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Biomethane Microturbines as a Storage-Free Dispatchable Solution for Resilient Critical Buildings

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Abstract: Climate-change-related events are increasing the costs of power outages, including losses of product, revenue, and productivity. Given the increase in meteorological disasters in recent years related to climate change effects, the number of costly blackouts, from an economic perspective, has increased in a directly proportional manner. As a result, there is increasing interest in the use of alternators to supply dependable, instantaneous, and uninterruptible electricity. Traditional research has focused on the installation of diesel backup systems to ensure power requirements without deeply considering the resilience capabilities of systems, which is the ability of a system to recover or survive adversity, such as a power outage. This research presents a novel approach focusing on the resiliency impact of backup systems' storage-free dispatchable solutions on buildings and compares the advantages and disadvantages of biomethane microturbines, natural gas engines, and diesel engines backup systems, discussing the revenue resulting from the resilience provided by emergency generators. The results show that, for several diesel fuel and natural gas safety assumptions, natural gas alternators have a lower probability of failure at the time of a blackout than diesel generators, and therefore, resilience increases.

Keywords: energy resilience; backup generators; biomethane microturbines; economic analysis; resiliency analysis

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1. Introduction

The modern economy and supply chain depend heavily on electricity in their day-to-day operation [1–3], and this dependency is especially critical in cities. Climate-change-related events are increasing the risk of power outages that can cause significant problems in both households and commercial buildings [4], which is of significant importance in the commercial sector and critically important in food distribution [5]. In this regard, power outages cause lost sales in shops [6–8], damage to equipment [4], a loss of data on computers [9], and the deterioration of products [10–13]. In addition to interrupting daily work [14], critical care facilities such as hospitals may have difficulty keeping necessary emergency power [15,16]. The electrical grid is vulnerable to extreme weather conditions [17], and these events are related to climate change consequences. As shown in Figure 1, the aging of the power grid, which must meet growing demand—as well as an increase in the number of storms and extreme environmental situations that can damage the power system—has caused an increase in the number of blackouts in the US. Mechanical failures, part defects, and transformer and power cable failures are common causes of power system problems [18]. Natural hazards such as earthquakes, storms, floods, and heat waves are among the main causes of power outages [19].

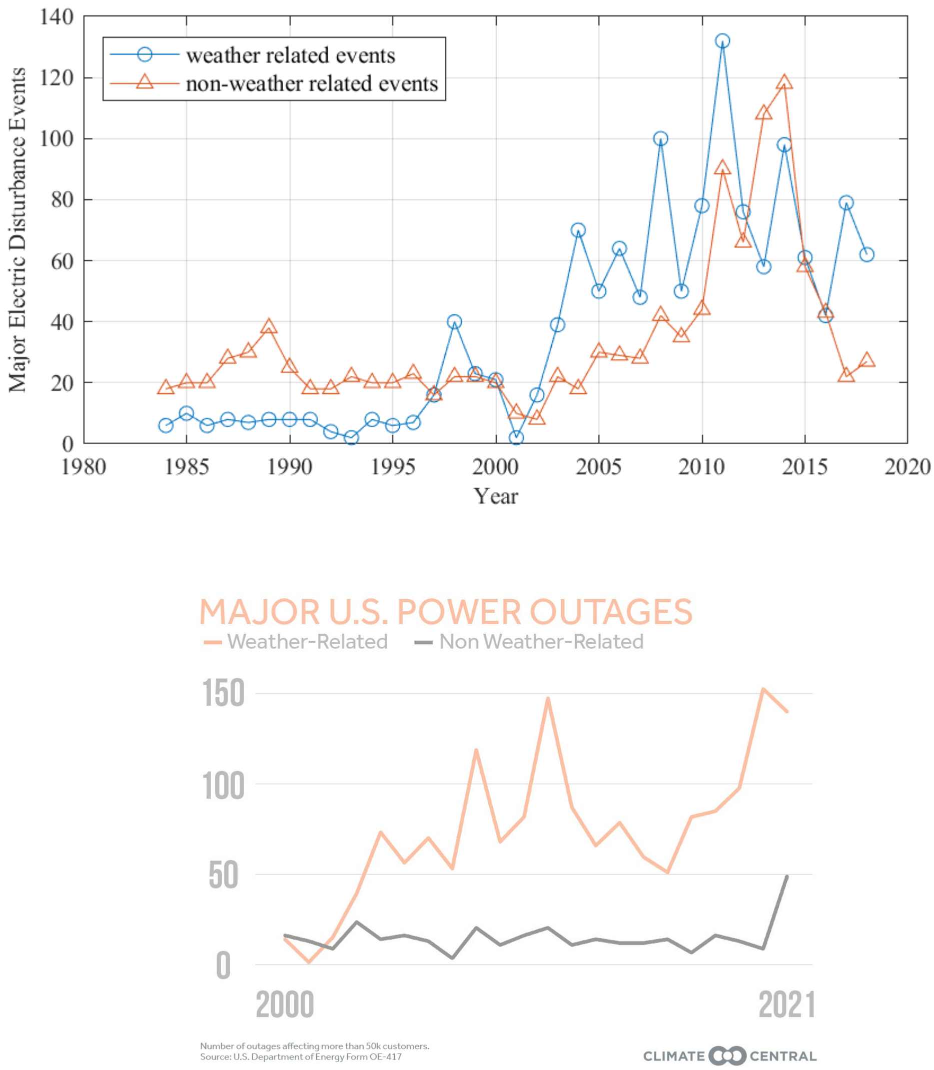

Figure 1. Number of electrical disturbances between 2000 and 2021 in the US. Source of data: [20].

