Solar-plus-storage benefits for end-users placed at radial and meshed grids: An economic and resiliency analysis

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Abstract

A resilient photovoltaic system, which comprises from the joint use of photovoltaic solar panels and electrochemical storage that is able to operate both with and without grid connection, is capable of providing an added service both during normal grid-connected operation and when a blackout occurs (as opposed to a traditional solar system). When the conventional power grid is in normal operation, resilient photovoltaic systems are able to generate revenue and/or reduce the electricity bill. During blackouts, resilient photovoltaic systems are capable of providing critical emergency power to help backup diesel generator systems. The research presented here evaluates the technical and economic feasibility of systems based on photovoltaic solar energy and electrochemical storage in three critical infrastructures which have to account with a typical backup diesel generator. To this end, the research presented here assigns a monetary value to the cost of avoiding a blackout. Thus, the REopt Lite software has been used to optimally select and dimension different resilient schemes. For each of the cases evaluated the resilient systems were able to obtain benefits associated with the substitution of the energy use of the electricity grid, the reduction of charges for the use of energy during peak energy periods, and the modification of energy purchase periods from periods of high cost to periods of low cost. For all cases the model found the optimal combination of technologies capable of minimizing the cost of energy throughout the life cycle of the project. The obtained results show that assigning a value to the cost of blackouts can have a major impact on the economic viability of a resilient solution. For all cases the net present value of a system was always higher when a value was assigned to resilience. The values assigned to resilience were higher for users plugged to radial networks, which are more prone to blackouts, and lower for users connected to meshed grids, usually more reliable. Despite the fact that for the investigation presented here only three types of infrastructures were assessed, similar results could be expected for other critical infrastructures with similar loads and electricity tariffs. Resilient systems using photovoltaic solar installations that are limited in size could provide both economic savings during normal grid-connected operation and limited emergency power during blackouts. When these systems based on photovoltaic solar energy and electrochemical storage are used in conjunction with an emergency diesel generator, these resilient "hybrid" systems are capable of satisfying critical loads during short- and long-term blackouts.

Keywords Solar-plus-storage; radial grid segments; network grid segments; economic analysis; resiliency analysis

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Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CAIDI	Customer Average Interruption Duration Index
DCO	Distribution Company
DoE	Department of Energy
FDNY	Fire Department of the City of New York
GW	Gigawatt
ICE	Interruption Cost Estimator
MEP	Mechanical, electrical and plumbing
NPV	Net Present Value
NYPD	New York City Police Department
PV	Photovoltaics
SAIFI	System Average Interruption Frequency Index
U.S.	The United States of America

1. Introduction

The resilience of electrical systems focuses on preventing power outages, protecting life and goods dependent on the electricity service [1] as well as minimizing the time needed to restore service and recovering the electricity supply [2]. As climate change leads to increasingly severe and frequent devastations around the world, strengthening the resilience of energy infrastructure has become an urgent priority [3,4], particularly in shelters, hospitals and emergency supply stores [5]. Although standby power sources usually run on gas and diesel generators [6], the use of microgrids also has potential applications in terms of energy resilience and safety [7].

Total losses resulting from natural disasters in the United States have exceeded $50 billion per year in five out of the ten years from 2003 to 2013 [8]-note the fact that, on average, those countries with longer durations of power outages experience higher scale losses [9]. In some cases, the lack of backup power has meant that it has been impossible to feed critical loads for several days [10]. As far as fuel supply is concerned, it should be borne in mind that, although pipelines are highly resistant to inclement weather, they have the drawback of potentially being able to break or be damaged - this would have to be closely monitored to prevent any small problem from becoming a major problem if there is an interruption in fuel supply [11]. Finally, it should also be noted that weather phenomena combined with outdated infrastructure could increase the risk of blackouts [12].

Including major storms, the average duration per affected customer for radial networks in New York in the period between 2012 and 2016 was 35.28 hours on average per year; while this value for meshed networks in New York during the same period was just 7.9 hours on average per year. That said, in 2012 the average duration per affected customer was 102.05 hours and 6.33 hours, respectively [13]. As part of the 2011 reliability report, the Consolidated Edison Company of New York identified a total of six major storms affecting customers connected to radial networks and four winter snow/ice events affecting customers connected to meshed networks [†][14].

During Hurricane Sandy events, it should be noted that after large portions of New York City suffered a power outage at approximately 8:00 PM on Monday, October 29, 2012, the city deployed as many generators as it could to satisfy a demand that exceeded the number of requests for any other incident [15]. In total, the city deployed approximately 230 generators in hospitals, nursing homes and large multi-family buildings [15].

As far as New York City is concerned, the amount of hazardous materials stored and used temporarily cannot exceed 5 gallons of gasoline, or 250 gallons of any other flammable liquid, and 300 gallons of any combustible liquid-the storage or use of hazardous materials in greater quantities requires a specific permit for each place where such storage or use occurs [16]. Assuming a building equipped with a 175 kW diesel generator, a 250 gallon (946 liters) fuel tank and a consumption of 10.5 gallons/hour (40 liters/hour) [17], the fuel would run out in less than 24 hours.

Overall, for three days after Sandy, all fuel terminals in the New York metropolitan region were completely out of service [18]. Even 10 days after the storm, only 79 percent were operational [18]. As a result of Hurricane Sandy, New York required substantial amounts of fuel for critical energy restoration and emergency public transportation [19]. In this case, the Federal Emergency Administration, as a result of the consequences of this hurricane, had to pay 6.37 million dollars for 1.7 million gallons of gasoline [19].

These types of disasters cause widespread and long-lasting disruptions and lead to loss of production, wages and inventory [20]. Between 2003 and 2012, climate-related disruptions are estimated to have cost to the U.S. economy an annual inflation-adjusted average from $18 trillion to $33 trillion. Annual costs fluctuate significantly and are highest in the years of major storms, such as Hurricane Ike in 2008, when cost estimates ranged from $40 to $75 billion, and Hurricane Sandy in 2012, when cost estimates ranged from $27 to $52 billion [21]. In the event of a power outage affecting end-users, such as hospitals, electronic medical equipment can cease to function and thus, the effect on patients could be fatal [22]. Although it is impossible to make a precise estimate of the cost of blackouts [23,24], that cost undoubtedly exists.

The current cornerstone of resilience, a backup capacity provided by fossil fuel generators, is useful for overcoming short outages, but for longer ones these systems are vulnerable to fuel supply chains that may be, and have been, compromised due to physical damage to transport and distribution infrastructure [20]. Moreover, emergency diesel generators have a finite reliability which must be considered and, due to its non-continuous operation, cannot be measured through the commonly used reliability metrics [25]. Even using specific metrics for well-maintained emergency diesel generators, they are only 80% likely to provide power for the duration of a two-weeks grid outage [25].

Hybrid renewable energy systems (combinations of PV systems, electrochemical batteries and diesel generators) can serve as an alternative or complement to existing forms of backup power, extending the limited supply of fuel and providing greater system redundancy [20]. A renewable energy hybrid system can withstand longer interruptions for a given amount of diesel fuel by reducing the operating time (and therefore fuel consumption) of the diesel generator, thereby increasing the site's energy resilience [20]. A hybrid renewable energy system can also expand the scale of available backup energy by extending backup power to loads that would not otherwise be powered [20]. In addition, these hybrid renewable energy systems can be operated for economic gain when the network is in operation, offsetting energy purchases, reducing peak demand charges,

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[†] In electricity grids, most of the connected loads are normally concentrated in distribution systems, which generally consist of radial feeders. One consequence of the use of radial feeders is that many customers may be affected in cascade by the failure of a single component.

performing energy arbitrages and providing ancillary services [20]. In addition, other smaller-scale renewable resources, such as biomass, and hydropower, can also complement solar energy by providing rapid-dispatchable back-up energy, base-load (biomass and run-of-river hydropower stations) or peak-load (hydropower plant with reservoir) energy similar to that provided by fossil and nuclear energy sources [26].

Currently, traditional photovoltaic systems are configured to shut down during power outages as anti-islanding protections prevents their operation [27]. This configuration protects the safety of the workers of the electricity distributors [27]. However, if configured to enhance resilience, photovoltaic solar energy can continue to operate and supply power during power outages [27]. There are three standard ways to make PV resilient [27]:

1. Coupling solar modules with batteries to store energy for later use (this is known as photovoltaic solar energy with battery backup).
2. Coupling solar energy with auxiliary generation, like a diesel generator.
3. Using an inverter with an emergency power socket that provides limited power.

It should be noted that the addition of battery storage to photovoltaic solar panels (i) can improve the viability of projects by reducing the costs associated with electricity demand as well as (ii) serve as an opportunity to align the sustainability and resilience goals of cities [28]. In most solar photovoltaic + storage applications, investors are responsible for (i) making decisions about charging batteries, (ii) providing electricity to the load, and/or (iii) providing electricity to the grid [28]. With the right switches, inverters also allow photovoltaic panels and storage (and/or other distributed generators) to function as an "isolated" autonomous microgrid, providing electricity to an individual building or community [29].

Between 2011 and 2016, New York increased its use of solar energy by almost 800% [30]. The State Energy Plan is a comprehensive roadmap for building a clean, resilient and affordable energy system for all New Yorkers [31]. The initiatives outlined in the State Energy Plan, along with private sector innovation and the investment driven by "Energy Vision Reform", will put New York State on track to achieve 50% of electricity from renewable energy sources [31] and expand New York's distributed solar energy target by 2025 to 6 GW [32].

Electricity storage systems allow higher levels of intermittent renewable generation, which can help overcome the barriers associated with new renewable energy projects [33]. Solar energy and storage are strongly synergistic, with combined net present values that are significantly higher than the sum of individual net present values for solar energy and storage alone [34]. Distributed energy resources, such as energy storage and combined solar storage systems, are increasingly valuable both to the New York grid and to the commercial and industrial energy consumers who depend on it [35]. The ability of commercial and industrial energy consumers to generate, store, consume and share low-cost energy can significantly offset energy costs, while making the network cleaner and less costly to operate [35]. With the goal of expanding New York's distributed solar power by 2025 to 6 GW [32], the research presented here aims to conduct an economic and resilience analysis of the benefits of introducing photovoltaic solar power and storage in end-users located in radial and meshed networks.

