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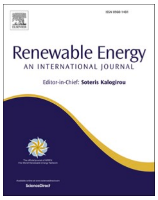

Microgrids as a mechanism for improving energy resilience during grid outages: A post COVID-19 case study for hospitals

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ABSTRACT

The high number of natural disasters in recent years, combined with the emergence of COVID-19 and the pressure it has exerted on healthcare services, has led to the need to guarantee the power supply to critical infrastructures. In this context, ensuring critical loads of hospital has become a mandatory task. Thus, the aim of the work presented here is to improve the energy resilience of a hospital through the installation of a microgrid consisting of a photovoltaic system working together with a diesel generator in the energy resilience scenario. In the first scenario, it has been evaluated how a microgrid es economically viable for the case where there is no grid outage. In the second scenario, the microgrid has been optimised taking into account both the economic profitability and the ability to withstand a 24-h outage in the month of lowest radiation. The results obtained have shown that the microgrid consisting of a PV system, an energy storage system and a backup diesel generator was able to withstand an average outage time of 72 h, providing the hospital with a net gain of 24 h in terms of energy resilience compared to the business as usual (BaU) and a reduction in utiliy cost of $ 147,354.

1. Introduction

The term energy resilience is based on preventing power outages and restoring power as quickly as possible when an outage occurs, while mitigating the consequences of the outage [1]. In recent years, a series of events such as the increase in natural disasters or the emergence of COVID-19 have led to energy resilience and its importance in critical infrastructures taking on high relevance in the planning [2–6] carried out by different governmental organisations and associations. On the one hand, the USA alone has suffered a total of 20 natural disasters in the last year with economic effects that reached or exceeded one billion dollars [7], leading to numerous negative effects such as possible shortages of fuel supply for transport and power generation, damage to physical infrastructure, changes in energy demand, and widespread long-term interruptions to power grid users [8]. On the other hand, the pandemic caused by COVID-19 has had innumerable effects on many sectors of the global economy, especially the healthcare sector [9] where the number of people admitted to intensive care (ICU) grew considerably in the USA [10] and the rest of the countries, resulting in a worldwide increase in the energy demands of hospitals [11].

In this context, it is important to remember that hospitals are considered as one of the 16 critical infrastructures by the U.S. Department of Homeland Security (DHS) [12], which implies that their critical loads must have access to uninterrupted power, even in the event of sudden power outages [13], to ensure the surgical processes, the comfort and quality of life of patients, as well as the refrigeration of medicines and vaccines [8], especially at the present time when hospitals also serve as COVID-19 vaccination centres. Moreover, the main vaccines developed to fight against COVID-19, such as Pzifer, Moderna or Janssen COVID-19, have high refrigeration requirements, as they require the use of freezers/refrigerators to store them at low temperatures (see Table 1.) and to keep them at the right temperature until the time of administration [14] (see Table 2).

Therefore, the increase in the number of natural disasters together with the increase in hospital pressure and energy demand caused by the COVID-19 pandemic, has positioned hospitals as the main reference when analysing the importance of improving energy resilience in critical infrastructures, in order to guarantee the operation of their critical loads regardless of external events. For this reason, for this study we will focus

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Nomenclature

NREL	National renewable energy laboratory
RE	Renewable energy
MILP	Mixed integer linear programming
LCC	Life cycle cost
N	Duration of years
LID	Light induced degradation
SoC	State of charge
BESS	Battery energy storage system
BaU	Business as usual
NPV	Net present value

Table 1
Vaccine storage temperatures.

Vaccine	Storage Temperature ∘C
Pzifer-BioNTech	−70
Moderna	−25
Janssen COVID-19	2

Table 2
Inputs and outputs for the site and utility. Source: Own elaboration.

Site and Utility		
Parameters	Value	Reference
Site location	Chino, California	–
Latitude	34.02557	–
Longitude	−117.685639	–
Land available (acres)	Unlimited	–
Roof space available (sq. ft)	Unlimited	–
Electricity rate	Southern California Edison Company: Time – Of – Use – General Service – Large: TOU – 8 CPP (2 kV–50 kV)	[34]
Net metering system size limit (kW)	0	–
Wholesale rate ($/kWh)	0	–

on hospital facilities, specifically on the Chino Valley Medical Center located in the county of San Bernandino, in the US state of California, more specifically in Chino Valley.

Traditionally, diesel generators have been used in hospitals to provide backup power to critical loads in the event of power outages. However, diesel backup generators have a number of drawbacks in terms of resilience as: i) they are rarely used and sometimes poorly maintained, so they may have problems in the time of a real emergency; ii) they often have a limited supply of fuel, so if the supply disruption continues, more fuel must be supplied [15], which may be impossible in situations of natural disasters; iii) the diesel backup generators cannot directly provide their rated power due to the temperature of the oil, which may hinder their backup function.

Furthermore, the decrease in recent years in both renewable energy (RE) and storage systems (BESS) costs [16,17], has led to the increased use of microgrids, based on renewable energy (RE) and energy storage systems (BESS), to improve resilience in critical infrastructure, as the implementation of microgrids allows to isolate generation sources and local loads from a faulty grid and to operate independently for extended periods of time [18].

Therefore, the use of microgrids based on renewable energy (RE) and energy storage systems (BESS) can serve as an alternative or supplement to existing diesel generators in hospital facilities, extending limited fuel supplies and providing greater system redundancy [1]. Furthermore, it should not be forgotten that microgrids, when working connected to the grid, generate savings on electricity bills by reducing peak demand and energy costs [19].

After reviewing the scientific literature related to the subject matter of this article, the feasibility, benefits and technical challenges of microgrids as sources of energy resilience have been evaluated in Ref. [20]. Also in Ref. [21] the advantages offered by the joint use (hybridisation) of generation systems together with energy batteries versus the individual use of both systems have been analysed. In addition, H. Masrur et al. [22] proposes a technical-economic analysis for the study of the resilience provided by a microgrid in an airport environment. The different scenarios proposed by the authors demonstrate that the system proposed is capable of providing economic benefits throughout its useful life and of withstanding an interruption in the electricity supply. It is important to note that the authors do not value the resilience provided by the microgrid in economic terms. In a similar way, J. Marqusee [23] proposes a novel use of the REopt tool to optimally size the different distributed renewable resources of the microgrid taking into account the number of diesel backup generators and also assesses the relative cost and performance of a hybrid microgrid versus a diesel-only microgrid in different locations in the USA. Other studies applied to large offices such as the one conducted by E. Rosales-Asensio et al. [24] show that an optimal design of a microgrid consisting of solar PV and energy storage is able to provide higher economic benefits and superior resilience and reliability with respect to diesel backup generators as emergency sources. In Ref. [25] the authors propose a methodology to quantify both the economic and resilience-related benefit provided by a hybrid microgrid (PV + Storage + Diesel Generator) for a telecommunication facility, in this paper the authors have only quantified resilience in terms of survival time and have not considered the assignment of an economic value to resilience. In the same methodological line but applied to similar case studies to the one presented in our research work, we can find different investigations focused on studying and improving energy resilience in the healthcare sector through the implementation of microgrids [8,26–28]. It is important to note that these studies have not considered the influence that COVID-19 has had on the energy demand of healthcare centres and the importance of increasing the percentage of critical loads that must be supplied during a period of grid interruption. However, only the work carried out by H. Masrur et al. [27] is after the appearance of COVID-19, so it is logical that the works [8,26,28] do not take this circumstance into account in their research.