Three out of the five costliest hurricanes in the history of the US took place in 2017 [21]. Florence [22] and Hurricane Michael [23] also caused major power outages in 2018. In October 2008, a power company in Northern California intentionally cut off the electricity supply to nearly 60,000 users to reduce the risk of fire from power lines during extreme winds [24]. In practice, the cost of blackouts associated with a particular level of reliability is difficult to estimate because such costs can consist of a combination of direct and indirect components [25]. Although these costs may not be correct, they are clearly significant [26]. The 2003 blackout between the United States and Canada affected more than 50 million people and had an estimated cost of more than USD 6 billion [27], of which USD 1 billion corresponded to New York City alone [28]. The annual costs of severe weather-related blackouts fluctuate significantly and are higher in storm years, such as with Hurricane Ike in 2008 (a year in which the estimated cost was between USD 40 billion and USD 75 billion), and Superstorm Sandy in 2012 (a year in which the cost of blackouts ranged from USD 27 billion to USD 75 billion) [29]. Electronic equipment is now being used extensively in retail outlets, so better power quality standards are needed [30]. With respect to backup systems, the decision to invest in such systems and the total cost of the outage increases as the duration of the outage increases [31]. In this regard, the growing number of users who have installed their own backup systems is a result of the excessive cost of blackouts [32]. Many businesses without a backup system are considering their purchase, and those who already are in possession of a backup electricity supply are examining how to add more resilience against blackouts. Understanding the costs and potential benefits, in addition to the resilience linked to the emergency power systems, is critical to plan.

In the scientific literature, it is possible to find many research papers exploring how to improve energy resiliency and backup generator applications; however, this literature lacks a deep analysis of storage-free dispatchable solutions in terms of building resilience. Among the most notable studies may be those carried out by Diboma et al., who estimated power interruption costs to industries [33]; Abdisa, who examined how firms respond to power outages [34]; Szakonyi et al., who conducted an empirical examination of how the use of generators has changed in the industry [35]; Kim et al., who estimated the power outage costs of the industrial sector by not only considering production loss but also the customer's inconvenience and various damages [36]; Wolf et al., who quantified the macroeconomic costs resulting from power outages [37]; Amoah et al., who provided new estimates of households' willingness to pay to reduce electricity outages and contributed to debate the validity of contingent valuation results for energy reliability [38]; and the investigation conducted by Oseni, who examined the extent to which an improvement in publicly supplied electricity can reduce backup generation [39].

Earlier research lacks a comparison of prime mover types for storage-free dispatchable solutions for enhancing reliability and resiliency in commercial buildings and applications where these events can result in extensive economic and social damage. This research presents a novel approach in order to study the best design of storage-free dispatchable solutions in commercial buildings to ensure maximum flexibility and resilience in cases of power disruption events. A novel deep survey of gray literature and updated literature related to the topic is addressed in the paper, and it was possible to find that—despite the diversity of approaches—this paper contributes to the pool of existing knowledge by providing a novel economic and resilience analysis of backup generators for commercial buildings.

The paper is structured as follows: this first section briefly discusses outage economics issues; in the next section, a theoretical background on economic and resiliency issues about backup systems will be explored; in the second section, the calculation methodology used to conduct the research will be shown; in the third section all the case studies will be presented and discussed; and, subsequently, in the last section, conclusions will be presented. Our novel conclusions prove that the differences in failure probability between diesel and natural gas generators are quite small and depend on several factors. Regarding biomethane microturbines, they have the lowest probability of the three technologies assessed to fail at the time of a blackout and can also be combined with biomethane generation systems. The results show that, from an economic point of view, it can be concluded that the use of diesel engines as a backup system can be the best option.

Literature Review

In the present research, it will be assumed that the backup system will consist of a single generator that can meet all the peak loads demanded by the building in which it is installed. For the year 2006 and for the United States, Philips et al. [40] showed that the percentage of all installations with a backup generator using diesel fuel, natural gas, and propane was 85%, 10%, and 4%, respectively. From an economic point of view, being powered by tanker trucks (as is the case with backup generators that use diesel as fuel) is detrimental [41]. Natural gas is supplied through pipelines [42], which ideally ensure an interruptible fuel source [43]. Oil has the advantage over natural gas of being able to be stored on-site, which is not generally an option for natural gas [44]. Although extremely rare, interruptions in natural gas supply and/or transportation affect the risk profile of each power plant (or group of power plants) [45]. Generators using natural gas as a fuel must necessarily have access to pipelines [46,47]. On the other hand, diesel generators require constant refueling, which results in higher operating costs, negative environmental impacts, and more complex fuel planning [48].

Refueling problems are more severe during earthquakes or electromagnetic pulse attacks, which can affect multiple regions within a country [49]. In this case, because of the problems caused by major power outages, the private refueling process will be interrupted [49]. Unfortunately, many fuels, especially gasoline and diesel, have a limited storage time [50]. This is the reason why it is impractical to store massive quantities of gasoline or diesel to prepare for emergencies [50]. Under normal storage conditions, it is expected that fuel can remain in a usable condition for twelve months, after which, it is advisable to replace the deposit with "fresh" fuel if possible [51]. Because emergency diesel generators are normally found in densely populated areas, their increased use for electricity generation will also increase public exposure to their harmful emissions [52,53].