In the scientific literature, it is possible to find a large number of research papers exploring how to improve the resiliency of electricity grids by using microgrids. Among the most notable may be those carried out by Panwar *et al.*, who used a real-time resiliency framework for analysis and sizing of energy storage [36]; Mohagheghi and Rebennack who studied a two-stage stochastic and nonlinear optimization model for operating a power grid exposed to a natural disaster [37]; Shahid *et al.* who, in order to improve the resilience of the microgrids control, a distributed consensus-based control was utilized by spreading an information network across the small distribution grid [38]; Rocchetta and Patelli who proposed a framework for advanced uncertainty quantification and vulnerability assessment of power grids [39]; Barnes *et al.*, who developed a method to evaluate the benefits of networked microgrids for improving resilience [40]; Ilo who presented an architecture for smart grid operations that matches the electricity market rules and the cyber security and privacy requirements [41]; Khomami and Sepasian, who proposed a new method for restoration and emergency reaction planning [42]; Hussain *et al.,* who proposed a three-step analysis in order to elaborate the role of microgrids in enhancing the resilience of power systems [43]; Ding *et al.*, who proposed a novel load restoration optimization model to coordinate topology reconfiguration and microgrid formation while satisfying a variety of operational constraints [44]; Lin and Bie, who presented a new tri-level defender-attacker-defender model for distribution system [45]; or the investigation conducted by Mousavizadeh *et al.*, who proposed a linear path-based approach to model the topological characteristics of the network [46].

Despite the previous studies, the solar-plus-storage benefits for end-users placed at radial and meshed grids from an economic and resiliency analysis have not been studied in a comparative way widely (just few studies such as [47]), so more studies that address both of them simultaneously are found to be necessary. From a deep survey of grey and the most recent scientific literature related to the topic, considering the existing different approaches, it was found that – the economic valuation of the power resilience in critical infrastructures, considering the connection to radial or meshed networks, may affect when optimizing for maximum financial benefits. Thus, this paper undoubtedly contributes to the pool of existing knowledge by giving an economic and resiliency analysis of solar-plus-storage benefits for end-users placed at radial and meshed distribution power grids (to our knowledge, so far not addressed explicitly in the scientific literature). Moreover, to validate our conclusions, three different facilities worth of interest in case of natural disasters conducting to power outages have been analyzed and compared.

This first section briefly discusses the economic and resiliency benefits of using solar-plus-storage for end-users placed at radial and meshed grids; in the second section, the method used to conduct the research will be exposed; in the third section, case studies on the implementation of solar-plus-storage for end-users placed at radial and meshed grids will be presented and discussed; subsequently, in the fourth section, conclusions will be presented.

2. Facilities description

In order to carry out the research presented here, three typical sites with critical infrastructures were selected, in which the performance of installations with photovoltaic solar panels and battery storage could be evaluated. Within the set of possible critical infrastructures to be considered, high schools, fire stations and residences for the elderly were selected, due to their usual nature, especially in urban areas, and the feasibility of the installation of solar PV systems, with and without energy storage devices. The majority of the data used for the modelling of the three facilities is open access directly on the internet or through the DOE applications. For comparative reasons, similar modelling, analysis approach and facilities than those selected in [47] have been chosen. Appendix A summarizes the modeling assumptions used for each site.

2.1. Tottenville High School (100 Luten Avenue New York City, Staten Island, New York 10312)

Tottenville High School is located on Staten Island and served as a safe haven for the aftermath of Hurricane Sandy [48-52]. Considering the high school student body (3856 students), data provided by the U.S. Department of Energy and the New York City Climate Zone (ASHRAE Climate Zone 4A) it has been estimated the power load profile of the facility and, according to the model, an annual energy consumption of 1 883 392 kWh/year has been obtained. With respect to the months of May and September, peak loads do not increase during the summer months (late August/early September) due to holiday periods.

Tottenville High School is contracted at SC-9 - General Large Low-Tension Service [NYC] [53]. The institute of higher education is suitable for a net metering contract. In the absence of first-hand information, it will be assumed that Tottenville High School is a site that has two or more transformers to feed a single customer (spot network), which would require expensive additional equipment for the solar photovoltaic system to export surplus energy to the power grid. As a consequence, for the analysis carried out in the investigation presented here it will be assumed that a reverse power relay will be used to prevent the export of electricity.

The total area available on the roof for PV installation is 2632 m^2 (28 300 ft^2). According to [54], it has been estimated that the critical load of the facility is 10% of the total load. In the absence of first-hand information, it will be assumed that Tottenville High School does not have diesel generators as backup power.

2.2. 43rd Battalion, Engine 245, FDNY Ladder 161 (2929 West 8th Street, Greenwich Village, NY)

The 43rd Battalion, Engine 245, FDNY Ladder 161 is located at 2929 West 8th Street in Greenwich Village, and provides firefighting services [55]. These corps and the NYPD's 60th Precinct share a combined fire and police station built in 1971. The facility is approximately 0.25 miles north of Lower New York Bay and 0.25 miles south of Coney Island Creek [56]. The facility lost functionality during Hurricane Sandy because of significant damage to mechanical, electrical and plumbing equipment. Flood inundation was approximately 5 feet above grade and damaged interior finishes, contents, and equipment throughout the first floor. 45 days after Sandy, the FDNY was operating from the station on generator power. The fuel service station was still inoperable because they lacked power to pump fuel to vehicles.

Considering that fire stations are not one of the types of commercial reference buildings provided by the United States Department of Energy, this load has been assimilated to that of an apartment located in a low-rise building (to represent firefighter accommodation). For its part, and considering the climate zone of New York City (ASHRAE climate zone 4A), it has been estimated the power load profile of the facility and, according to the model, that the obtained annual energy consumption is 42 530kWh/year.

The 43rd Battalion, Engine 245, FDNY Ladder 161 has contracted the SC-9 - General Large Low-Tension Service [NYC] [53] rate. The fire station is ideal for a net balancing contract. It will be assumed that the 43rd Battalion, Engine 245, FDNY Ladder 161 is located on a radial network.

The total area available on the roof for PV installation is 485 m^2 (5210 ft^2).Based on [57,58] it has been estimated that the critical load of the fire station is 50% of the total load. These charges would include lighting charges, computers, telecommunications equipment and pumps to fill trucks with fuel. On the other hand, it will be assumed that the 43rd Battalion, Engine 245, FDNY Ladder 161 does not currently have any backup power.

2.3. Brighton/Manhattan Beach Senior Center (60 West End Av. Brooklyn, Brooklyn, NY 11235)

The Brighton/Manhattan Beach Senior Center is located at 60 West End Avenue Brooklyn, NY 11235. Hurricane Sandy left the senior center without power or heat from October 29, 2012 until January 2013 [59,60]. Moreover, the Brighton/Manhattan Beach Senior Center is considered by the New York authorities as a "high risk area" [61].

Considering that the Brighton/Manhattan Beach Senior Center has 148 residents [62], according to the recommended criteria provided by the U.S. Department of Energy, it has been assumed that the demand for a senior center can be assimilated to that of a midrise apartment. The New York City climate zone (ASHRAE climate zone 4A) conducted to estimate the annual energy consumption in 564 896 kWh/year, according to the estimated power load profile model.

The facility has contracted the SC 8 - Multiple Dwellings Redistribution TOD Service [NYC] [63] rate.

Moreover, it has been observed that this facility is suitable for a net metering contract. It is connected to a secondary network system with geographically separated network units and the network-side terminals of the network protectors interconnected by low-voltage cables that span the distance between sites. In this case the low-voltage cable circuits of the grid networks are supplied by numerous network units (i.e., the senior center is connected to an "area network") [64].

The total area available on the roof for PV installation is 1650 m^2 (17 760 ft^2). Based on [57] it has been estimated that the critical load of the fire station is 40% of the total load. It will be assumed that the Brighton/Manhattan Beach Senior Center does not currently have any back-up power.

3. Methodology

3.1. Economic evaluation of resilience

As Sullivan *et al.* [65] have found, the desire to accept measures to reduce vulnerabilities produces an estimated value greater than the desire to pay for such measures. The problem of evaluating resilience from an exclusive "electrical" perspective has been applied in most of the schemes based on photovoltaic solar energy and electrochemical storage connected to the conventional electricity grid, but the economic valuation of the provided resilience is usually neglected in the financial analysis [66, 67].

The research presented here provides, through the REopt Lite model [68-70], a monetary value for electrical resilience in order to evidence its impact on the design of the scheme and on the economics of the project. According to Anderson *et al.* [71], the monetary value of electrical resilience will be equal to the reduction in the cost of the electrical disturbance that a hybrid system based on renewable energies would provide. The cost of power outages depends, among other factors, on the number of users, the frequency of events and the vulnerability of users to them [72].

In the event that a hurricane affects critical infrastructure, it is possible for the following to occur cascading second-, third-, and fourth-tier effects stemming from the loss of power (for example in September 2017, Hurricane Irma caused significant damage to Puerto Rico; in this case water pumps shut off and water testing labs were affected, causing further delays in accessing safe, potable water) [73].

There are two different ways of quantifying power failure costs: the macroscopic method and the microscopic method [74]. In order to determine the resilience value of the facilities evaluated in the research presented here, the macroscopic method was chosen. This is because it is widely applicable and replicable at other facilities and could be applied without the need for lengthy data collection activities at the facility under analysis. In order to calculate blackout costs, the Interruption Cost Estimator (ICE) [75] was used to represent the value of electrical resilience at each site (using metrics relating to electrical reliability and the characteristics of these sites).

The ICE considers, among others, the average household income, the annual electricity consumption, the average duration of an individual interruption, or reliability indices such as the Customer Average Interruption Duration Index (CAIDI) [76].

Since 2005, the Department of Public Service of the New York State has published an annual report on the reliability of electric service [77]. The Public Service Commission relies primarily on two commonly used industry metrics to assess performance relative to reliability: the System Average Interruption Frequency Index (SAIFI) and the CAIDI or duration [77]. The frequency of blackouts (SAIFI) depends on whether the installation is in a meshed network or in a radial network. These values are summarized in Table 1. It must be noted that the SAIFI value is usually lower for meshed networks as, in case of power outage, customers can be served from different paths, while on radial networks, customers down stream the power outage are forced to suffer the blackout.