However, it should be noted that, in most of the works referenced in the previous paragraph, the term VoLL (Value of Lost Load), a term related to the economic benefits of surviving a power outage, has not been mentioned or quantified. The authors in Ref. [19] proposes a novel method where they incorporate the concept of Value of Lost Load (VoLL), managing to quantify and include the value of resilience provided by the microgrid (PV + BESS) in different locations in the USA, demonstrating that the inclusion of VoLL in the technical-economic analysis can make a system become economically viable where it was not before. Furthermore, E. Rosales-Asensio et al. [29] have analysed different scenarios (radial and meshed grids) and configurations of microgrids in three critical infrastructures, highlighting that hybrid solar-diesel microgrids with batteries are the most cost-effective option. Additionally, assigning an economic value to the cost of outages has shown that in all the scenarios studied, both for radial and meshed grids, the NPV was always higher when this value was assigned to resilience.

Following the above, the work presented in this paper aims to address the problem of possible power outages that may occur in critical infrastructures, especially those related to the health sector during the COVID-19 pandemic, a period when the energy requirements of critical loads are much higher. Therefore, this paper will study how the implementation of hybrid microgrids (PV + BESS + Backup Diesel Generator) can increase energy resilience, obtain economic benefits and reduce the consumption of polluting energy sources. Furthermore, with respect to most of the scientific literature, that has addressed energy resilience in critical infrastructures; our approach has analysed and studied the economic benefits of adding economic value to the energy resilience provided by the hybrid microgrid.

The increase in the number of natural disasters in recent years, together with the effects caused by the emergence of COVID-19, has highlighted the need to study and improve the energy resilience of so-called critical infrastructures, especially those related to the health sector. Thus, after a brief overview of microgrids and energy resilience, of the different studies carried out and of the analysis objectives to be achieved throughout this work, the other three sections that make up this article will be briefly presented. In the second section "Materials and methods", the case to be studied, the tool used for the simulation, as well as all the parameters to be introduced will be presented. In the third section "Results", the different scenarios will be analysed and the results obtained for each of the scenarios will be presented. Finally, in the last section "Conclusions", the final remarks and future lines of research will be presented.

2. Materials and methods

This section describes the selected case study, the methodology, the simulation tool (REopt®) used to quantify the economic, and resilience benefits provided by a microgrid, and summarises the assumptions made and the main inputs to the analysis.

2.1. Case study

As a case study, a hospital facility has been selected which, due to the health situation caused by COVID-19, also performs its functions as a vaccination centre. This factor increases the hospital's critical loads and the importance of interrupted power supply in the event of a power outage. For the present study, the Chino Valley Medical Center has been analysed. It is a private hospital located in Chino, California and was founded in 1972. Currently it has a total of 112 beds, an emergency department with 10 intensive care beds, full radiology and laboratory services, as well as an operating room with separate gastroenterology and pain facilities [30]. Chino Valley Medical Center's emergency department receives about 37,000 visits a year.

Although this is a case study, the characteristics and representativeness allow the results to be extrapolated to other critical facilities, especially those located in the United States.

2.2. REopt®

In this paper we have used the REopt® optimisation tool provided by the National Renewable Energy Laboratory (NREL) to evaluate the optimal sizing of the different technologies that make up the microgrid, their optimal energy dispatch, as well as their ability to "survive" a power outage.

REopt® aims to solve a mixed-integer linear programme (MILP). The objective function minimises the total life cycle cost (LCC), which consists of a set of possible revenues and expenses over the analysis period defined, subject to a set of integer and non-integer constraints to ensure that the thermal and electrical loads are satisfied at each point in time by some combination of the selected technologies [31].

For a complete analysis of the case study, two scenarios were simulated using the REopt® tool, as it allows scenarios with different energy objectives to be simulated. Firstly, a scenario based on minimising the life cycle costs (LCC) of the installation without any interruption to the grid, i.e. during normal grid operation, has been simulated. Secondly, a 24-h grid interruption scenario was simulated. Thus, REopt® optimally sizes the selected technologies for grid-connected operation (LCC minimisation), while at the same time ensuring the maintenance of critical loads during a pre-defined grid interruption period [32].

It should be noted that REopt® solves a single year optimisation to determine future cash flows for N years, assuming constant production and consumption over the N years set for the desired analysis [32].

For a more detailed description of the main points regarding the REopt® tool, please refer to Refs. [31,32]. The online tool can also be found at [33].

2.3. Model data and assumptions

In the following subsections, all the inputs of the model will be detailed together with the technical-economic hypotheses that have been used, and the references consulted to assume these hypotheses will also be specified.

A summary of the main inputs and outputs used by REopt® can be seen in Fig. 1.

2.3.1. Location and electricity tariff

For the simulation, a critical infrastructure has been selected, such as a hospital, located in the city of Chino, California (USA).

In relation to the electricity tariff, the Southern California Edison electricity company is one of the companies responsible for supplying energy to the city of Chino, California. In view of the hospital's characteristics and energy demand, the "Time - Of - Use - General Service - Large: TOU - 8 CPP (2 kV–50 kV)" tariff was used for this analysis. According to this tariff, the service voltage must be less than 50 kV and the peak demand cannot exceed 4 MW [35].

Furthermore, this tariff promotes the installation of photovoltaic energy since, observing the hourly distribution of the different periods for both energy and power, the periods with the highest economic load, such as P4 and P5 for the energy consumed and P3 for the power term, are located in the hours of highest solar production. The electricity tariff applied to this study is presented in detail in Table 3 [34].

2.3.2. Load profile

The load profile of the simulated building will be evaluated for a full year and a consumption of 3,228,120 kWh/year has been estimated. In order to estimate this consumption, it has been used Ref. [36], where the energy consumption of a hospital is analysed according to its climatic zone. For the case of a Mediterranean climate, similar to certain areas of California, an electricity consumption per bed of 26,460 kWh/bed is indicated. The typical load profile shown in Fig. 2, is simulated based on the DOE Commercial Reference Building Hospital model for the California climate zone [37]. The average daily load is 368.51 kW, with a minimum load of 225.70 kW in February and a maximum load of 577.07 kW in April. Table 4 shows in detail the values related to the load profile entered in the model.

In addition, the daily load profile of the hospital considering a tipical week day and a weekend can be observed in Fig. 3 and Fig. 4 (see Fig. 5).

2.3.3. Resilience

The interruptions in the electricity grid are defined by their duration (in hours), their date and their start time [8]. For the energy resilience analysis, an interruption period of the electricity grid has been selected that will only occur once a year. This interruption will have a duration of 24 h, a start time of 1 a.m. and will take place on 18 December. As can be seen in Fig. 6, December is the month of the year with the lowest solar radiation and the 18th of that month is the day with the highest load (538.72 kW). This allows us to simulate and quantify the microgrid in the most adverse scenario (period of highest load and lowest solar radiation). In addition, the microgrid must be able to supply the hospital's critical loads during the interruption period.

The different bibliographical sources that have been analysed in order to establish the base value of the critical loads, without taking into account the effects that COVID-19 has had on them will be presented below. Thus, in Ref. [38] different case studies are analysed where different values are established for the critical loads depending on the