The main aim of an emergency power system is to grant electricity in case of a power failure [54]. That said, it is also possible to conduct an integration of energy into the grid, which might bring added benefits to backup system installations [54]. Allowing the sale of electricity generated by backup systems during peak demand and being able to take part in the "installed capacity market" could reduce the price of electricity and increase reliability for all users [55].

2. Proposed Methodology

This section describes the different methods used to analyze system resilience, and the proposed model is used to calculate the results shown in Section 4.

2.1. Backup System Reliability

NEI 99-02 [56] offers guidance on the data and calculations relating to the identification and definition of the three types of failure in emergency diesel generators [57]: (i) failure to start, (ii) failure to load and run, and (iii) failure to run [56]. Each of these types of failures has a reference reliability value [57].

2.1.1. Failure to Start

The failure to start (FTS) represents the failure of a generator to either manually or automatically (i) start on a bus under-voltage condition, (ii) reach the required rate of voltage and speed, (iii) close the output breaker, (iv) participate in a black start process, or in other words, sequence safety-related electrical loads into the respective safety-related bus [58]. Emergency generators normally run infrequently and for a limited period [59]. In this sense, the regulations of the United States Environmental Protection Agency limit the operation of emergency generators to a maximum of 100 h per year for testing and maintenance (while the electrical grid is available) [59] and to an unlimited period when there is a failure in the electrical grid [59]. A further analysis of the mode of operation of backup systems shows that a modest percentage of generation that can be given to this technology is indicative of a country's development and the reliability of its electricity grid [60].

A crucial element to consider is the fact that emergency diesel generators are taken out of service for testing and maintenance [61]. Maintenance is conducted to repair any faults or to correct any degradation (corrective maintenance) and through planned maintenance to ensure that the emergency diesel generator runs reliably, i.e., to prevent equipment failure (preventive maintenance) [61]. In this sense, the unavailability of diesel generators due to testing and maintenance may be the dominant part of the overall unavailability of emergency diesel generators [61–63].

It should also be mentioned that data availability may enable the owners of backup generators to reschedule maintenance to ensure the availability of more generators [64]. In this sense, power producers usually schedule the maintenance of units during the low season, during periods of lower demand, when energy and capacity prices are lower on average [65]. There are a few elements that will influence unexpected unavailability. One of the most notable in emergency diesel generators is voltage control failures, which can be identified as starting failures given the inclusion of the requirement to achieve the required speed and voltage [57].

2.1.2. Failure to Run

Failure to start likelihood is normally calculated through a model that only depends on the time-independent stress induced by the starts [58,66]. In contrast, failure to run is calculated based on demand and rate probabilities on an hourly basis and is, therefore, time-dependent [67]. According to the failure to start probability defined by Fairfax et al. [68], the failure to start probabilities for standby demands and load demands are 0.67% and 0.15%, respectively. According to hourly failure rates from Fairfax et al. [68], failure to run probabilities for standby demands and load demand are 0.172% (508 h) and 0.086% (1160 h), respectively.

2.1.3. Failure of Fuel Supply

To supply a few hours' reserve, the calculated fuel tank size will vary [69]. Annex A of National Fire Protection Association 110 suggests 48 to 96 h as a minimum fuel capacity for emergency generators [70]. It also offers suggestions for long-term fuel storage [70].

- Diesel Fuel Supply

According to Philips et al., backup generators that use diesel as a fuel and that are placed at store retailer facilities can provide, on average, a power duration of 36 h [40]. Because the research presented here focuses on commercial facilities, a duration of 36 h was used as a baseline assumption. Diesel generators are strictly dependent on stored or transported fuel for operation, which creates significant vulnerability during major disasters [71,72]. In this sense, because the storage capacity of a tank depends on (i) the average fuel consumption, (ii) the security of the fuel supply, and (iii) economic factors [73], high-capacity fuel storage will reduce the risk of blackouts due to fuel supply failure [73].

- Natural Gas Fuel Supply

Diesel fuel needs to be stored in copious quantities on-site to ensure a certain running time for the generators [74]. In contrast, natural gas and renewable natural gas (RNG) are transported through underground pipelines [75] and are susceptible to several incidents in the gas network [76]. The inherent reliability of natural gas pipelines has led to the acceptance of this technology by companies, which have progressively chosen more backup natural gas generators [77]. Because natural gas is supplied through underground pipelines rather than by diesel trucks, supplies are less likely to be compromised during major disasters that result in power outages [77]. A common cause of pipeline damage is the construction and excavation activities of contractors, construction companies, and homeowners—this damage can be avoided by checking where underground utilities are before digging [78]. In this respect, natural gas/RNG can be much more dependable than electricity supplies, with the added advantage that gas can be stored if needed [79].

- Correlation between electrical and natural gas interruptions

Compared with aboveground storage, the underground storage of natural gas supplies significantly higher and cheaper volumes of necessary storage [80]. Moreover, if carefully constructed and checked, these facilities supply added levels of security compared with aboveground storage [80]. Consequently, natural gas is typically stored underground [81,82] in three types of facilities. These underground facilities are (i) depleted deposits in oil and/or natural gas fields, (ii) aquifers, and (iii) salt cave formations [83,84]. Independent of the electricity grid [85,86], natural gas infrastructure is also more resilient [85] and performs better in terms of reliability and availability [87]. That said, irrespective of the theoretical independence between gas distribution networks and electricity networks, in practice, there are interdependencies between these networks that have a final impact on the security of the supply [88]. Although less vulnerable than aboveground infrastructure [89], extreme conditions can also affect underground infrastructure [89]. This was the case in December 2017 in California when a few severe landslides carrying large rocks formed openings in the ground and exposed underground pipelines [89]. Similarly, a loss of electricity due to damage to the electrical infrastructure can create a "demand-side destruction" in areas where natural gas supplies fuel for power plants [89]. This was the case in Florida, where aggregate demand for natural gas fell considerably between the 7th and 11th of September 2017, largely because of a loss of demand for electricity [89].