Table 1. Edison DCO five-year average SAIFI values for customers connected to radial and meshed networks. Source: [77]

Grid segment	**Number of Customers Affected Per Customer Served (SAIFI)**
Radial	0.45
Network	0.02

Table 2 shows two different values for the CAIDI: "including major storms" and "excluding major storms" (referenced in the technical analysis scenario respectively as "long-term" and "short-term" scenarios). This procedure imposes an upper and lower limit for the duration of blackouts for both meshed and radial networks, and establishes cases of short and long duration for the scenarios analyzed. As it can be seen in [78], CAIDI for 2012 (the year of Hurricane Sandy) was 71.91 h, but the 4-year average value for the period 2013-2016 was only 2.91 h. On the other hand, the estimated outages costs per kWh tend to decline as outage duration increases (both in commercial and industrial and residential scenarios), having power outage durations higher than 16 h almost negligible impact on the interruption costs [79, 80]. For this reason, as a compromise solution, and in order to deal with the possibility of repeating circumstances similar to those of 2012, it has been considered appropriate to assume a CAIDI value of at least 16 h per year for both radial and meshed networks within the "long" outage scenario. It can be observed that, for short duration power outages, the CAIDI value is shorter for radial networks than for meshed ones. This can be explained because, although more frequent, is typically easier to restore service in radial networks than on meshed ones.

Table 2. Edison DCO CAIDI values for customers connected to radial and meshed networks. Source: [77]

Grid type	CAIDI (hours/year)	Technical analysis scenario
Radial		
Average duration per customer affected excluding major storms (five years average)	1.92	Short
Average duration per customer affected including major storms (assumption taking into account the most restrictive year in the last five years, 2018)	16.00	Long
Network		
Average duration per customer affected excluding major storms (five years average)	7.77	Short
Average duration per customer affected including major storms (assumption taking into account, apart from the last five years, 2012 and Hurricane Sandy)	16.00	Long

The specific costs of interruptions (i.e. the annual value of resilience) were developed using ICE [75]. Using the metrics shown in Table 1 and Table 2 respectively, values for each of the proposed facilities have been calculated (see Table 3). The Unit Cost of Interruption is averaged over the 16 hours that the ICE is able to analyze to provide an average cost of interruption.

Table 3. Value of resiliency for study facilities. Source: Adapted from [75]

	Short outage scenario				**Long outage scenario**			
Site	**Cost per event (2016$)**	**Cost per average kW (2016$)**	**Cost per unserved kWh (2016$)**	**Total cost (2016$)**	**Value of resiliency provided (2016$/hour/year)**	**Cost per average kW (2016$)**	**Cost per unserved kWh (2016$)**	**Total cost (2016$)**
Tottenville High School	$ 4976.00	$ 1443.37	$ 185.76	$ 99.52	$ 9893.67	$ 2869.82	$ 179.36	$ 197.87
43rd Battalion, Engine 245, FDNY Ladder 161	$ 1050.49	$ 304.71	$ 158.70	$ 21.01	$ 9893.67	$ 2869.82	$ 179.36	$ 4452.15
Brighton/Manhattan Beach Senior Center	$ 4976.00	$ 1443.37	$ 185.76	$ 99.52	$ 9893.67	$ 2869.82	$ 179.36	$ 197.87

3.2. Financial and general hypothesis

Appendix A summarizes the modeling assumptions used for each site. From these assumptions, it must be highlighted the financial parameters. There is no common agreement in the literature on the choice of parameters, such as the discount rate or the costs escalation rates (which may affect the electricity and operation and maintenance costs). Moreover, some of these parameters may show great dispersion (e.g., the discount rate can be found in the range from 2.4% to 15%), depending on the case study. The chosen value of the discount rate must clearly be carefully evaluated, as it can modify the investment decision. It must be taken into account that the discount rate depends on the cost of capital, including the balance between debt-financing and equity-financing, and an assessment of the financial risk. Currently, the costs of financing are relatively low in most countries (i.e. in the USA, the latest discount rate is 0.25% according to [81]), but the political and social uncertainties rise the risk factor. In this case, a conservative value of 8.1% has been considered, observing that it is a value between the bounds and it is aligned with the consideration of long-term projects according to the U.S. Treasury borrowing rates and the average private sector return of investment [82]. In a similar way, it has been concluded that a realistic and acceptable cost escalation rate can be established around 2.5% (See Appendix A for further details).

On the other hand, on those scenarios where an Energy Storage System is considered, a simplified battery model has been used. The life expectancy of a battery is typically assumed to be between 10 and 12 years; as a result, amortized replacement costs can be included in the model. A battery may not last the entire time period (10 or 12 years), however, especially if it experiences an excessive number of deep charge/discharge cycles. Although degradation as a result of cycling can be included in the optimization model, it increases computational complexity. Therefore, the model implemented typically assumes a useful battery life of 10 or 12 years, based on calendar degradation; the dispatch is then post-processed using the rain-flow algorithm [83, 84]. to verify the assumption.

Regarding the diesel supply, less severe but more frequent incidents, affecting only the power supply of the facilities are considered. These are determined by the power grid quality, evaluated through the CAIDI and SAIFI values. Under these scenarios, fuel reserves are usually not affected (no structural damages are considered) and, thus, it has been considered as a reasonable hypothesis that the diesel generators are fully available during the power outages.

Finally, it must be highlighted that in the recent years, the NYC has published, in accordance with the Fire Department, the CUNY and some energy agencies, some guides and rules on the installation of stationary storage battery systems [85]. Particularly, it can result of application the 2015 International Residential Code (2015 IRC) and the 2015 International Fire Code (2015 IFC). Both codes establish conditions, limits and permitting processes for batteries installations both indoors and outdoors that must be considered in a real application.

3.3. Definition of the cases study

The REopt Lite model was used to size several schemes based on photovoltaic solar energy, batteries and/or diesel generators for four different scenarios, evaluating both economic and resilience benefits. All the combinations are shown in Table 4. As it can be observed, a total set of 13 scenarios for each facility have been evaluated (52 different cases).

Table 4. Description of the set of evaluated scenarios. Source: Own elaboration

Scenario and case study	Installation	Energy storage	Blackout duration	Resiliency economic valuation
1.1	Solar PV (optimized from a pure economic perspective)	No	N/A	No
2.1.a	Solar PV + Batteries (optimized from a resilience perspective)	Yes (Electrical)	Short	No
2.1.b			Short	Yes
2.2.a			Long	No
2.2.b			Long	Yes
3.1.a	Solar PV + Batteries + Diesel Generator (hybrid system)	Yes (Electrical + Fuel)	Short	No
3.1.b			Short	Yes
3.2.a			Long	No
3.2.b			Long	Yes
4.1.a	Diesel generator ("classical" backup system)	Yes (Fuel)	Short	No
4.1.b			Short	Yes
4.2.a			Long	No
4.2.b			Long	Yes

For each facility, three different aspects have been considered:

- **The optimization criteria for the facilities sizing:** While the first scenario selects the solar and storage resources that are profitable for the installation while it is connected to the electricity grid, and then evaluates the economic benefits that these schemes provide to the system, in the others, the electricity resilience is also considered. In these scenarios, the generators and storage sizes will be optimized considering the need to sustaining critical electrical loads during power outages. Only PV + battery systems, hybrid PV + battery + Diesel generators systems and only diesel generators systems have been considered. Although natural gas generators, co-generators and other distributed generators may also offer economic and resilience benefits, they were not modeled because they are outside the scope of the research presented here as it would involve to analyze the thermal demand of the buildings (in the case of cogeneration systems) and it may affect the fuel reservoir for emergencies in the case of diesel generators or similar.

  In this work, fuel reserves for feeding the backup diesel generator are considered to be not affected by the causes of the power outages, and thus, these generators have been simulated fully available during the power outage. Nevertheless, it must be observed that, during extreme natural disasters, such as hurricanes, infrastructure damages can be produced, and thus, fuel reserves may be affected and make fuel generators unavailable or limited.

  The state of charge of the battery immediately before a blackout will affect its optimal sizing and results. Thus, in this work it has been considered that the battery is fully charged when entering the blackout as a reasonable initial assumption that allows to compare the power dispatch during the outage among the different scenarios.

  It will also be assumed that the battery will have to be replaced once throughout the 25-year project life cycle, and that the cost of replacement is amortized through the initial capital cost. The number of cycles to the end of the battery life varies depending on the depth of discharge [86]. On the other hand, the useful life of a lithium ion battery can reach 12 years (at a temperature of 25 ºC and with a limited cycle of discharge depth) [87]. As a general approach, it has been considered that an appropriate BMS (Batteries Management System) is installed in each facility avoiding a deep of discharge lower than 20%, and the battery system is placed indoors (or outdoors but in a mobile trailer or similar equipped with a HVAC system) with an almost constant ambient temperature close to 25 ºC, making reasonable to consider a constant rectifier and round-trip efficiencies of 96% and 97.5% respectively. The batteries control strategy (peak-shaving) will also try to minimize the number of consumed equivalent full charge/discharge cycles, thus maximizing the batteries' lifespan.

- **The blackout duration:** two outage durations have been evaluated (short and long). While the long-term blackout has been stablished in 16 hours for all the facilities, the short duration depends on the network configuration and it yields between 1.92 up to 7.77 hours (see Table 2).

  Because solar resource and critical loads are both variable over time, sizing a photovoltaic solar-based scheme to meet electrical resilience needs will vary depending on when the blackout begins. In this sense, to adequately consider the stochastic nature of the critical load and the solar resource, the model should be simulated several times with the blackout starting at different times of the year. Therefore, the largest scheme required to maintain the critical load during the different simulations of the scheme would represent the worst case, and it can be assumed that it satisfies the critical load at any time.

  Due to the computational complexity of the model, for the purposes of this analysis, the worst blackout will be assumed to occur during the period with the highest load and the lowest solar generation. On the other hand, it will be assumed that it the battery system is fully charged and available when the blackout occurs.
- **The economic valuation of the electrical resilience:** economic value of the blackout duration will be added or not on each scenario, which will influence the optimal sizing and expected revenues.

3. Results and Discussion

3.1 Scenario 1: Sizing of a solar photovoltaic installation from an economic perspective (no requirement is imposed regarding the resilience of the system)

Scenario 1 takes only one alternative: 1.1 where the solar PV installation is sized from a strictly economic perspective, not considering the added electrical resilience value (which is also called "business as usual"). Table 5 presents a summary of the optimal size and the net present value of the future cash flows along the project lifespan (25 years) arising from the new facilities, for each of the cases study. It can be observed that the highest NPV value is estimated for the Brighton/Manhattan Beach Senior Center, while the lowest value is estimated for the 43rd Battalion, Engine 245, FDNY Ladder 161 center.