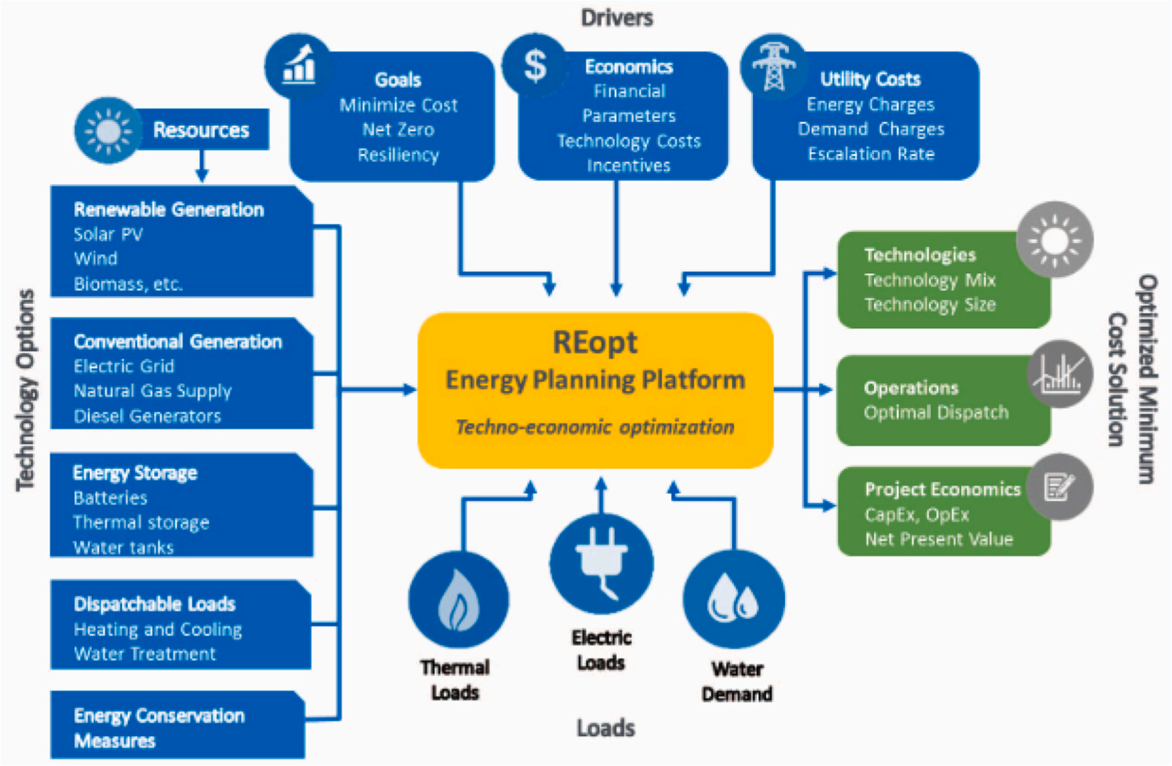

Fig. 1. Summary of the main inputs to and outputs from REopt model. Source [32].

Table 3
Applied electric tariff. Source: [34].

Southern California Edison Company: Time – Of – Use – General Service – Large: TOU – 8 CPP (2 kV–50 kV)	
Parameter	Value
Fixed Charge [$/month]	319.47
Seasonal/Monthly Demand Charge Structure [$/kW]	14.88
Time of Use Demand Charge Structure	
Period 1 (P1) [$/kW]	0
Period 2 (P2) [$/kW]	6.41
Period 3 (P3) [$/kW]	23.24
Demand Reactive Power Charge [$/kVAr]	0.51
Tiered Energy Usage Charge Structure	
Period 1 (P1) [$/kWh]	0.06426
Period 2 (P2) [$/kWh]	0.08397
Period 3 (P3) [$/kWh]	0.05902
Period 4 (P4) [$/kWh]	0.08222
Period 5 (P5) [$/kWh]	0.1351

infrastructure to be studied, but always the maximum value of these does not exceed 50% of the total load. Furthermore, in Ref. [39] the authors describes the challenges and opportunities faced by hospitals in the event of a power outage, analysing and exploring different solutions to solve these problems. Thus, the authors state that it is necessary to establish a range of between 30% and 50% of all hospital energy as critical loads to ensure the essential operation of the hospital.

Thus, taking as a base load 50% of the total and taking into account, the new scenario in terms of energy caused by COVID-19 [10,14,40], it has been decided to increase the critical loads factor to 60%. Within the critical loads are different essential services such as the storage of medicines and vaccines for COVID-19, the continuity of vital surgical procedures, other non-interruptible loads (life support systems) and a small amount of energy needed to allow safe evacuation of the public from the building in case of failure of normal power. The resilience values introduced in the model are shown in detail in Table 5.

In addition, for a more complete analysis in terms of energy resilience, we will also assess the amount of time the optimised microgrid can survive grid interruptions over a year.

Finally, it is very important to highlight the role of quantifying the avoided outage costs when analysing a resilience investment. That is, the avoided outage costs are the losses that the site would experience if the critical load were not covered [31]. This is probably the most difficult value to quantify, due to lack of data and government policy [41]. In order to quantify this, the most common parameter used is the value of lost load (VoLL), which can include loss of assets, damage to machinery, business outage costs and outage costs [42], which is expressed in $/kWh. Therefore, the avoided outage costs are calculated by multiplying the value of the lost load (VoLL) in $/kWh by the average number of hours that the critical load can be fed by the microgrid, and multiplying by the average critical load [31].

For the purpose of this analysis, a value of the lost load (VoLL) of $12.7 per kWh has been considered. This value is taken from Ref. [43], for an outage of 16 h. It is necessary to indicate that our outage has a duration of 24 h, so the VoLL for our case may have a higher value, since it covers a total of 8 h more than the 16 h of the chosen value. However, due to the complexity of quantifying the VoLL, it has been decided to take the closest value specified in Ref. [43].

2.3.4. *Financial parameters*

A period of 20 years has been selected for the financial analysis, which is the time we have considered to be the useful life of the main equipment that forms the microgrid.

On the other hand, we have assumed an increase in the nominal cost of electricity of 2.3% and an increase in the nominal cost of fuel of 2.7%. Table 6 shows in detail the financial values introduced in the model.

2.3.5. *Photovoltaic system*

To obtain the electricity generation produced by the PV system, REopt® uses the PVWatss application of the NREL [31]. The total energy produced by the PV system at any given time is proportional to the

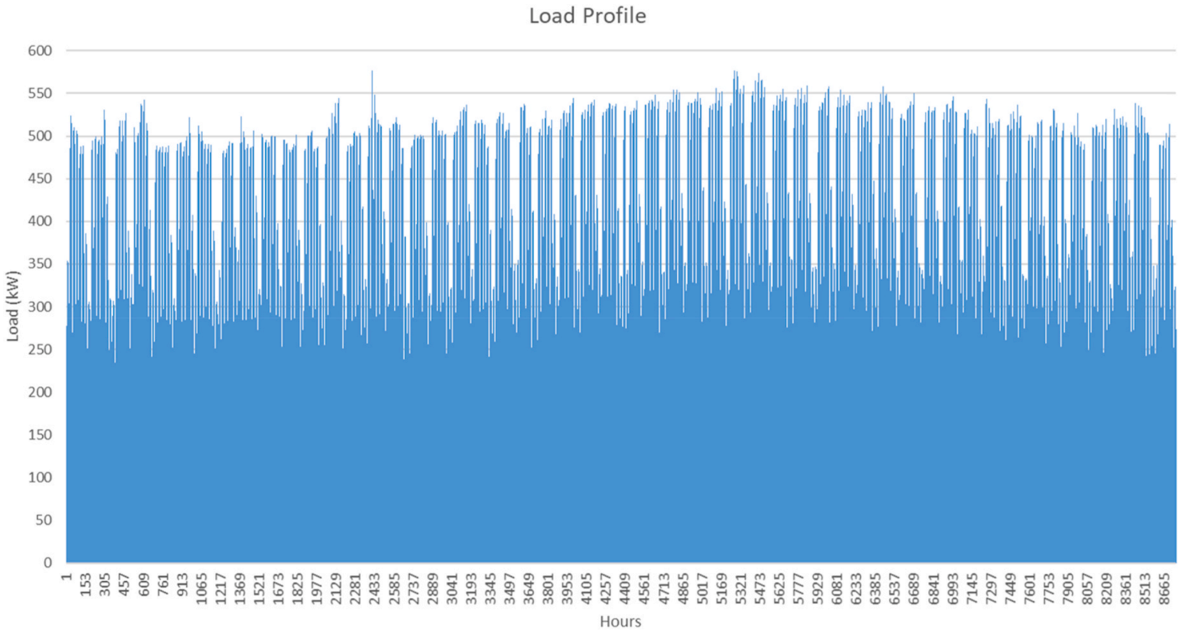

Fig. 2. Annual load demand of the hospital. Source [36,37].

Table 4
Inputs and outputs related to the load profile. Source: Own elaboration.