A greater correlation between systems implies a greater probability of coincidental interruptions [90]. For the investigation presented here, the probability of a coincidental interruption in natural gas and electricity systems was differentiated according to the criteria of whether (i) the interruption is of short duration or whether (ii) a significant long-term failure exists. A significant power failure is usually defined as any long-term incident that requires the involvement of local and/or state emergency management organizations to coordinate the provision of food, water, heating, and shelter [91]. In this regard, because extreme conditions are needed for underground gas infrastructure to be affected [89] and because these extreme conditions will typically lead to long-term outages, it is expected that these outages will have higher system correlations than short-term outages.

With the gray literature existing at the time of the writing of the research presented here, it was only possible to obtain an incomplete picture of the frequency of failures that occur interdependently between natural gas and electricity infrastructures [92]. Recent experience with the interdependence between natural gas and electricity networks is a call to action to improve the availability of data on the operational characteristics of both [92]. To illustrate the situation, the North American Electric Reliability Corporation recognized the absence of the systematic collection of statistical data on natural gas system outages [93]. That said, several reports have been selected to present relevant information about the possibility of coincidental power outages (see Table 1).

Table 1. Power outages, natural gas interruptions, and percentage of coinciding interruptions for several events in the US. Source: adapted from [89,94–102].

Event	Year	Power Outages (Total Number of Users)	Natural Gas Interruptions (Total Number of Users)	Percentage of Coinciding Interruptions
California wildfires 2003 [94]	2003	58,700 [99]	1000 [99]	1.70%
February 2011 Southwest Cold Weather Event [95]	2011	4,400,000 [100]	50,000 [100]	1.13%
Hurricane Sandy (New Jersey) [96]	2012	2,615,291 [101,102]	32,000 [101,102]	1.22%
Hurricane Sandy (New York) [96]	2012	2,097,933 [101,102]	80,000 [101]	3.06%
California wildfires 2017 (San Diego Gas & Electric Company) [97]	2017	85,000 [89]	4800 [89]	5.65%
California wildfires 2017 (Pacific Gas and Electric Company) [98]	2017	359,000 [89]	42,000 [89]	11.70%

Analyzing the percentage of coincidental interruptions in Table 1, it can be seen how this percentage is much higher for the California wildfires of 2017. The explanation for this circumstance could be that fires in general can cause interruptions to natural gas networks in infrastructure found aboveground [89]. In the case of Hurricane Sandy in New York, the percentage, 3.06%, is also relatively high. The explanation for this result could be the fact that New York's natural gas infrastructure has been in use for almost two centuries and that aging pipelines are more prone to leakage and vulnerable to storm damage and ground movement [101]. Therefore, these results are considered outliers.

As a result of these considerations, the base probability of coincidental gas and electricity outages for long-duration events was estimated to be 1.5%, which is approximately halfway between the percentage of coincidental outages in Table 1. Because fuel supply agreements typically show that all deliveries will be made within 24 to 36 h after the order has been placed [103], this upper limit of 36 h has been chosen to define when an outage should be considered "long-term". It should be considered that, as shown in Table 1, most of the time, only electricity and not natural gas outages occurred. Since no data are available on correlations for short-term outages, it was assumed that the probability of simultaneous electricity and natural gas interruption ranges from zero to the upper limit, which represents long-term blackouts. Table 2 shows a short, clear description of system failure rate estimation.

Table 2. Estimates of system failure rates. Source: adapted from [40,68,89,94–103].

Type of Failure	Reference Estimate	Lower Range	Upper Range
Failure to start (standby demand) [68]	0.67%	0.33%	1.48%
Failure to start (load demand) [68]	0.15%	0.08%	0.3%
Failure to run (standby demand) [68]	0.172%	0.086%	0.346%
Failure to run (load demand) [68]	0.086%	0.043%	0.173%
Diesel fuel supply [40,103]	36 h	18 h	72 h
Fuel supply failure (natural gas long-duration) [89,94–102]	1.5%	0.75%	3%

2.2. Costs and Benefits

Standby generators are installed for reliability purposes to keep the service of critical processes in case of the loss of the electrical power source [104]. However, costs may be a major factor in choosing a diesel generator or using natural gas or RNG [105,106]. The total cost of generating power from a backup system includes capital costs, non-fuel operating and maintenance costs, fuel costs, and decommissioning [107–109]. The benefits of backup generators include improved power reliability [110] and the ability to supply auxiliary services to the electricity grid [111]. This section supplies a cost summary of the backup generator and its associated economic benefits.