Table 5. Results for Scenario 1: Scheme based on a photovoltaic solar installation and electrochemical storage considering only an economic perspective. Source: Own elaboration

System 1.1: No value is included for resilience			
Site	Tottenville High School	43rd Battalion, Engine 245, FDNY Ladder 161	Brighton/Manhattan Beach Senior Center
Size of solar photovoltaic system (kW-DC)	108	0	3
Electrochemical battery storage size (kWh)	170	9	273
Battery charge/discharge capacity (kW)	58	2	45
Net present value	$ 62 728	$ 1867	$ 100 237

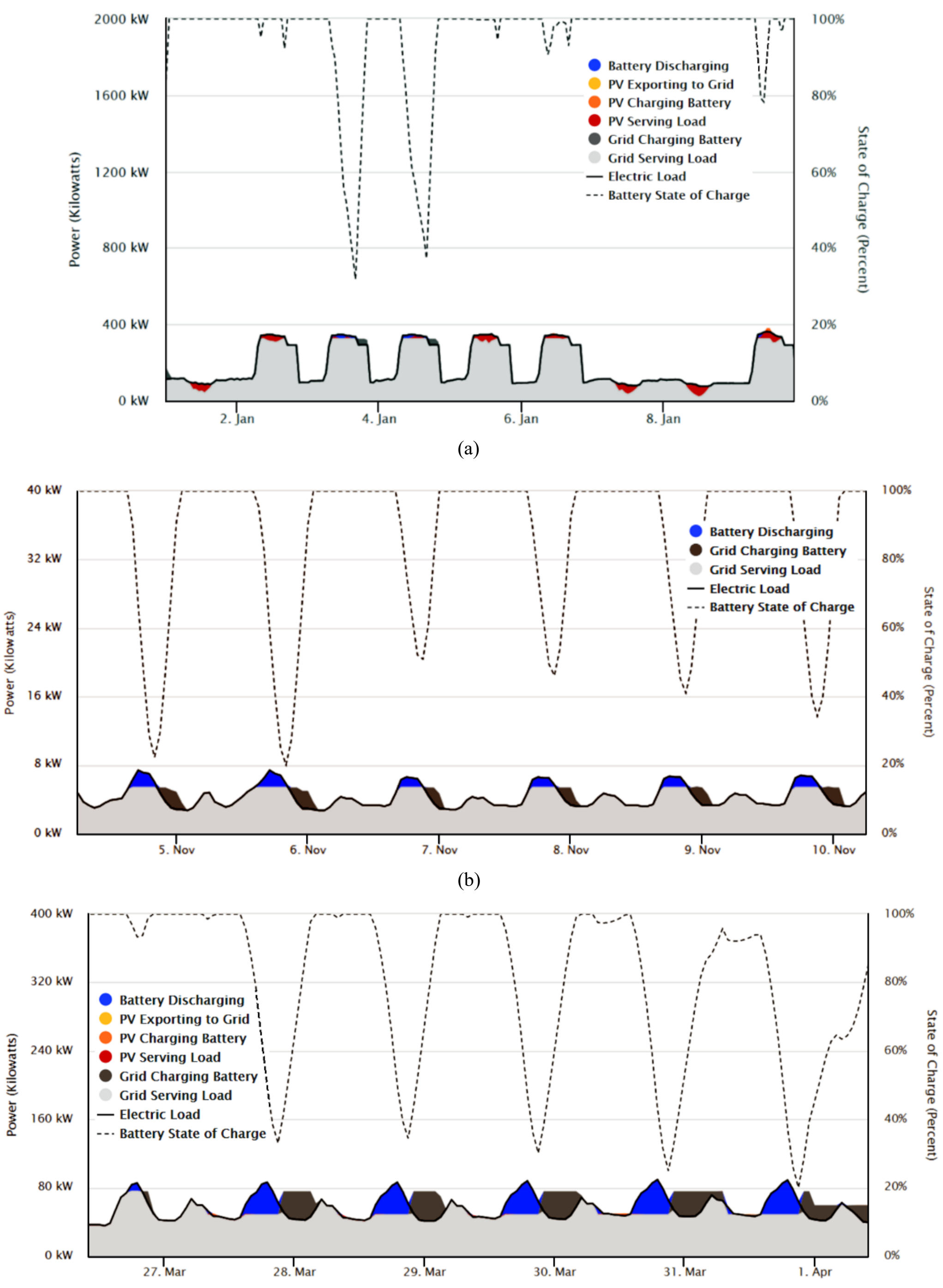
It must be noted that for the 43rd Battalion facilities the optimal size of the solar PV system is 0 kW, which means that it is unprofitable due to its electrical load profile and electrical tariff. Nevertheless, for this facility, a 9 kWh capacity battery system can contribute to reduce its peak consumption, as it can be seen in Fig. 1.b.

Under this classical approach for system sizing, the Tottenville High School center obtains savings through demand management during peak demand periods, as it can be seen in Fig. 1.a. It can be clearly observed that the optimal power dispatch makes the battery to be charged from PV surplus and from the grid during low price tariff periods, and then discharged at load peak periods. As it results unaffordable a net metering strategy for this installation, no PV or battery injections to the external grid can be found.

If an optimized net metering strategy were allowed for the Tottenville High School, it must be considered that the estimated cost of installing such a system is often considerably more expensive than the potential benefit to be gained as a result of the revenues from the exported surplus over the 25 years of the project's useful life. As a consequence, the installation of a reverse power relay seems to be the best option from a strictly economic point of view.

A similar strategy than that observed for the 43rd Battalion facilities can be observed for the Brighton/Manhattan Beach Senior Center (see Fig. 1.c), but with a significant greater impact on the peak load shaving, which explains its estimated high NPV value.

In all the three cases, the batteries systems can be used both for peak demand management and for demand response strategies (by assigning a percentage of the capacity for it). Optimizing the use of batteries to simultaneously manage peak demand and demand response requires detailed modeling. In this sense, the research presented here will assume that the battery will be used for peak demand management rather than for demand response, which will provide higher revenues.



(a)

(b)

(c)

Fig. 1. Optimal power dispatch strategies examples for the three analyzed facilities. (a) Tottenville High School, (b) 43rd Battalion, Engine 245, FDNY Ladder 161, (c) Brighton/Manhattan Beach Senior Center. Source: Adapted from ReOpt Lite software

3.2 Scenario 2: Sizing of the solar photovoltaic facility to meet electrical resilience needs

The optimal sizing conditions in this scenario includes not only the maximum benefit during normal operation of the facilities, but also the electrical resilience needs during power outages. Table 6 summarizes the results for the three facilities and the four possible alternatives according to the blackout duration and the economic valuation of the resilience (see Table 4). All the parameters for the evaluation model can be found in Appendix A.

Table 6. Results for Scenario 2: Sizing of a PV installation + electrochemical batteries considering electrical resilience needs. Source: Own elaboration

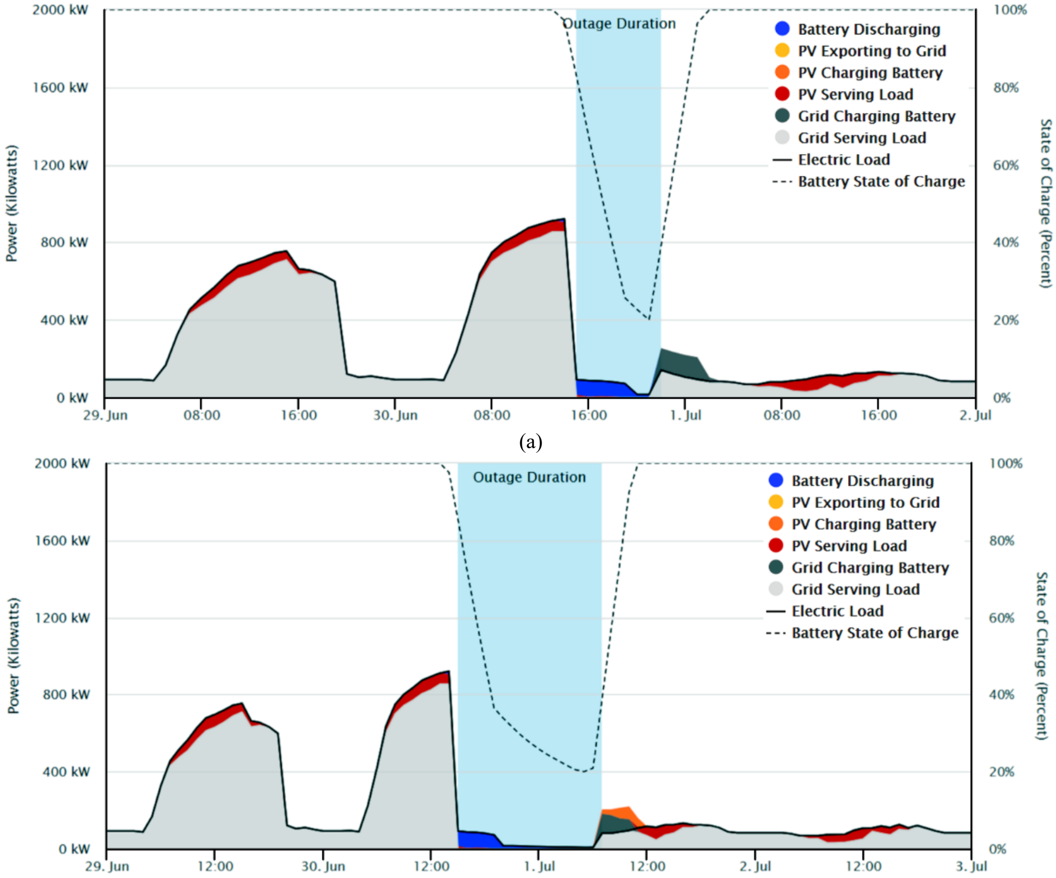
Scenario and case study	2.1.a	2.1.b	2.2.a	2.2.b	
Outage	Short	Short	Long	Long	
Resilience value	No	Yes	No	Yes	**Site**
Size of solar photovoltaic system (kW-DC)	108	108	108	108	Tottenville High School
	0	0	4	4	43rd Battalion, Engine 245, FDNY Ladder 161
	34	34	105	105	Brighton/Manhattan Beach Senior Center
Battery storage size (kWh)	567	567	664	664	Tottenville High School
	19	19	89	89	43rd Battalion, Engine 245, FDNY Ladder 161
	602	602	869	869	Brighton/Manhattan Beach Senior Center
Battery charge/discharge capacity (kW)	109	109	119	119	Tottenville High School
	7	7	7	7	43rd Battalion, Engine 245, FDNY Ladder 161
	77	77	97	97	Brighton/Manhattan Beach Senior Center
Net present value before microgrid investment	$ 18 902	$ 18 902	$ 3838	$ 3838	Tottenville High School
	$ - 3403	$ - 3403	$ - 28 684	$ - 28 684	43rd Battalion, Engine 245, FDNY Ladder 161
	$ 29 501	$ 29 501	$ - 46 331	$ - 46 331	Brighton/Manhattan Beach Senior Center
Avoided outage costs	$ 0	$ 147 253	$ 0	$ 177 546	Tottenville High School
	$ 0	$ 1622	$ 0	$ 8470	43rd Battalion, Engine 245, FDNY Ladder 161
	$ 0	$ 66 936	$ 0	$ 8470	Brighton/Manhattan Beach Senior Center
Net present value after microgrid upgrade costs and benefits	$ 100 654	$ 126 303	$ 40 541	$ 137 005	Tottenville High School
	$ - 4689	$ -3067	$ - 32 996	$ - 24 526	43rd Battalion, Engine 245, FDNY Ladder 161
	$ - 2759	$ 64 178	$ - 32 996	$ - 24 526	Brighton/Manhattan Beach Senior Center