Load profile		
Parameters	Value	Reference
Building type	Hospital	–
Load profile	Simulated	[37]
Annual energy consumption (kWh)	3,228,120	[36]

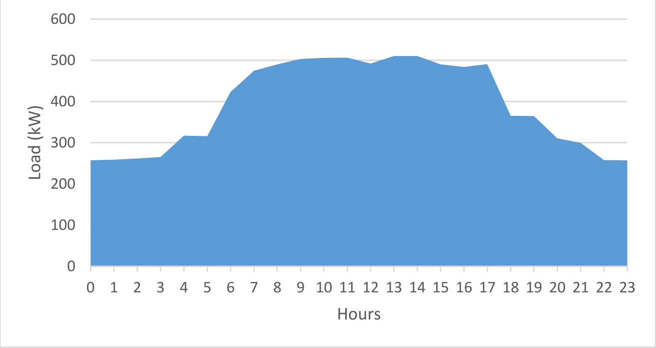

Fig. 3. Typical 24 h load profile for a week day.

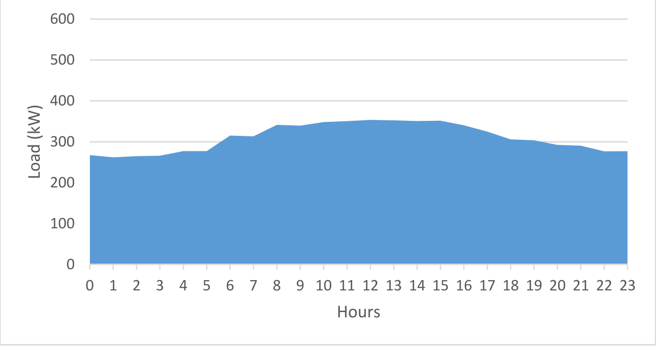

Fig. 4. Typical 24 h load profile for a weekend.

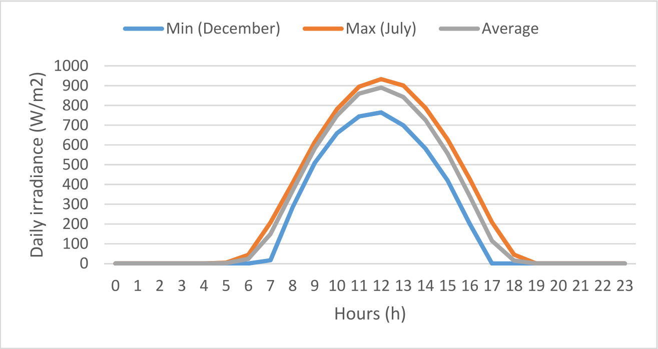

Fig. 5. Daily irradiance for minimum, maximum and average month.

hourly capacity factors of the site. Fig. 6 shows the monthly radiation levels for the town of Chino, California and it can be seen that the month with the lowest radiation is December, the month that will be chosen for the study of the energy resilience scenario. The solar radiation data has been obtained from PVGIS®, an online tool developed by the Joint Research Centre of the European Commission [46].

For this analysis we have assumed that the photovoltaic modules will be of standard type and that they will be installed on the roof of the building, they will be anchored to it by using specialised photovoltaic structures for roofs and will have an orientation of 0° to the South and an inclination of 10° with respect to the roof's ground.

According to Ref. [44] an investment cost of 1,600 $ per kW installed and a system O&M cost of 16 $ per kW installed has been assumed. In addition, we have assumed overall system losses of 14%, caused by soiling, shading, mismatch, wiring, light-induced degradation (LID), availability, etc. Table 7 shows in detail the values related to the PV system introduced in the model.

2.3.6. *Energy storage system*

Energy storage technologies are aimed to capture revenue through different alternatives such as: i) demand cost reduction or "peak shaving"; ii) time-shifting excess renewable energy production; iii) performing energy arbitrage [31].

For the analysis we have assumed that the energy storage system is

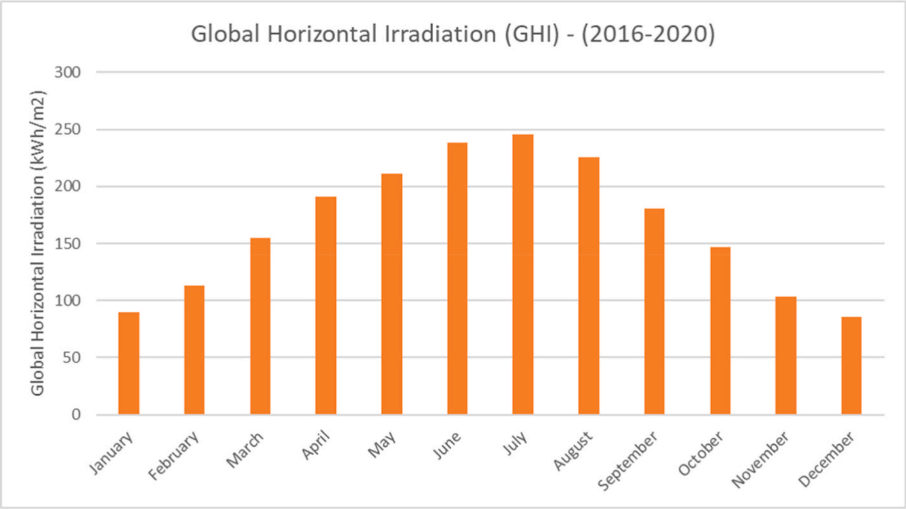

Fig. 6. Average global horizontal irradiation in Chino, US. Source [46].

Table 5
Inputs and outputs related to the resilience. Source: Own elaboration.

Resilience		
Parameters	Value	Reference
Critical load factor (%)	60	–
Outage durations (hours)	24	–
Outage start date	December 18	–
Outage start time	1 a.m.	–

Table 6
Inputs and outputs related to the financial analysis.

Financial		
Parameters	Value	Reference
Analysis period (years)	20	–
Nominal host discount rate (%)	8.3	[44]
Nominal electricity cost escalation rate (%)	2.3	[45]
Nominal generator fuel cost escalation rate (%)	2.7	[45]
Host effective tax rate (%)	26	[44]
O&M cost escalation rate (%)	2.5	[44]

Table 7
Inputs and outputs related to the PV module.

Solar PV module		
Parameters	Value	Reference
System capital cost ($/kW)	1,600	[44]
Minimum new PV size (kW DC)	0	–
Maximum new PV size (kW DC)	Unlimited	–
O&M cost ($/kW per year)	16.0	[44]
Module type	Standard	[47]
Array type	Rooftop, Fixed	[47]
Array azimuth (deg)	180.0	[47]
Array tilt (deg)	10.0	–
DC to AC size ratio	1.2	[47]
Systems losses (%)	14.0	[47]
Federal percentage-based incentive (%)	26.0	[48]
Incentive duration (yrs)	1	[48]
MACRS schedule (yrs)	5	[48]
MACRS bonus depreciation (%)	100	[48]

based on the characteristics of a lithium-ion battery. REopt® models energy storage systems as "reservoirs", where the energy produced at one point in time can be consumed at another time [32]. We have also assumed a minimum state of charge (SoC) of 20%, while a value of 50% has been taken for the initial state of charge. According to K. Mongird et al. [49], the lifetime of lithium batteries is in the range of 10–20 years. In this case, it has been considered that the grid can charge the batteries if necessary. Table 8 shows in detail the values related to the energy storage system introduced in the model.

2.3.7. *Back-up diésel generator*

For the analysis, it has been assumed that the hospital has a back-up unit consisting of a 400 kW diesel generator. We have assumed that the generator has a tank capacity of 660 gallons (2,498.37 L) and a lifetime of 10 years. The back-up diesel generators will not involve any capital cost, as they are already in place.

The diesel generator will only operate in the event of an outage in the electricity grid, as by law it can only be operated in emergencies [32] to supply the critical loads of the building. Table 9 shows the detailed values entered in the model.