The dimensioning of backup systems is mainly based on the verification of technical reliability and the calculation of the lifecycle costs of the system [112,113]. The general equation to be solved is (Equation (1)):

$$\text{Life cycle costs} = \text{Installation costs} + \text{Decommissioning costs} + \text{Maintenance costs} + \text{Fuel costs} - \text{Benefits} \quad (1)$$

The prices of fuel, supply, maintenance [114,115], and the electrical load to be satisfied [115] are key factors in the evaluation of lifecycle costs and system reliability. Regulators and planners of electrical power systems often use the term "lost load value" to refer to the lost electrical load [116]. This term stands for the amount that the average consumer would pay to avoid a blackout [116,117]. It should be noted that the information about what individuals and society are willing and able to pay to avoid the consequences of blackouts is limited [118]. For the investigation presented here, the term "lost load value" will be considered within the potential revenues and included in the avoided outage costs.

In the past, the use of gaseous fuels in industrial applications for backup power purposes was avoided [119,120]. This decision was based on the following criteria: cost-effectiveness, power density, and perceived reliability [120]. Nevertheless, recent technological innovations such as air/fuel mixture optimization have changed these criteria [120]. Considering nominal power ranging between 350 kW to 500 kW, a cost of USD 264/kW was assumed for diesel generators, USD 792/kW was assumed for natural gas generators [121], and USD 1185/kW was assumed for biomethane microturbines [119].

To prove their ability to start and accept the required loads, standby systems should be evaluated periodically according to a documented schedule [122,123]. In the investigation presented here, an operation and maintenance cost of USD 20/kW/year was assumed for diesel generators, USD 30/kW/year was assumed for natural gas generators, and USD 8/kW/year was assumed for biomethane microturbines [119,124]. While some maintenance cost models differentiate between fixed O&M (operation and maintenance) costs (USD /kW) and variable O&M costs (USD/kWh) [119], other models compute O&M costs on a global basis [124]. In the investigation presented here, only fixed maintenance costs will be considered.

Although biomethane microturbines and natural gas generators need higher first costs, operating costs are typically much lower than those of diesel generators [125]. In this respect, both biomethane microturbines and natural gas can be expected to offer much lower incremental fuel costs than diesel [126,127].

Apart from avoiding the costs associated with electricity outages, backup generators can generate economic benefits for the owner if they also meet the operation requirements. Outage costs vary depending on (i) the time of day, (ii) the season, (iii) the duration and size of the outage, (iv) who suffers the loss of power, and (v) whether the outage is expected or unexpected [128,129]. Ancillary services can generate revenue for the owner of standby generators if they meet the performance requirements [130]. In this sense, these benefits can be provided, among other mechanisms, through energy sales in the hourly market [130]. As a result, the actual net revenues of a backup system will be the revenues obtained from the sale of energy and ancillary services (like commercial generators) minus operating expenses [131], as stated in the next equation (Equation (2)):

$$\text{Net revenue} = \text{Energy sale revenue} + \text{Ancillary service revenue} - \text{Operating expenses} \quad (2)$$

The size of these revenues will increase if operational efficiency is improved [131].

To make a comparison between the different generator technologies, the net present Value (*NPV*) is used (Equation (3)):

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \quad (3)$$

where

- R_t: net cashflow (revenues–expenses) for a specific period t;
- i: interest rate;
- t: number of time periods.

2.3. Simulation with REopt Lite

For the analysis of the different scenarios for each generator type, the REopt Lite application was used. REopt Lite is NREL's REopt web tool, which perfects the size and operating strategies of microgrids, storage, and energy/water systems. This tool is a monolith mixed-integer linear program that recommends the best mix of renewable and distributed energy, conventional generation, and energy storage technologies. This model is an extension of [132], which seeks design and dispatch decisions for a system of distributed energy resources that minimizes the cost of capital, operations, maintenance, fuel, utilities, the net of production incentives, and energy exports.

Economic resilience and environmental targets can be set in Reopt, and these are its main data inputs:

- Drivers: Energy costs and revenues, economic factors, and resilience and environmental goals;

- Technology options: Renewable generation, conventional generation, and energy storage;
- Loads: Electric loads, heating and cooling loads, and dispatchable loads.
- Once the optimization is finished, the next outputs are obtained:
- Technology recommendations;
- Optimal dispatch strategy;
- Economic outputs: Capital cost, operating cost, lifecycle cost, and net present value.

Regarding resiliency, REopt has three types of resiliency analysis within the model:

1. Optimizing for grid-connected benefits and evaluating added resiliency;
2. Optimizing system sizes for a given outage duration;
3. Including the value of resiliency in the objective function.

For this study, the second resiliency analysis was chosen since an outage duration is provided as the model input. In addition, the simulation considers a critical load factor of 75% [133].

It is also relevant to mention some of the assumptions and caveats considered by REopt Lite since they affect this study too [134]. These are the most relevant ones for this case:

- The load data reflecting one year of consumption and future loads may change (increase, decrease, and/or shift in timing).
- Optimization is based on modeling the hourly loads, generation, and storage dispatch; intra-hour variability may impact savings.
- Optimized dispatch reflects the model's optimal forecast of modeled loads, so the results present the maximum economic potential of the modeled technologies.
- Critical loads can be difficult to estimate; this contributes uncertainty to resilience analysis.
- In case of grid outage, additional integration costs may be needed to facilitate microgrid capabilities that allow the system to operate independently.
- When operating in grid-connected mode, REopt assumes that batteries are dispatched to minimize operational costs, and they may not be at a high state of charge when the outage occurs.

3. Results and Discussion

Among all possible types of commercial facilities, supermarkets were chosen for the assessment presented herein. This is because electrical and fire codes do not force these retailers to have emergency power systems. Nonetheless, there is a chance of substantial economic losses during blackouts because of lost sales in addition to the deterioration of frozen goods. In the investigation presented here, it is assumed that the backup system is adequately estimated to completely feed the critical loads of the facility at the time of an outage from the electricity grid. An important finding was the fact that using backup systems might either curtail expenses or generate benefits for a few scenarios.

