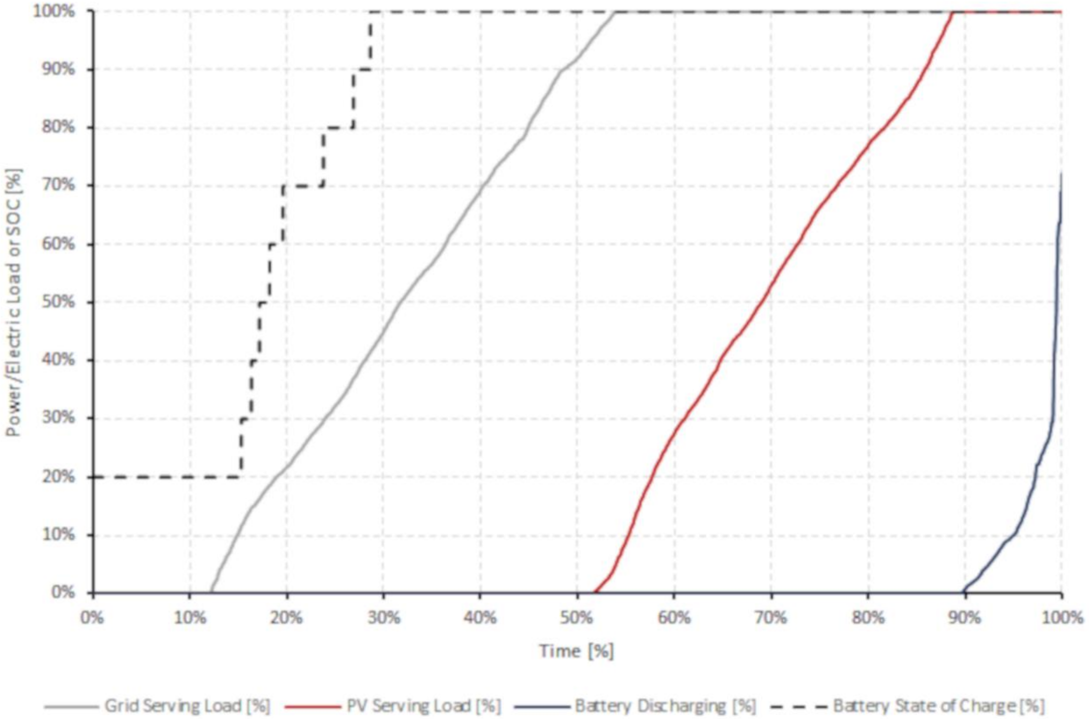


Fig. 3. Duration curves for grid serving load, PV serving load and battery discharging referred to the power load demand; and duration curve for the energy storage SoC. Source: Own elaboration.

For the energy resilience evaluation, the proportion of usual demand to be satisfied at the time of an electrical interruption of service (critical load) has been considered to be the 50%.

To evaluate the repercussion of the considered scheme on the microgrid resilience, blackouts were simulated in the power grid with durations between one hour and two weeks, which would occur randomly throughout the year. In order to calculate the probability of surviving a power cut, all simulated cuts were divided into 24-hour periods. The proportion of power cuts that the microgrid could sustain for each 24-hour period is shown in Fig. 4, where it is possible to see how adding the optimal power size of 282 kW of the solar photovoltaic array and an optimal electrochemical storage (29 kW of nominal power and 55 kWh of rated capacity) to the office building, the time that the microgrid would survive a cut of electricity would extend from the 0 to 4 hours, with a 40% probability. The minimum resilience has been estimated to be 0 hours (as expected), while maximum resilience is estimated in 18 hours.

For the estimation of the average amount of time that the system can sustain the critical load, 8,760 outage simulations are run - one for each hour of the year - and the average, minimum and maximum resiliency is calculated as the average, minimum and maximum time survived during the simulated outages, respectively. The battery SoC at the start of each outage is determined by the economically optimal dispatch strategy. This means that if the battery was being used for peak shaving prior to the outage, it may be at a low SoC when the outage occurs. Note that in order to gain this resiliency, the microgrid will operate in islanded mode (IM). This incurs additional costs, associated with transfer switch and control, above the normal operation set at GCM.