3. Results and discussion

This section presents the main results obtained from the different simulations carried out using REopt® software. Two different scenarios have been considered in this study.

Table 8
Inputs and outputs related to the energy storage system.

Energy storage system		
Parameters	Value	Reference
Energy capacity cost ($/kWh)	420.0	[50]
Power capacity cost ($/kWh)	840.0	[50]
Allow grid to charge battery	Yes	–
Minimum energy capacity (kWh)	0.0	–
Maximum energy capacity (kWh)	Unlimited	–
Energy capacity replacement cost ($/kWh)	200.0	[50]
Energy capacity replacement year	10	[51]
Power capacity replacement cost ($/kW)	410.0	[50]
Power capacity replacement year	10	[51]
Minimum power capacity (kW)	0.0	–
Maximum power capacity (kW)	Unlimited	–
Rectifier efficiency (%)	96.0	[52]
Round trip efficiency (%)	97.5	[52]
Inverter efficiency (%)	96.0	[52]
Total AC-AC round trip efficiency (%)	89.9	[52]
Minimum state of charge (%)	20.0	[52]
Initial state of charge (%)	50.0	–
MACRS schedule (yrs)	7	[53]
MACRS bonus depreciation (%)	100	[53]

Table 9
Inputs and outputs related to the back-up generator.

Generator		
Parameters	Value	Reference
Install cost ($/kW AC)	500.0	[54]
Diesel cost ($/gal)	3.0	[54]
Fuel availability (gallons)	660.	[55]
Existing diesel generator	Yes	–
Existing diesel generator size (kW)	400.0	–
Fixed O&M cost ($/kW per year)	10.0	[54]
Variable O&M cost ($/kWh)	0.0	[54]
Fuel burn rate (gallons/kWh)	0.076	[56]
Generator replacement year	10	–

- **Normal operation of the grid.** This scenario will serve as an introductory thread, as the main objective of the study is to analyse the energy resilience provided by the microgrid. Thus, only the optimal sizing and dispatch of the microgrid will be analysed from purely economic criteria, without any resilience requirements. It should be specified that this scenario does not take into account the presence of a back-up diesel generator.
- **Optimal sizing of a microgrid with resilience requirements.** This is the main scenario of the paper and the one on which we have spent the most effort. In this scenario, the hybrid microgrid will be optimised with the consideration of feeding the critical loads during a 24-h outage in the month of December. This scenario aims to analyse the following aspects: i) optimal sizing and dispatching of the microgrid for a 24-h outage; ii) the analysis and comparison of the amount of time the microgrid optimised by REopt® can survive grid outages over the year compared to the BAU case; iii) the economic valuation of the energy resilience provided by the microgrid. For this scenario, the existence of a 400 kW back-up generator at the hospital has been assumed.

The main characteristics of these scenarios can be seen in Table 10.

3.1. Scenario 1: Normal operation of the grid

As mentioned above, the main objective of this scenario is to obtain the optimal sizing and energy dispatch of the microgrid, consisting only of a photovoltaic system and an energy storage system, from an economic point of view. Consequently, the microgrid is optimised to maximise the economic benefits during its normal grid operation.

Table 11 summarises and compares the techno-economic parameters of the financial case with the Business as Usual (BaU) case. The results provided by REopt®, in relation to the optimal size of the microgrid, shows that the simulated hospital is able to minimise its energy cost by installing a microgrid based on a photovoltaic system of 796 kW peak power and an energy storage system of 263 kWh capacity and 115 kW nominal power. Before the installation of the microgrid, the simulated hospital presented an average annual energy supplied by the grid of 3,228,120 kWh, after the installation of the microgrid, the grid supply has become a value of 2,090,512 kWh. In this way, the microgrid provides to the hospital with 35% of the total annual energy consumed and a saving in the electricity bill of $146,295 per year.

For this scenario, the main financial results provided by REopt® that will be taken into account are: i) Net Present Value (NPV); ii) Payback period; iii) Levelized Cost of Energy (LCOE). First, when we refer to Net Present Value (NPV), we refer to the difference between the life cycle cost of the optimised case and the life cycle cost of the Business as Usual (BaU) case [31], case without the microgrid installation. The life cycle energy cost without microgrid (BaU) is $3,580,027, while with the implementation of the microgrid proposed by REopt® it is $3,328,145. Thus, the Net Present Value (NPV) of the investment is $251,882. Second, the payback of the investment is 7.42 years. Finally, the Levelized Cost of Energy (LCOE) value is $0.071/kWh.

Table 10
Main simulation scenarios.

Scenario	Optimised from	Interruption duration	Diesel generator	Resiliency economic valuation
1	Economic perspective	N/A	No	No
2	Resilience perspective	24 h	Yes	Yes

Table 11
Techno-economic comparision between the BaU and Financial Case.

	Business As Usual	Financial Case	Diference
System size and energy production			
PV Size	0 kW	796 kW	796 kW
Battery Power	0 kW	115 kW	115 kW
Battery Capacity	0 kWh	263 kWh	263 kWh
Generator Size	400 kW	0 kW	400 kW
Average Annual PV Energy Production	0 kWh	1,175,086 kWh	1,175,086 kWh
Average Annual Energy Supplied From Grid in Year 1	3,218,106 kWh	2,090,512 kWh	1,127,594 kWh
Utility Cost (year 1) – Before Tax			
Utility Energy Cost	$ 248,609	$ 151,342	$ 97,267
Utility Demand Cost	$ 163,920	$ 115,710	$ 48,210
Utility Fixed Cost	$ 3,834	$ 3,834	$ 0
Utility Minimum Cost Adder	$ 0	$ 0	$ 0
Total Year 1 Utility Cost	$ 416,363	$ 270,886	$ 145,477
Life Cycle Cost			
CAPEX + Replacements	$ 0	$ 892,403	$ 892,403
O&M Costs	$ 34,912	$ 111,141	$ 76,229
Generator Fuel Costs	$ 11,731	$ 0	$ 11,731
Total Utility Electricity Cost	$ 3,573,007	$ 2,324,601	$ 1,248,406
Summary Financial			
Life Cycle Energy Cost (LCC)	$ 3,619,651	$ 3,367,769	$ 251,882
Net Present Value (NPV)	$ 0	$ 251,882	$ 251,882

Fig. 7 shows the optimised energy dispatch for the Chino Valley Medical Center after the installation of the optimised microgrid during its normal grid operation, both in the month of lowest solar radiation and in the month of highest solar radiation.

Fig. 7 (a) shows how the energy dispatch of the different technologies is carried out in the month with the lowest radiation. In general terms, the microgrid, consisting of the photovoltaic system and the energy storage, works in a coordinated way to cover the demand for electrical energy of the hospital, minimising the electrical energy imported from the grid. During the hours when there is solar resource in the month of lower solar radiation, the photovoltaic system alone is not able to cover the entire electricity demand of the hospital, so the grid supplies the remaining portion. As the objective of the microgrid is to meet the hospital's demand at the lowest possible cost, the energy dispatch provided by REopt® prioritises the production of the photovoltaic system over the energy storage, which only comes into operation at certain times of the day. Energy storage is discharged between 3-8 p.m. when photovoltaic generation is decreasing and the price of energy provided by the grid is still high, thus slightly reducing peak demand and achieving saving. Normally, the battery is charged when its state of charge (SoC) reaches its minimum value, which in this case is 20% and, on the other hand, it is usually charged from the grid when the cost of electricity is minimal. In this case, from 9 p.m. the price of electricity reaches a minimum value, at which time the battery is charged from the grid.