Some supermarkets have backup systems that are only capable of supplying electricity to the cash registers and lighting but not to the refrigerators [135]. This was the case in 2012 for the only large supermarket in the city of South Amboy, New Jersey [135,136]. After 84 years of operation, this supermarket was forced to close in 2012 because of losses caused by a major power outage [135,136]. In the investigation presented here, an analysis will be conducted for a hypothetical supermarket found at the following site:

- 611 Bordentown Ave, South Amboy, NJ, 08879.

3.1. Electricity Consumption

To generate the average hourly energy demand profiles, values accessible through Commercial Reference Buildings [137,138], the U.S. Energy Information Administration [139], and the REopt software [140] were used. A short statement of the main points of the power estimated for a single-story, 45,000 ft^2 (4180 m^2) supermarket is included in Table 3 and Figure 2.

Table 3. Peak demands for the modeled supermarket. Source: adapted from [137–140].

Monthly Peak Demand (kW)	
Month	
January	344.89
February	322.55
March	362.03
April	356.71
May	389.22
June	453.46
July	481.46
August	469.61
September	415.77
October	387.56
November	375.90
December	348.00
TOTAL ENERGY (kWh)	2,018,760
AVERAGE LOAD (kW)	230.45
MAXIMUM ANNUAL PEAK DEMAND (kW)	481.46

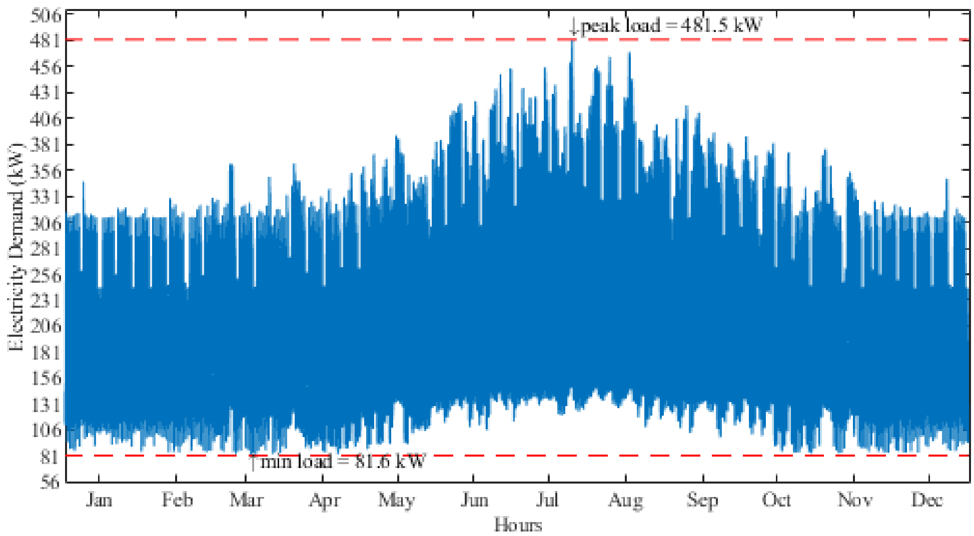

Figure 2. Typical annual demand profile for a one-story, 45,000 ft^2 (4180 m^2) supermarket found in South Amboy, New Jersey. Source: adapted from [137–140].

3.2. Assumed Costs

Table 4 supplies a summary of the backup system installation costs and the maintenance costs for the three types of diverse generators: diesel, natural gas, and biomethane microturbine. The backup system expenses include switching equipment (circuit breakers, disconnectors, and other types of switches), as well as any emission controls needed to be run for non-emergency purposes. Expenses related to the fuels that are used to supply power at the present time (2021) and predicted expense increases for the assessment span are presented in Table 5.

Table 4. Capital, running, and maintenance costs for a 350 to 500 kW rated generator. Source: adapted from [119,121,124].

Generator Type	DG	NGG	BMT
Fixed, one-time expenses incurred on the purchase (USD/kW) [119,124]	264	792	1185
Operation and maintenance costs (USD/kW/year) [121]	20	30	8
Annual increase in maintenance costs	2%	2%	2%

Table 5. Variations in fuel costs and electricity tariffs. Source: adapted from [141–159].

Variation in Fuel Costs and Electricity Tariffs	
Cost of natural gas (USD/kWh), Year 0 [141–145]	753.2
Cost of biomethane (USD/kWh), Year 0 [146–154]	2840
Cost of diesel (USD/kWh), Year 0 [155–157]	5504
Cost of diesel (USD/gallon), Year 0 [155]	11.73
Cost of electricity	Variable according to tariff
Annual increase in the cost of natural gas [143–145]	2.2%
Annual increase in the cost of biomethane [146]	2.5%
Annual increase in the cost of diesel [158]	1.3%
Annual increase in the cost of electricity [159]	−0.15%

3.3. Backup System

In supermarkets, refrigeration is the most critical load in the energy system since it manages to keep the products in good condition. Hence, the minimum size of the backup system should fulfill the refrigeration demand, which is between 43% [160] and 57% [161] of the total installed load. Since the maximum annual peak demand is 481.46 kW for the analyzed case, it is assumed that a backup generator with nominal power ranging in size from 275 to 500 kW will be sufficient to meet critical loads. Furthermore, for the simulation, a critical load factor of 75% [133] will be used, which stands for the ratio of actual kilowatt-hours used to the total possible kilowatt-hours that could be used at the kW level.