In Table 6, it must be observed that some proposed optimal batteries' capacities exceed 600 kWh. According to the latest NYC regulations [85], particularly the 2015 International Residential Code (2015 IRC) and the 2015 International Fire Code (2015 IFC), electrochemical energy storage systems shall be segregated into groups not exceeding 50 kWh, and the maximum allowable capacity for installation of lithium-ion batteries is 600 kWh. Thus, in a real application, this restriction must be considered and the real NPV may result slightly lower. Moreover, depending on the sort of facility (indoors/outdoors or small/medium/large size) special requirements on the installation, free spaces and distances, maintenance schedules and supervision conditions may be asked.

Fig. 2 shows the optimized power dispatch during a short blackout (estimated in 7.77 hours) and a long blackout (estimated in 16 hours) for the Tottenville High School facilities, according to its conditions. On the other hand, Fig. 3 shows the same results for a long blackout of 16 hours length for the other two cases study. In order to be conservative, in all cases the worst scenario has been analyzed: low solar irradiation and high demand. It must be noted that, during the power outage, the power load decreases to its critical value, which has been set to 10% in all cases.

As it can be observed, in all the cases, although the PV modules provide some energy during the blackout, the majority of the critical loads are fed by the energy provided by the battery system. It must be also noted that the economic valuation of the power resilience does not affect the optimal sizing of the self-consumption installation. Only the duration of the blackout conditions the installation size (both for the PV system and the battery size). However, as it can be seen in Table 6, the valuation of the power resilience affects significantly to the NPV as the avoided outage costs can rise to $ 145 000 (Tottenville High School).

The valuation of the power resilience increases the NPV value a 25.48%, 34.59% and a 2425.73 % for a short blackout, respectively, while for a long blackout, the NPV increments rise 237.94%, 25.67% and 25.67% respectively.



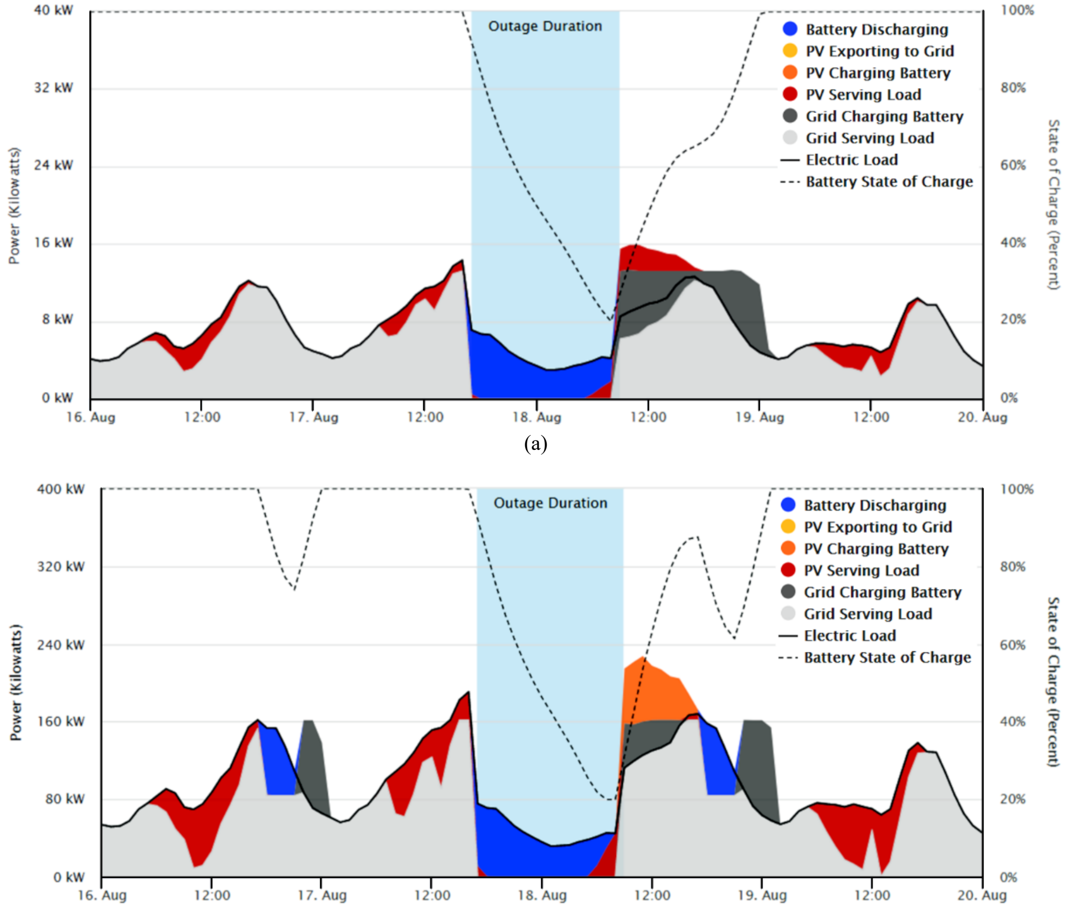
(a)

(b)

Fig. 2. Power dispatch during a short [7.77 h] (a) and long [16 h] (b) power outage of the optimal sized system for the Tottenville High School. Source: Adapted from ReOpt Lite software

In the case of the 43rd Battalion facilities, due to the fact that not a PV array has been considered for the short blackout scenarios due to being uneconomical; or it has been assigned a very reduced nominal power (<4 kW) when considering long blackout scenarios, only a limited percentage of the daily power energy demand can be satisfied, so it is necessary that the batteries account with a large capacity; see Table 6.

It results remarkable that, despite the provision of valuated power resilience, for the 43rd Battalion and the Beach Senior Center facilities, none of the scenarios are cost-effective, i.e. provide a positive NPV. This means that the systems designed to cope with blackouts are not able to compensate for their higher capital costs. As far as battery capacity is concerned, it results variable, requiring greater storage capacity for long term blackouts, as initially expected. This larger capacity is required because solar photovoltaic systems are only capable of satisfying the total required energy by themselves. In Fig.3, where the critical day (worst conditions) was selected to simulate the blackout, it can be seen how the battery has to provide almost all the energy to supply the critical loads during the blackout period.



(a)

(b)

Fig. 3. Power dispatch during a 16-hours blackout of the optimal sized system for the 43rd Battalion, Engine 245, FDNY Ladder 161 (a) and Brighton/Manhattan Beach Senior Center (b). Source: Adapted from ReOpt Lite software

3.3 Scenario 3: Sizing of the scheme assuming a hybrid system based on solar energy and a diesel generator to meet the needs of electrical resilience.

Cases in Scenario 3 consider not only the optimal sizing of a PV field, but also the optimal sizing of a diesel generator that can only operate during the blackouts, then providing added resilience to the facilities. Table 7 summarizes the results for the four considered alternatives for the three analyzed facilities.

Table 7. Results for Scenario 3: Sizing of photovoltaic solar installation + electrochemical storage + diesel generator to meet electrical resilience needs. Source: Own elaboration

Scenario and case study	**3.1.a**	**3.1.b**	**3.2.a**	**3.2.b**	
Outage	Short	Short	Long	Long	
Resilience value	No	Yes	No	Yes	**Site**
Size of solar photovoltaic system (kW-DC)	108	108	108	108	Tottenville High School
	0	0	0	0	43rd Battalion, Engine 245, FDNY Ladder 161
	29	29	21	21	Brighton/Manhattan Beach Senior Center
Battery size (kWh)	512	512	270	270	Tottenville High School
	12	12	11	11	43rd Battalion, Engine 245, FDNY Ladder 161
	508	508	332	332	Brighton/Manhattan Beach Senior Center
Battery size (kW)	102	102	70	70	Tottenville High School
	2	2	5	5	43rd Battalion, Engine 245, FDNY Ladder 161
	70	70	53	53	Brighton/Manhattan Beach Senior Center
Diesel generator size (kW)	14	14	51	51	Tottenville High School
	5	5	4	4	43rd Battalion, Engine 245, FDNY Ladder 161
	14	14	36	36	Brighton/Manhattan Beach Senior Center
Diesel generator fuel used (litres)	30	30	106	106	Tottenville High School
	15	15	160	160	43rd Battalion, Engine 245, FDNY Ladder 161
	35	35	180	180	Brighton/Manhattan Beach Senior Center
Net present value before microgrid investment	$ 27 105	$ 27 105	$ 30 716	$ 30 716	Tottenville High School
	$ - 1135	$ - 1135	$ - 1568	$ - 1568	43rd Battalion, Engine 245, FDNY Ladder 161
	$ 54 299	$ 54 299	$ 74 519	$ 74 519	Brighton/Manhattan Beach Senior Center
Avoided outage costs	$ 0	$ 149 575	$ 0	$ 208 466	Tottenville High School
	$ 0	$ 5797	$ 0	$ 53 811	43rd Battalion, Engine 245, FDNY Ladder 161
	$ 0	$ 68 794	$ 0	$ 105 602	Brighton/Manhattan Beach Senior Center
NPV after microgrid upgrade costs and benefits	$ - 10 848	$ 138 727	$ 2779	$ 283 245	Tottenville High School
	$ - 2027	$ 3770	$ - 2452	$ 51 359	43rd Battalion, Engine 245, FDNY Ladder 161
	$ 26 030	$ 94 823	$ 53 972	$ 159 574	Brighton/Manhattan Beach Senior Center

According to the results shown in Table 7, the optimal combination of a self-consumption PV field and a diesel generator provides a positive NPV at the end of the project lifespan in all cases but for the 43rd Battalion facility when the power resilience is not economically valuated, independently of the blackout duration. It also results not economically feasible for a short blackout with no valuation of the resilience in the Tottenville High School case.