Fig. 7(b) shows the equivalent energy dispatch, but for the month with the highest solar resource. As can be seen, the behaviour of the microgrid is different with respect to Fig. 7(a). Between 9 a.m. and 1 p.m., the photovoltaic system is able to meet the entire electricity demand

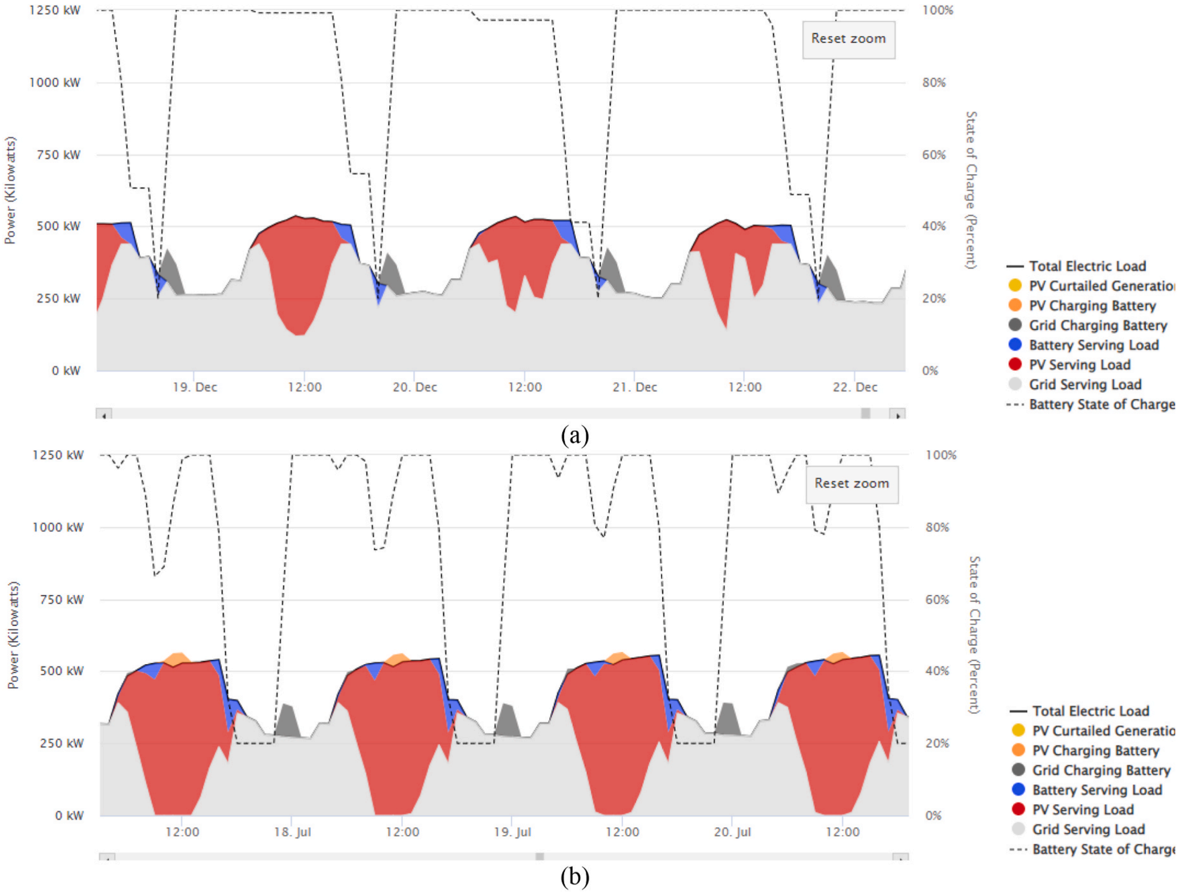

Fig. 7. Energy dispatch of microgrid under: (a) Winter and (b) summer.

of the hospital and even has surpluses that are used to charge the energy storage, something that did not happen in the previous case. During the night, it is the grid that provides the electricity supply. Energy storage injects energy both in the morning and in the late afternoon, when the price of energy is in periods of high prices and photovoltaic generation is losing importance due to the lack of solar resources in the late afternoon. Therefore, both in the month with the lowest solar resource and in the month with the highest, energy storage has performed the function of reducing peak demand (peak shaving) as well as energy arbitrage, charging from the grid at times when the price of energy is minimal, and from the photovoltaic surplus in the months with the highest solar resource, and injecting energy into the microgrid at times with the highest energy consumption and the highest energy price.

3.2. *Scenario 2: Microgrid with resilience requirements*

In this scenario, REopt® optimises the microgrid to meet the hospital's energy demand with the minimum life cycle, with the additional constraint that the hospital's critical load must be met during a 24-h outage period. A critical load for the hospital of 60% has been assumed. The simulation carried out for the resilience requirements suggests a microgrid consisting of a 799 kW peak power photovoltaic system and an energy storage system with 280 kWh capacity and 118 kW nominal power to complement the 400 kW diesel backup generator, which already existed in the hospital.

Table 12 summarises and compares the techno-economic parameters of the optimal case with resilience requirements with the Business as Usual (BaU) case. There is a decrease of 1,139,129 kWh in electricity demand from the grid. The life cycle energy costs of the optimal case have a value of $3,365,120, resulting in an NPV of $254,531. It is calculated as the difference between the life cycle energy cost of the Business as Usual (BaU) case and the life cycle energy cost of the optimised case [31], a positive NPV indicates that the project is economically feasible (see Table 13).

Table 12
Techno-economic comparision between the BaU and Optimal Resilience.

	Business As Usual	Optimal Resilience	Diference
System size and energy production			
PV Size	0 kW	799 kW	799 kW
Battery Power	0 kW	118 kW	118 kW
Battery Capacity	0 kWh	280 kWh	280 kWh
Generator Size	400 kW	400 kW	0 kW
Average Annual PV Energy Production	0 kWh	1,179,691 kWh	1,179,691 kWh
Average Annual Energy Supplied From Grid in Year 1	3,218,106 kWh	2,078,977 kWh	1,139,129 kWh
Utility Cost (year 1) – Before Tax			
Utility Energy Cost	$ 248,609	$ 150,334	$ 98,275
Utility Demand Cost	$ 163,920	$ 114,841	$ 49,079
Utility Fixed Cost	$ 3,834	$ 3,834	$ 0
Utility Minimum Cost Adder	$ 0	$ 0	0
Total Year 1 Utility Cost	$ 416,363	$ 269,009	$ 147,354
Life Cycle Cost			
CAPEX + Replacements	$ 0	$ 903,528	$ 903,528
O&M Costs	$ 34,912	$ 146,489	$ 111,577
Generator Fuel Costs	$ 11,731	$ 6,611	$ 5,120
Total Utility Electricity Cost	$ 3,573,007	$ 2,308,492	$ 1,264,515
Summary Financial			
Life Cycle Energy Cost (LCC)	$ 3,619,651	$ 3,365,120	$ 254,531
Net Present Value (NPV)	$ 0	$ 254,531	$ 254,531

Fig. 8 shows the optimised power dispatch during the 24-h power

Table 13
Hours of system survival.

	Business as Usual	Resilience
Survives Specified Outage	YES	YES
Average time	39 h	72 h
Minimum time	31 h	41 h
Maximum time	54 h	108 h

outage for the Chino Valley Medical Center facilities. In section 2. Materials and Methods the main inputs related to the resilience scenario are detailed. In summary, the blackout starts at 1:00 a.m. on 18 December and ends at the same time on 19 December. In order to be conservative, the case has been analysed for the worst-case scenario: the month with the lowest solar resource and the day of that month with the highest demand. Finally, it should be noted that during the outage, the hospital's electrical load decreases to its critical value, which has been set at 60%, 10% higher than the usual value used in energy resilience analyses for hospitals.