Microgrid upgrade costs are supposed to reach 30% of the system's capital cost [162]. and avoided outage costs are supposed to be USD 3 per kWh [162]. Apart from (i) fixed, one-time expenses incurred on the purchase and (ii) operation and maintenance costs, it is necessary to consider fuel consumption costs. The fuel consumption data for generators were obtained from representative generator model data sheets. Fuel consumed depending on the percentage load is shown in Table 6. The linear adjustments of the data available in Table 6 are shown in Figure 3. From an electrical point of view, diesel engines are the most efficient technology, as can be seen in Figure 3.

Table 6. Fuel consumption for a 500 kW rated emergency power system depending on load percentage. Source: adapted from [163–167].

Generator Type	Diesel (l/h) [163]	Diesel (US Gallon/h)	Diesel (kW)	Natural Gas (m^3/h) [164]	Natural Gas (kW)	Biomethane Microturbine (l/h)	Biomethane Microturbine (kW) [165–167]
Percentage of load at 25%	42.28	11.17	454.26	72	747.33	44.74	480.64
Percentage of load at 50%	66.28	17.51	712.16	103	1069.71	89.22	958.34
Percentage of load at 75%	91.42	24.15	981.79	135	1397.95	133.93	1438.98
Percentage load at 100%	121.13	32.00	1301.24	166	1720.33	178.67	1919.62

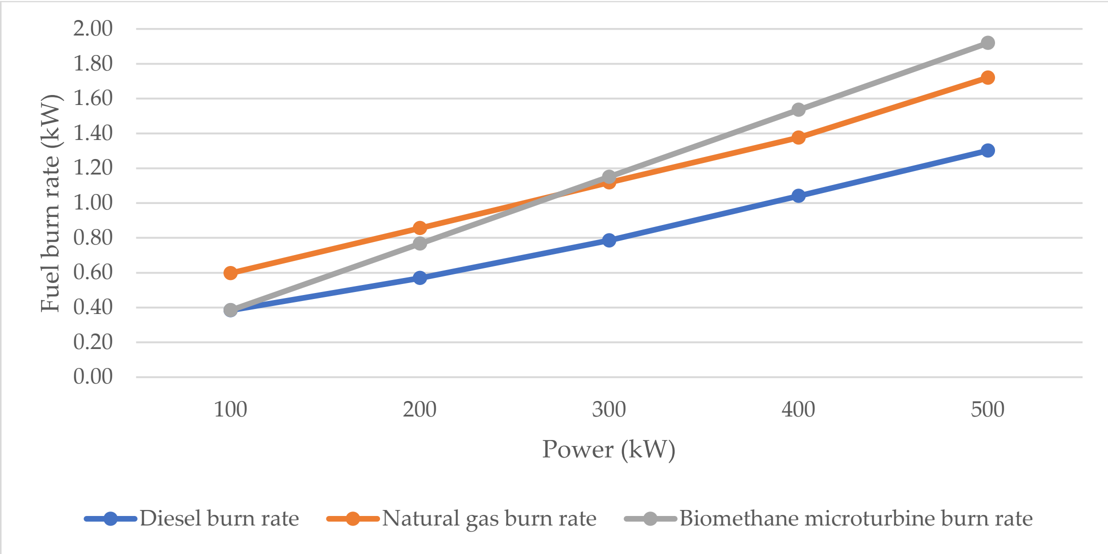

Figure 3. Fuel consumption for modeled generators. Source: adapted from [163–167].

Table 7 shows that, considering only variable costs, both NGG and biomethane microturbines show a lower marginal cost for energy produced by the generator than the DG.

3.4. Average Availability Depending on the Type of Generator Used

Table 8 shows how dependable the diverse types of generators (diesel, natural gas, or biomethane microturbines) are against power outages. During this time, the generators are considered to offer both backup and ancillary services. As can be seen in Table 8, the biomethane microturbines have a considerably greater probability of continuity than the other technologies.

Table 7. Total discounted expenses per unit of kWh produced. Source: adapted from [119,168–176].

Generator Type	Diesel Engine	Natural Gas Engine	Biomethane Microturbine
Plant size (MW)	0.35 to 0.5	0.35 to 0.5	0.35 to 0.5
Fuel cost (USD/kWh)	5504	753.2	2840
Amount of thermal energy needed to generate one electrical kWh (heat rate) [170–173]	3.08	2.64	3.27
Fixed operation and maintenance costs (USD/kW-y)	20	30	8
Variable operation and maintenance costs (USD/kW-y)	0	0	0
Costs necessary for the construction of the plant without considering interest rates	264	792	1185
Interest rate [119,174,175]	8.3%	8.3%	8.3%
Mortgage period (years)	20	20	20

Table 8. Weighted average availability by resource category, ISO-NE, 2010–2013. Source: adapted from [176–178].