By integrating a diesel generator in combination with a photovoltaic solar array and electrochemical batteries, the scheme can cope with a longer-lasting blackout at a much lower cost than it would be incurred if the scheme were composed solely of a photovoltaic + batteries system. Moreover, the longer the blackout and the more valuated the power resilience, the higher the NPV for all the cases. Particularly, the NPV after microgrid upgrade costs and benefits can achieve $ 283 245 (scenario 3.2.b for the Tottenville High School) and $ 159 574 (scenario 3.2.b for the Brighton/Manhattan Beach Senior Center).

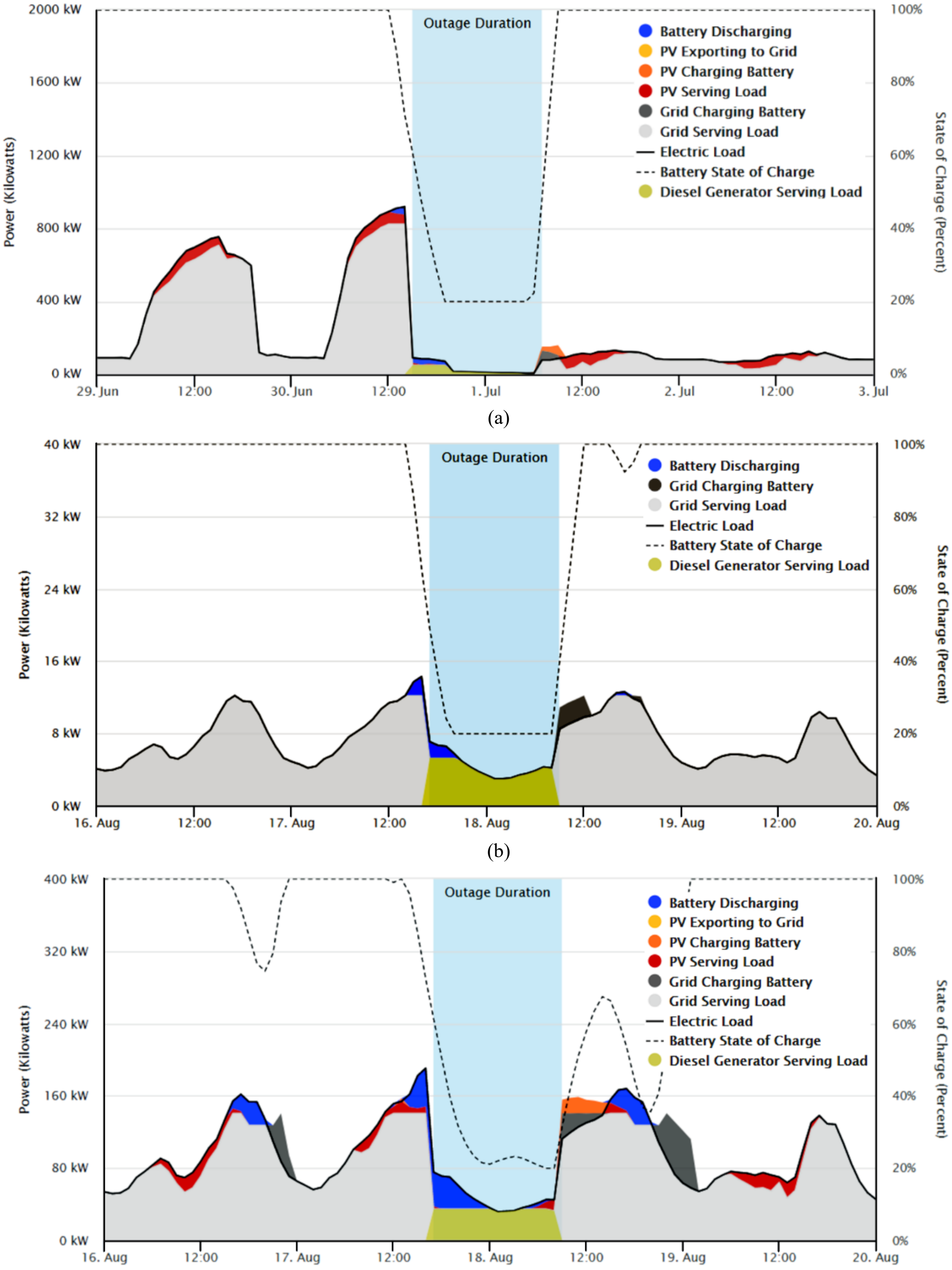
The optimal PV array size remains the same for the Tottenville High School (108 kW DC) for the four alternatives as in Scenario 2, while it decreases for the other facilities. This results especially remarkable for the Beach Senior Center, which in comparison with Scenario 2, recommended installed PV capacity decreases from 34 to 29 kW DC (14.71%) and from 105 to 21 kW DC (80.00%), for short and long blackout scenarios, respectively.

On the other hand, by observing the optimal size of the battery's capacity, it decreases significantly in all cases in comparison with Scenario 2. Furthermore, the battery size decreases from short blackout scenarios to long blackout scenarios. This can be explained because a much larger battery would be required to cope with a long blackout. In this sense peak demand management provides diminishing benefits and the savings from battery charge management do not outweigh the costs of a larger battery. Note that the solar PV + battery system allows to install a smaller diesel generator to cover the critical load (see Figs. 4.a, 4.b and 4.c). Let's notice in Fig 4 that the outage may occur on different periods because it has been assumed that it will occur during the period with the highest load and the lowest solar generation, in order to evaluate the worst case.

Finally, it must be observed that the capital costs for systems designed to be able to cope with short term blackouts are slightly higher than those designed to be able to cope with long term blackouts due to the larger size of the batteries; however, the payback times for the latter are shorter.

In case the 43rd Battalion facilities only by assigning value to the power resilience the system would be cost effective. Note that none of the scenarios conducts to install a solar PV generator for this facility.

Finally, it must be noted that for the Brighton/Manhattan Beach Senior Center, by assigning a higher value to resilience for long blackouts over short duration ones increases the NPV by about $ 20 000. For this case, the battery provides a demand saving during normal operation conditions. On the other hand, and in order to reduce the size of the required diesel generator (and its operating time), the battery also satisfies part of the critical load during the blackout.



(a)

(b)

(c)

Fig. 4. Optimal power dispatch strategies for a 16-hours blackout with a solar PV + battery + diesel generator system. (a) Tottenville High School, (b) 43rd Battalion, Engine 245, FDNY Ladder 161, (c) Brighton/Manhattan Beach Senior Center. Source: Adapted from ReOpt Lite software

3.4. Scenario 4: Sizing of the scheme assuming a system based exclusively on a diesel generator to meet electrical resilience needs

Finally, cases study from Scenario 4 consider only a diesel generator to provide power resilience during a blackout. This means that during normal operation conditions, no power load shifting or reduction can be made thanks to the self-consumption facility and, during a power outage, no added support to the diesel generator can be provided and the facilities are condemned to the fuel reservoir duration. Table 8 summarizes the obtained results for the four alternatives and the three analyzed facilities.

As it can be seen, the net present value for all the alternatives in Scenario 4 where none value is assigned to the power resilience result negative. Only when considering an economic value to the power resilience, the proposed systems are economically feasible, with the exception of the Tottenville High School facility where no scenario results viable.

The rated power of the diesel generator is independent of the blackout length, as it only depends on the critical peak load to satisfy. However, the fuel consumption is proportional to the blackout duration.

For the 43rd Battalion facility, the only feasible scenarios are 4.1.b and 4.2.b, where an economic value is assigned to the power resilience for short and long-lasting blackouts. However, for the Beach Senior Center, a diesel generator results only cost effective in scenario 4.2.b when a value is assigned to high duration resilience.

Table 8. Results for Scenario 4: Sizing of the scheme assuming a system based exclusively on a diesel generator to meet electrical resilience needs. Source: Own elaboration

Scenario and case study	4.1.a	4.1.b	4.2.a	4.2.b	
Outage	Short	Short	Long	Long	
Resilience value	No	Yes	No	Yes	**Site**
Diesel generator size (kW)	92	92	92	92	Tottenville High School
	7	7	7	7	43rd Battalion, Engine 245, FDNY Ladder 161
	76	76	76	76	Brighton/Manhattan Beach Senior Center
Diesel generator fuel used (litres)	128	128	155	155	Tottenville High School
	25	25	180	180	43rd Battalion, Engine 245, FDNY Ladder 161
	130	130	225	225	Brighton/Manhattan Beach Senior Center
Net present value before microgrid investment	$ - 55 792	$ - 55 792	$ - 55 988	$ - 55 988	Tottenville High School
	$ - 4283	$ - 4283	$ - 4427	$ - 4427	43rd Battalion, Engine 245, FDNY Ladder 161
	$ - 46 152	$ - 46 152	$ - 46 826	$ - 46 826	Brighton/Manhattan Beach Senior Center
Avoided outage costs	$ 0	$ 50 933	$ 0	$ 58 523	Tottenville High School
	$ 0	$ 8154	$ 0	$ 58 357	43rd Battalion, Engine 245, FDNY Ladder 161
	$ 0	$ 45 940	$ 0	$ 78 776	Brighton/Manhattan Beach Senior Center
Net present value after microgrid upgrade costs and benefits	$ - 60 377	$ - 9443	$ - 60 573	$ - 2050	Tottenville High School
	$ - 4638	$ 3516	$ - 4782	$ 53 575	43rd Battalion, Engine 245, FDNY Ladder 161
	$ - 49 929	$ - 3989	$ - 50 603	$ 28 143	Brighton/Manhattan Beach Senior Center

3.5 Comparison among scenarios

Table 9 compares the final net present value for scenarios 2, 3 and 4 and the three facilities. It can be observed that, when considering a mixed installation with a solar PV field + electrochemical batteries + diesel generator (scenario 3), the highest net present value for high duration blackouts is achieved, outstanding among any other result. On the other hand, the worst results appear for the 43rd Battalion and the Beach Senior Center facilities, when considering a PV installation to meet the critical load during a high duration power outage and no valuation of the power resilience is done. For the Tottenville High School the worst case (according to the final NPV) is when considering a hybrid installation when optimized for short blackouts without economic valuation of the power resilience. This means that the power profile, the revenues for surplus energy injected to the external grid and the diesel generator backup affect significantly to the results.