During the outage, the diesel backup generator plays a major role in the hours where PV generation is zero. Thus, it covers the entire critical load during the first hours of the outage, which correspond to the hours where solar generation is zero. On the other hand, energy storage plays a minor role in the energy dispatch. Energy storage feeds the critical loads of the hospital between 6 and 9 a.m., when photovoltaic generation is not yet high enough to meet the load on itself. Once the BESS reaches its minimum SoC value, it stops feeding the critical loads. From that moment on, the photovoltaic generation is responsible for supplying all the electricity to the hospital's critical loads, allowing the back-up diesel generator to stop operating. During the period when the photovoltaic system has surplus energy, this surplus energy is used to charge the energy storage. The back-up diesel generator comes back on line at 1 p.m. with a minimal role, and it supplies the hospital's entire electricity demand from 4 p.m. onwards, when the photovoltaic generation reaches its minimum generation. From this moment, the back-up diesel generator supplies the full load until the end of the outage. One aspect that should not be ignored is how in the last 2 h of outage, the energy storage system enters into operation for two main reasons. On the one hand, it reduces the electrical demand of critical loads, thus applying peak shaving and making the back-up diesel generator save fuel in the last 2 h of the outage period. On the other hand, the time when the outage ends corresponds to the time when energy has a lower price, so the energy storage system takes advantage of the last 2 h to discharge to the maximum allowed and once the outage period is over it continues with its operating strategy, which is to charge from the grid in the hours when energy has a minimum economic value. This behaviour has been detailed in the previous scenario, highlighting the role of energy storage as a method of energy arbitrage and peak shaving.

The microgrid scheme provided by REopt® allows the hospital to "survive" the 24-h outage (see Fig. 8.), providing a secure power supply, which allows to continue with the main activity of the hospital centre. It should be noted that the microgrid has been optimised to supply the critical loads of the hospital during a specific outage period, but as both the load profile of the hospital and the solar resource are variable throughout the year, the microgrid may not be able to sustain the same outage at another time in the year. Therefore, in order to ensure that the microgrid meets resilience requirements throughout the year, we have simulated that outages occur from every hour of the year (8,760 simulations) and REopt® has calculated the amount of time the microgrid can sustain the critical load during every outage [31].

The results are shown in Table 12, and indicate that not only does our microgrid withstand the outage we have proposed, but it is capable of

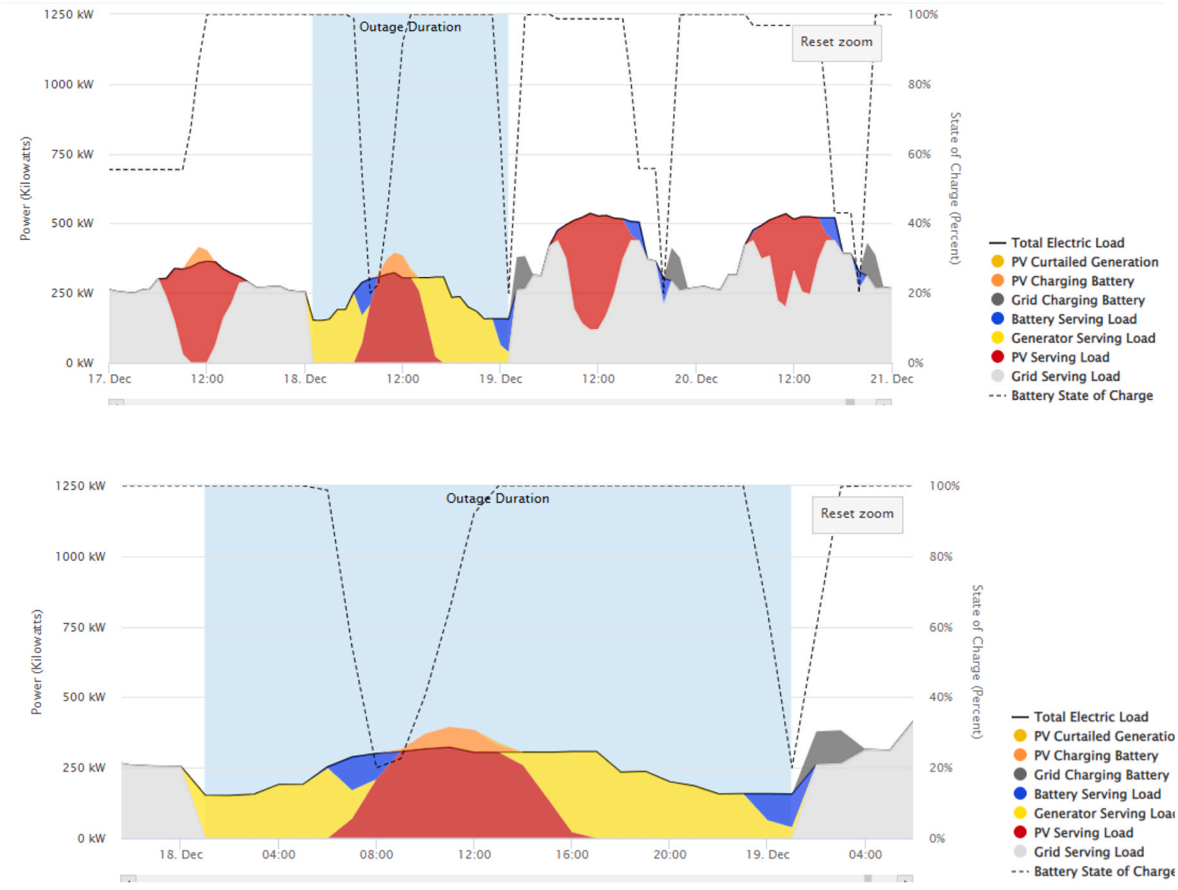

Fig. 8. Energy dispatch on December 18th with a blackout at 1 a.m. for 24 h.

withstanding in all cases an average of 72 h of energy self-supply capacity, with a maximum of 108 h and a minimum of 41 h, much higher than the business as usual (BaU) case.

Through this simulation, we have also observed how the addition of the microgrid consisting of a photovoltaic system with 799 kW peak power and an energy storage system with 280 kWh capacity and 118 kW nominal power to the existing installation, consisting of a 400 kW diesel backup generator, has increased the net resilience of the Chino Valley Medical Center. The Fig. 9 shows the number of outage hours that business as usual (with only the 400 kW backup generator) can withstand compared to the optimised microgrid (combination of photovoltaic system, energy storage and existing generator). Considering a fixed fuel supply and that no additional fuel supply is made during the outage, business as usual (BaU) has a 90% probability of surviving simulated outages of over 34 h. In the optimal case (Microgrid + Backup diesel generator), there is a 90% probability of surviving the simulated outages of over 58 h. Thus, by implementing the microgrid, the hospital achieves a net gain in resilience of 24 h compared with business as usual (BaU), this is due to the decrease in fuel consumption, because during the hours where the PV generation is able to supply the critical loads on its own, the backup diesel generator does not operate, avoiding higher fuel consumption and extending the survival time of the system as a whole.

In most cases, attention is only focused on the question of whether the optimised microgrid is able to "survive" the outage period introduced and, on the other hand, whether it is economically viable over its lifetime, by comparing the Net Present Value (NPV) of the business as usual (BaU) case with the value of the optimal case. However, the economic benefits that can be gained from investing in an energy resilient system are neglected.

Therefore, in order to have a picture of the economic benefits in terms of energy resilience, it is necessary to put a financial value on the avoided outage costs of the microgrid. As explained in section 2.3.3, in order to quantify these avoided costs, it is necessary to apply the following mathematical equation (1):

$$Avoided\ outage\ costs = VoLL \cdot Hrs_{average} \cdot Load_{average} \cdot \%_{critical\ load} \tag{1}$$

A value of lost load (VoLL) of \$12.7/kWh, an average survival period of 72 h, an average hospital consumption of 368.51 kW and a critical load factor of 60% have been considered. All these data can be found in detail in section 2. Materials and Methods. The Fig. 10 shows the result obtained. Therefore, the avoided outage costs amount to a total of \$202,179, which translates into an increase in the Net Present Value of more than 79% with respect to the Net Present Value of the case without valuing the energy resilience provided by the microgrid.