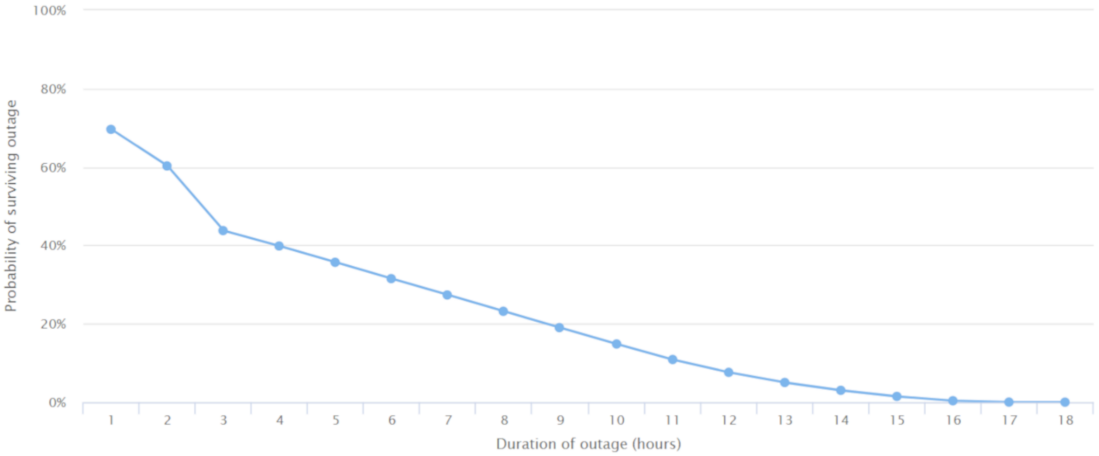


Fig. 4. Probability of surviving outage [hours] vs. duration of outage [hours]. Source: Own elaboration.

## 4 Conclusions

It can be concluded that the proper design of a microgrid including renewable energy sources and energy storage systems can improve significantly the power resilience of a large building without incurring in extra costs and with a better reliability than classical BDGs. It has been proposed a particular novel approach where, while optimizing the size of an integrated PV field and the energy storage, the building's resilience is quantified.

The results of the carried-out analysis in this research demonstrate how a scheme consisting of 282 kW of solar photovoltaic energy and an electrochemical energy storage system with a nominal power of 29 kW and 55 kWh of rated capacity would be able to produce $ 35,651 per year of savings regarding the energy consumption. Throughout the 20 years of the expected useful lifespan for the facility, the proposed microgrid would be able to generate a potential savings of $ 112,410. Moreover, the microgrid would be able to produce up to the 49% of the total required energy by the office building when operating in GCM, while it provides up to 4 hours of resilience capacity with 40% probability of surviving the blackout.

Furthermore, it must be considered the additional benefits of deploying microgrids based on renewable energy generators, that have not been detailed in the analysis of the LCC and that provide a direct economic value to this added survivability, as during a power outage, the incurred costs can be dramatically large for a business. This value, despite not being included in the economic analysis, should be considered in the investment decision.

Finally, it has been observed that the power demand profile, the electricity tariff, the generator technology costs, the incentives, as well as the solar resource play a critical role in determining the viability of this sort of systems, so each case must be evaluated in a particular way, through the proposed systematic approach.

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## *Appendix*

### *Appendix A. Results Comparison*

Table A.1. Comparison between the business as usual approach and the optimal case. Source: Own elaboration.

| | **Business As Usual** | **Optimal Case** | **Difference** |
|---|---|---|---|
| **SYSTEM SIZE, ENERGY PRODUCTION AND SYSTEM COST** | | | |
| **PV Size** | 0 kW | 282 kW | 282 kW |
| **Annualized PV Energy Production** | 0 kWh | 490,590 kWh | 490,590 kWh |
| **Battery Power** | 0 kW | 29 kW | 29 kW |
| **Battery Capacity** | 0 kWh | 55 kWh | 55 kWh |
| **DG System Cost (Net CAPEX + O&M)** | $ 0 | $ 321,186 | $ 321,186 |
| **Energy Supplied From Grid in Year 1** | 1,000,000 kWh | 572,718 kWh | 427,282 kWh |
| **UTILITY COST (YEAR 1) – BEFORE TAX** | | | |
| **Utility Energy Cost** | $ 79,088 | $ 43,438 | $ 35,651 |
| **Utility Demand Cost** | $ 74,239 | $ 50,116 | $ 24,124 |
| **Utility Fixed Cost** | $ 0 | $ 0 | $ 0 |
| **Utility Minimum Cost Adder** | $ 0 | $ 0 | $ 0 |
| **LIFE CYCLE UTILITY COST – AFTER TAX** | | | |
| **Utility Energy Cost** | $ 573,698 | $ 315,092 | $ 258,605 |
| **Utility Demand Cost** | $ 538,523 | $ 363,533 | $ 174,990 |
| **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)** | $ 1,112,221 | $ 999,811 | $ 112,410 |
| **Net Present Value (NPV)** | $ 0 | $ 112,410 | $ 112,410 |

## *Appendix B. Summary of model inputs*

Table B.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)** | Unlimited |
| **Roofspace available (sq ft)** | Unlimited |
| **Load profile** | Simulated |
| **Type of building** | Office - Large |
| **Annual energy consumption (kWh)** | 1,000,000 |
| **URDB rate** | Southern California Edison Co Time-Of-Use - General Service - Large: TOU-8 CPP (2kV-50kV) last updated 2016-02-10 |
| **Do you want to evaluate PV and/or Battery?** | Both |
| **FINANCIAL PARAMETERS** | |
| **Analysis period (years)** | 20 |
| **Host discount rate, nominal (%)** | 8.1% |
| **Host effective tax rate (%)** | 40% |
| **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 |

| **SOLAR PHOTOVOLTAIC SYSTEM** | |
|---|---|
| **Module type** | Standard |
| **Array type** | Rooftop, Fixed |
| **Array azimuth (deg)** | 180 |
| **Array tilt (deg)** | 5 |
| **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 |
| **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% |