When considering the hybrid facilities, electrochemical batteries provide demand savings during normal operation, and they contribute to satisfy part of the critical load during a blackout. This results in a reduction of the size of the required diesel generator, which, on the contrary, is less expensive ($/kW) than the extra PV capacity needed to provide the same power resilience under low irradiance conditions. For all scenarios based only on one diesel generator, the rated power for the diesel generator was 7 kW, while for scenario 3 the required backup diesel generator has a rated power of 5 kW or lower. Moreover, when compared scenarios 2 and 3, the battery size can be reduced thanks to the diesel generator backup, and furthermore, dependence on diesel fuel is reduced in comparison with scenario 4.

According to the capital costs, it must be noted that, although the diesel generators size on scenario 3 can be reduced between 2 and 6 times in comparison with scenario 4 for the Tottenville High School and the Brighton/Manhattan Beach Senior Center facilities, and between 1.4 and 1.8 times for the 43rd Battalion, Engine 245, FDNY Ladder 161, these are not enough to overcome the extra costs of the PV system and the EES unless other incentives are available (in this case, a 30% Federal capital cost based incentives have been considered).

Table 9. Comparison of net present value among Scenarios 2, 3, and 4 (most cost-effective option for dealing with blackouts). Source: Own elaboration

Case study	1.a	1.b	2.a	2.b	
Outage	Short	Short	Long	Long	
Resilience value	No	Yes	No	Yes	**Site**
Scenario 2 **(PV + EES)**	$ 100 654	$ 126 303	$ 40 541	$ 137 005	Tottenville High School
	$ - 4689	$ -3067	$ - 32 996	$ - 24 526	43rd Battalion, Engine 245, FDNY Ladder 161
	$ - 2759	$ 64 178	$ - 32 996	$ - 24 526	Brighton/Manhattan Beach Senior Center
Scenario 3 **(PV + ESS + DG)**	$ - 10 848	$ 138 727	$ 2779	$ 283 245	Tottenville High School
	$ - 2027	$ 3770	$ - 2452	$ 51 359	43rd Battalion, Engine 245, FDNY Ladder 161
	$ 26 030	$ 94 823	$ 53 972	$ 159 574	Brighton/Manhattan Beach Senior Center
Scenario 4 **(Diesel Generator)**	$ - 60 377	$ - 9443	$ - 60 377	$ - 2050	Tottenville High School
	$ - 4638	$ 3516	$ - 4782	$ 53 575	43rd Battalion, Engine 245, FDNY Ladder 161
	$ - 49 929	$ - 3989	$ - 50 603	$ 28 143	Brighton/Manhattan Beach Senior Center

For all the analyzed scenarios the consideration of the economic value of the resilience and its duration influenced the type of backup system that the site will have to install. Regardless of whether or not these sites assign an economic value to resilience, if a system that addresses the possible blackouts that may occur throughout the year is desired, the recommendation would be to install a hybrid system based on photovoltaic solar energy, electrochemical batteries and a diesel generator to meet the needs of electrical resilience. If backup power is not assigned an economic value, the NPV is almost independent of the duration of the power outage.

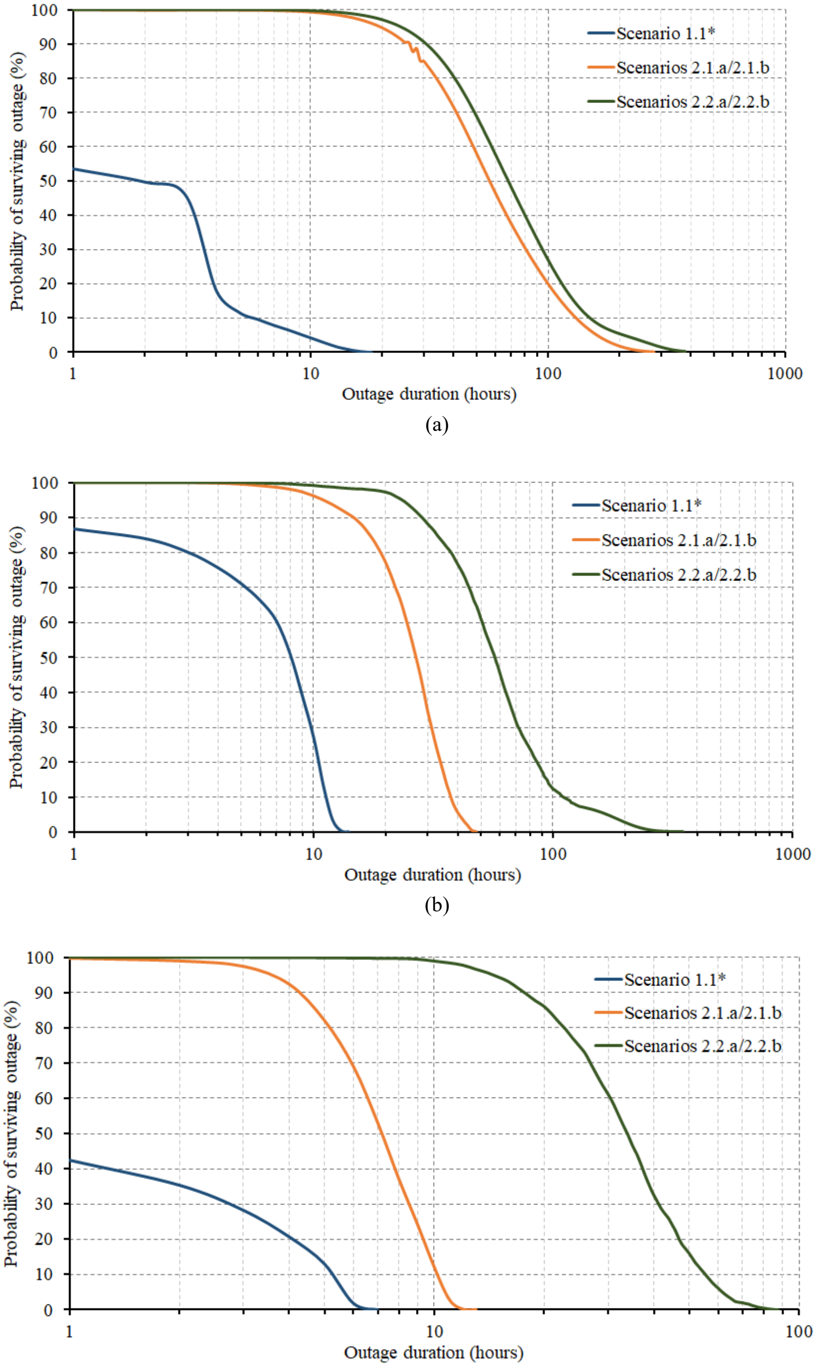
Finally, Table 10 compares the probabilities to survive different durations blackouts according to the scenarios and cases study. Table 10 and Figure 5 show the results of a series of 8760 simulations for each site performed to calculate the number of hours each configuration could sustain the critical load for outages beginning during every hour of the year. Therefore, variation in load, solar resource and battery state of charge can be considered to evaluate the resilience in probabilistic terms.

It must be remembered that short blackout durations are 2 hours for systems connected to radial networks (43rd Battalion facilities) and 8 hours for systems connected to meshed grids (Tottenville High School and Beach Senior Center). On the other hand, 16 hours is considered for long blackouts in all configurations. Results from Scenario 1.1, where no resilience is considered in the sizing optimization of the system are compared with results for Scenario 2 where the generators are optimized considering both short (2.1) and long (2.1) blackouts, and without (a) and with (b) economic valuation of this power resilience.

As results from the Scenario 1.1 column show, if resilience is not considered in the sizing optimization, power resilience cannot be guaranteed at any case. Furthermore, the shorter the blackout duration is considered in the sizing process, the lower the resilience capacity for long outages.

Table 10. Percentage of critical load that the system can feed. Source: Own elaboration

Scenario and case study	1.1	2.1.a/2.1.b	2.2.a/2.2.b	
Installation	Solar PV	Solar PV + ESS	Solar PV + ESS + DG	
Outage	Not considered	Short	Long	**Site**
2-hours blackout (worst conditions)	-	-	-	Tottenville High School
	35.4 %	99.04 %	99.9 %	43rd Battalion, Engine 245, FDNY Ladder 161
	-	-	-	Brighton/Manhattan Beach Senior Center
8-hours blackout (worst conditions)	6.6 %	99.63 %	99.88 %	Tottenville High School
	-	-	-	43rd Battalion, Engine 245, FDNY Ladder 161
	50.61 %	98.08 %	99.59 %	Brighton/Manhattan Beach Senior Center
16-hours blackout (worst conditions)	0.32 %	97.19 %	98.55 %	Tottenville High School
	0 %	0 %	93.04%	43rd Battalion, Engine 245, FDNY Ladder 161
	0 %	87.76 %	98.14%	Brighton/Manhattan Beach Senior Center
Outage duration with a 75 % of probability of surviving	< 1 h	42 h	49 h	Tottenville High School
	4.3 h	5.1 h	25 h	43rd Battalion, Engine 245, FDNY Ladder 161
	7.2 h	37.2 h	42 h	Brighton/Manhattan Beach Senior Center
Outage duration with a 50 % of probability of surviving	1 h	61 h	68 h	Tottenville High School
	4.9 h	6.4 h	33.5 h	43rd Battalion, Engine 245, FDNY Ladder 161
	9.1 h	52.1 h	61 h	Brighton/Manhattan Beach Senior Center
Outage duration with a 25 % of probability of surviving	3.8 h	87 h	107 h	Tottenville High School
	5.5 h	7.3 h	44 h	43rd Battalion, Engine 245, FDNY Ladder 161
	10.2 h	75 h	75 h	Brighton/Manhattan Beach Senior Center



(a)

(b)

(c)

Fig. 5. Probability of surviving an outage for the different scenarios analyzed. (a) Tottenville High School, (b) 43rd Battalion, Engine 245, FDNY Ladder 161, (c) Brighton/Manhattan Beach Senior Center. Source: own elaboration.