Finally, it should be noted that the results obtained do not take into account the costs of investment in additional hardware and software to make the microgrid work in both grid-connected and island mode. But we would like to make it clear that these costs can vary widely and can range from a minimum of 10% and a maximum of 50% of the total cost of the non-islandable system cost [19]. Thus, N.D. Laws et al. [19], investigates how to quantify the cost of investing in a microgrid that can work in island mode and determines that, although it is a difficult task, it is possible to establish a maximum cost that allows us to know whether or not the investment is economically viable compared to the case without island mode. Therefore, the maximum investment cost of an islanded microgrid is the NPV of the scenario with valued resilience (outage costs avoided), minus the NPV of the scenario without valued resilience (no outage costs avoided).

4. Conclusions

The aim of the research presented here is to evaluate the energy resilience, in strictly economic terms, provided by a microgrid during a 24-h outage of the electricity grid. The pandemic caused by COVID-19 has led to changes in many sectors of the economy and society, one of them being the health sector. The high number of patients hospitalised due to COVID-19, together with the massive vaccination campaigns carried out in hospitals, has led to an increase in energy demand and with it an increase in both their critical loads and the need to supply them in the event of possible network outages. In this situation, a hospital has been taken as a case study, in which two scenarios with different approaches have been analysed using the simulation tool REopt®. A first scenario, without any resilience requirements, where the size and optimal energy dispatch of the microgrid in the month of lowest and highest solar radiation has been analysed. The results of the analysis have shown how a microgrid consisting of a 796 kW photovoltaic system and an energy storage system with 263 kWh capacity and 115 kW nominal power is able to provide an NPV of \$251,882. It has also been

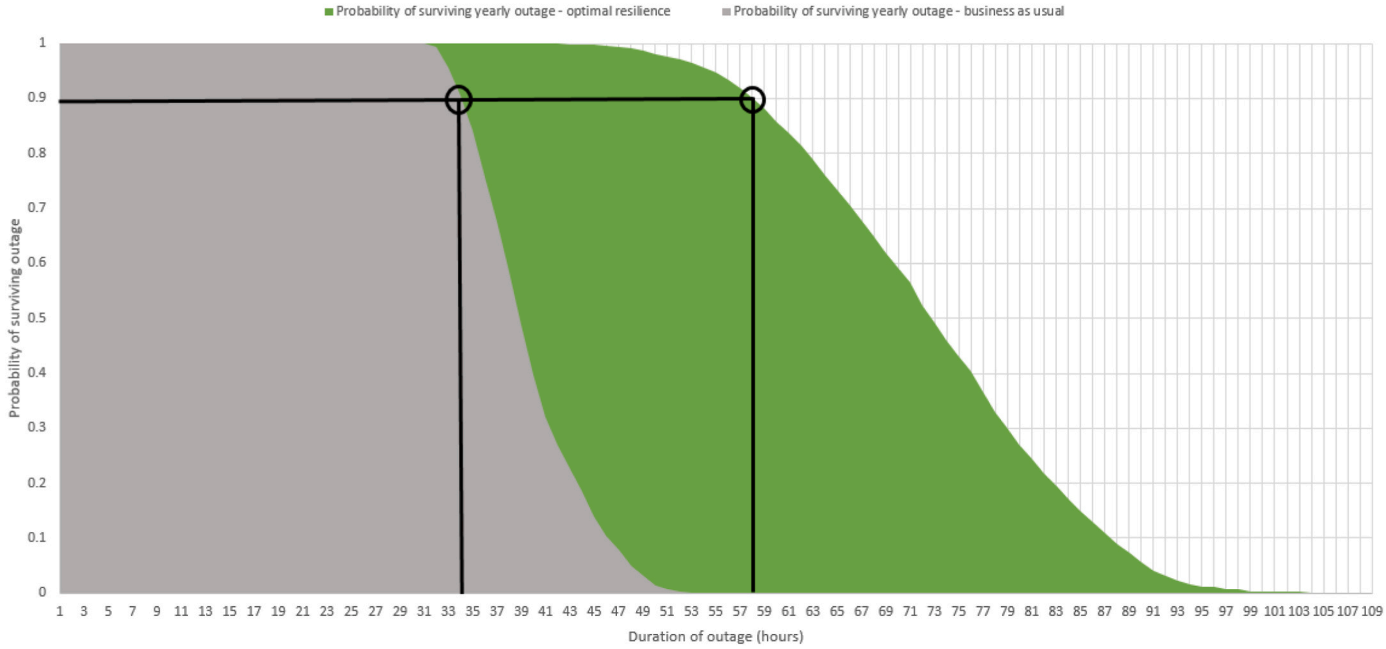

Fig. 9. Outage survival probability for the optimal resilience and business as usual cases. Source: Own elaboration.

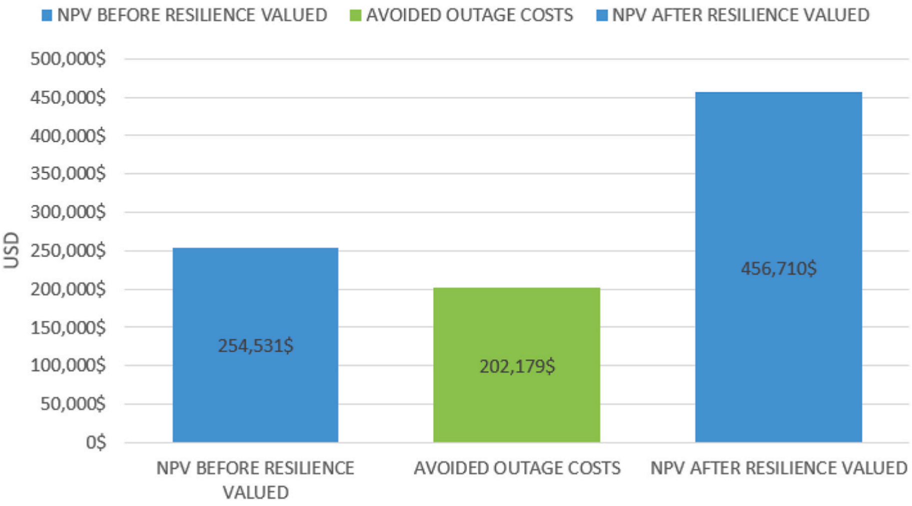

Fig. 10. Effect of resilience costs and benefits. Source: Own elaboration.

shown that only in months of high solar radiation the energy storage is charged from the PV system, while in months of low solar radiation the energy storage is only charged from the grid when energy prices are at their lowest. For the second scenario with resilience requirement, not only a 24-h outage has been introduced in the month of lowest solar radiation and on the day of highest load, but also, due to COVID-19, the critical load factor of the hospital has been increased to 60%. Thus, the results have shown that the microgrid optimised by REopt® is able to provide an NPV of $254,531 over its 20-year lifecycle and is not only able to withstand the specified outage, but is able to withstand it at any time of the year, providing the hospital with a net gain of 24 h in terms of energy resilience compared to business as usual case (BaU), thanks to the reduction in fuel consumption during grid outages. If the net gain provided by the microgrid is to be made profitable, the avoided outage costs should be valued. The quantification of these costs and their posterior analysis have resulted in an increase of 79% of the NPV. To summarise, it has been observed that the different variables introduced in the model and the different approaches play a critical role in determining the viability of a microgrid, so each case study must be evaluated individually. Finally, for future research work, it would be interesting to establish a methodology to quantify the additional costs involved in upgrading the microgrid to enable it to operate in island mode during an outage of the grid, providing a more objective view when deciding on the investment.

CRediT authorship contribution statement

Josep Hervás-Zaragoza: Data curation, Writing – original draft, Simulation. **Antonio Colmenar-Santos:** Conceptualization, Methodology, Writing – review & editing. **Enrique Rosales-Asensio:** Supervision, Writing – review & editing. **Lucía Colmenar-Fernández:** Conceptualization, Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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