Finally, it can be observed, from Table 10 and Figure 5, that the consideration of the power resilience when sizing the solar PV plant does affect significantly the power resilience of the facilities, increasing the probability of surviving a certain duration power outage. Moreover, it minimizes the needs of an emergency diesel generator, as it is observed that it provides very low increase of power resilience (measured as probability of surviving a power outage).

4 Conclusions

From the conducted research presented in this work it can be concluded that:

a) The results for the three sites indicate that systems based on photovoltaic solar energy + electrochemical storage; and systems based on photovoltaic solar energy + electrochemical storage + diesel groups, can provide a positive net present value whether or not their resilience is assigned an economic value. Regarding the economic viability of resilient systems based on photovoltaic solar energy, its NPV is, in general, higher than that of "classic" solar photovoltaic installations, mainly due to the ability of batteries to reduce the energy demand.

b) When a value is assigned to resilience, the economic viability of projects for all modeled systems is greatly improved for customers connected to radial networks. This is due to the higher frequency of blackouts on radial networks compared to meshed ones. When a value is assigned to resilience, the economic viability for all systems modelled in meshed networks is moderately improved.

c) Those systems based on solar photovoltaic energy specifically designed to obtain economic savings (not to obtain an improvement in resilience) are capable of providing limited benefits in terms of resilience. In this sense, the level of resilience provided by resilient systems based on photovoltaic solar energy + electrochemical storage will depend on when the blackout occurs, the state of charge of the battery and its capacity.

d) Resilient PV and hybrid systems can be NPV-positive with and without the consideration of an economic value of the resilience. In all cases, the economics of resilient PV are better than the classical PV sizing due to the battery's ability to reduce utility demand charges. Moreover, resilient PV sized for cost savings provide, in both studies, limited resiliency benefits. In both cases, solar-plus-storage and hybrid systems can offer the same benefits than diesel generators at a better lifecycle cost, although generators have a significant lower initial cost.

e) It has been obtained better results for project economics in all scenarios for customers connected to meshed networks when resiliency is given and economic value, although, these results are even better for customers connected to radial networks, , as also observed in [47].

f) Resilient systems based on solar photovoltaic energy + electrochemical storage; and hybrid resilient systems based on solar photovoltaic energy + electrochemical storage + diesel generators that have been designed to cope with short- and long-duration blackouts, result in larger and more expensive systems than systems designed exclusively to obtain economic savings.

g) Backup diesel generators as a resilient solution do not have a positive net present value except when resilience is assigned a value in "long" blackouts. Moreover, systems based on solar photovoltaic energy + electrochemical storage; and specially hybrid systems based on the combination of solar photovoltaic solar energy + electrochemical storage + diesel generators can offer the same benefits than classical systems based only on diesel generators backup at a lower cost throughout the life cycle of the project.

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Appendices

Appendix A. Assumptions for each system modelling

LOCATION AND ELECTRICITY DISTRIBUTOR			
INPUT	**SUGGESTED VALUE**	**RANGE**	**REFERENCES**
Site location	New York, NY	-	-
Electricity rate (Tottenville High School)	SC-9 - General Large Low Tension Service	-	[53]
Electricity rate (43rd Battalion, Engine 245, FDNY Ladder 161)	SC-9 - General Large Low Tension Service	-	[53]
Electricity rate (Brighton/Manhattan Beach Senior Center)	SC 8 - Multiple Dwellings Redistribution TOD Service	-	[63]
Net metering	Not considered	National regulations	[82]
Wholesale rate ($/kWh)	0	0.00 - 0.05	[83]
Building type (Tottenville High School)	High school	-	[48]
Building type (43rd Battalion, Engine 245, FDNY Ladder 161)	Fire station	-	[55]
Building type (Brighton/Manhattan Beach Senior Center)	Senior Center	-	[59]
Land available (Tottenville High School)	0.65 acres (2632 m^2)	-	[48]
Land available (43rd Battalion, Engine 245, FDNY Ladder 161)	0.12 acres (485 m^2)	-	[55]
Land available (Brighton/Manhattan Beach Senior Center)	0.41 acres (1650 m^2)	-	[59]
Available roof space (Tottenville High School)	0.65 acres (2632 m^2)	-	[48]
Available roof space (43rd Battalion, Engine 245, FDNY Ladder 161)	0.12 acres (485 m^2)	-	[55]
Available roof space (Brighton/Manhattan Beach Senior Center)	0.41 acres (1650 m^2)	-	[59]
LOAD PROFILE			
Type of building (Tottenville High School)	School - Secondary	-	U.S. DoE
Type of building (43rd Battalion, Engine 245, FDNY Ladder 161)	Midrise apartment	-	U.S. DoE
Type of building (Brighton/Manhattan Beach Senior Center)	Midrise apartment	-	U.S. DoE
Annual energy consumption (Tottenville High School)	1 883 392 kWh/year	-	U.S. DoE and ASHRAE Zone 4A
Annual energy consumption (43rd Battalion, Engine 245, FDNY Ladder 161)	42 530 kWh/year	-	U.S. DoE and ASHRAE Zone 4A
Annual energy consumption (Brighton/Manhattan Beach Senior Center)	564 896 kWh/year	-	U.S. DoE and ASHRAE Zone 4A
Critical load factor (%) (Tottenville High School)	10%	-	[54]
Critical load factor (%) (43rd Battalion, Engine 245, FDNY Ladder 161)	50%	-	[57,58]
Critical load factor (%) (Brighton/Manhattan Beach Senior Center)	40%	-	[57]

FINANCIAL			
Host discount rate, nominal (%)	8.1%	2.4 – 15%	[90,91]
Electricity cost escalation rate, nominal (%)	2.6%	-0.5 – 5.5%	[91-93]
Analysis period (years)	20	10 – 40	[90,94]
Host effective tax rate (%)	26%	-	[90-96]
O&M cost escalation rate (%)	2.5%	-0.6 – 4%	[90,91,97]
RESILIENCE			
Outage duration (hours) (Tottenville High School)	7.77 (short), 16 (long)	0 - 71 hours	[77]
Outage duration (hours) (43rd Battalion, Engine 245, FDNY Ladder 161)	1.92 (short), 16 (long)	0 - 71 hours	[77]
Outage duration (hours) (Brighton/Manhattan Beach Senior Center)	7.77 (short), 16 (long)	0 - 71 hours	[77]
Outage start date (Tottenville High School)	June 30	January 1 – December 31	REopt defaults
Outage start date (43rd Battalion, Engine 245, FDNY Ladder 161)	August 17	January 1 – December 31	REopt defaults
Outage start date (Brighton/Manhattan Beach Senior Center)	August 17	January 1 – December 31	REopt defaults
Outage start time (Tottenville High School)	3 pm	1 am – 23 pm	REopt defaults
Outage start time (43rd Battalion, Engine 245, FDNY Ladder 161)	5 pm	1 am – 23 pm	REopt defaults
Outage start time (Brighton/Manhattan Beach Senior Center)	3 pm	1 am – 23 pm	REopt defaults
Type of outage event	Major outage – Occurs once per Project lifetime	-	-
Fuel burn rate for diesel generator	0.078 gallons/kWh (0.2952 l/kWh)	-	[98]
Fuel curve and- intercept by generator capacity	0.009 gal/h (0.034 l/h)	0.004 - 0.0142 gal/h (0.015 - 0.054 l/h)	[99-102]
Diesel cost ($/gal)	$3/gal	$2.50 – $3.27/gal	[103, 104]
Min. loading for diesel generator (%)	30%	0%-100%	[105-107]
Microgrid upgrade cost (% CAPEX)	30%	N/A	-
Avoided outage costs ($/kWh)	100 $/kWh	0.0032 - 432.89 $/kWh	[108-110]
SOLAR PHOTOVOLTAIC SYSTEM			
System capital cost ($/kW)	$ 2000	$ 1638 – 2180	[90,111]
Capital Cost Based Incentives	30% Federal ITC, 5 year MACRS	-	[111-114]
O&M cost ($/kW/year)	$16	$11 – 20	[90]
Minimum size desired (kW DC)	0 kW	0 kW	-
Maximum size desired (kW DC)	Roof space limitation	-	-
Module type	Standard	Standard - Premium	-
Array azimuth	180º	0 - 360°	[115]
Array tilt - Rooftop, Fixed	10º	0 – 60°	[116]
DC to AC ratio	1.10	1.10 – 1.50	[117,118]
System losses - Soiling	2%	2 – 25%	[117-119]
System losses - Shading	3%	0 – 30%	[117,118-120]
System losses - Snow	0%	0% to 15% (usual)	[117-119,121]
System losses - Mismatch	2%	1.5 – 3%	[117-119]
System losses -Wiring	2%	0.7 – 2%	[117-119]
System losses - Connection	0.5%	0.3 – 0.1%	[117-119]
System losses – LID	1.5%	0.3 – 10%	[117-119]

System losses - Aging	3%	0 – 100%	[117,118]
TOTAL SYSTEM LOSSES	14%	5 – 100%	-
MACRS schedule	5 years	5 - 7 years	[122]
STORAGE (ION-LITHIUM BATTERIES)			
Energy capacity cost ($/kWh)	$500	$400 – 690	[123-124]
Power capacity cost ($/kW)	$1000	$800 – 1375	[123-126]
Battery replacement cost ($/kWh)	$230	$170 – 300	[123,124]
Energy capacity replacement year	10	4 - 20	[127-131]
Power capacity replacement cost ($/kW)	$ 460	$ 350-550	[127-131]
Power capacity replacement year	10	10-15	[127-131]
Rectifier efficiency (%)	96%	95 – 99%	[132]
Round trip efficiency (%)	97.5%	95 – 98%	[128,132]
Inverter efficiency (%)	96	95 – 99%	[132]
Minimum state of charge (%)	20	15 – 30%	[132]
Initial state of charge (%)	50	0 – 100%	-
Allow grid to charge battery	Yes	Yes – No	-
Incentives	0% ITC	-	[112-114]
MACRS schedule	7 years	5 - 7 years	[133-149]