Year	2010	2011	2012	2013
Diesel reliability (%)	93.3	93.2	92.2	93.5
Natural gas reliability (%) Difference (taking diesel engine reliability as a reference) (%)	95.8 +2.5	95.9 +2.7	96.1 +3.9	96.4 +2.9
Biomethane microturbines (%) (Set of 7 microturbines working in an emergency backup mode) Difference (taking diesel engine reliability as a reference) (%)	99.9 +6.6	99.9 +6.7	99.9 +7.2	99.9 +6.4

3.5. Markets and Revenue Opportunities

New Jersey has a wholesale electricity market in which electricity suppliers and buyers send bids to sell and buy energy [179]. The investigation presented here assumed that, through generators, it is possible to reduce power consumption quickly and, for a brief period, avoid peak consumption (peak shaving). In addition, sometimes it is possible to avoid buying electricity from the power grid because the user can generate his own electricity at a lower cost than the price of market electricity rates.

3.6. Market Analysis

New Jersey is found within the PJM control area [180]. In this case, the electricity supply company selected to conduct the analysis presented here is the Public Service Electric and Gas Company. For the case studies presented in this research, the "LPG Rate Schedule—General Lighting and Power Service" [181–183] rate was used. For the assessment presented here, it will be assumed that the supermarket does not choose a third supplier, thus using the Basic Generation Service, BGS [184].

3.6.1. Diesel Engine as Storage-Free Dispatchable Solution for Critical Power Supply

The REopt Lite software developed by NREL was used to perform the energy resilience analysis assuming the following inputs:

- Outage duration (hours): 36 h;
- Critical load factor (%): 75%;
- Microgrid upgrade cost: 30% of system capital cost;
- Avoided outage costs: USD 3 per kWh.

It can be seen that the most cost-effective diesel generator should be sized at 354 kW so that the critical load can be met at the proposed site. Figure 4 shows the system performance for the specified outage period, which is replicated throughout the year.

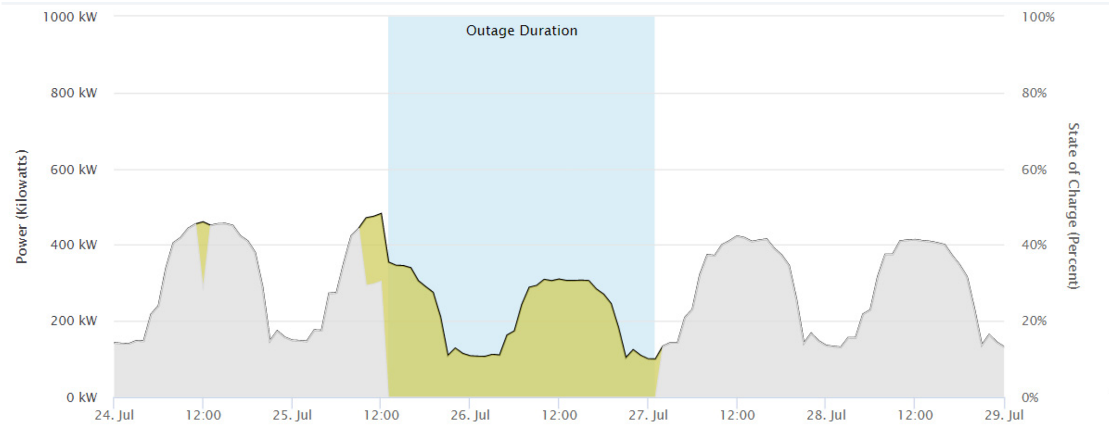

Figure 4. System performance for a diesel engine as a storage-free dispatchable solution for critical power supply. Source: own elaboration.

Figure 5 shows the reduction in peak load that occurs when a storage-free dispatchable 354 kW diesel engine is implemented for critical power supply.

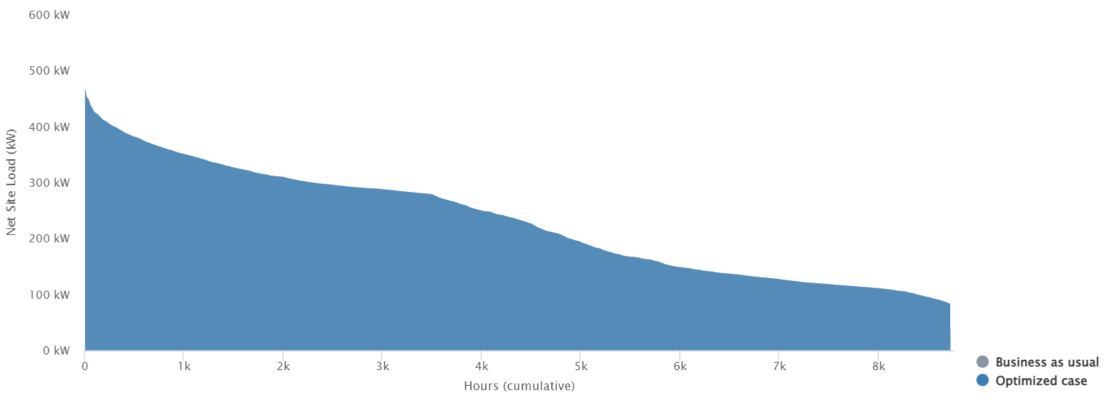

Figure 5. Net load duration for a diesel engine as a storage-free dispatchable solution for critical power supply. Source: own elaboration.

Figure 6 presents an evaluation of the amount of time that the proposed system will sustain the critical load for outages starting at every hour of the year.

Figure 7 shows that, supposing an avoided outage cost of USD 3 per kWh and a microgrid upgrade cost of 30% of the system capital cost, the *NPV*, after microgrid costs and benefits, will be USD 2,124,798. In this analysis, an avoided outage cost of USD 3/kWh is enough to obtain USD 2,124,798 of revenue if this diesel-based backup is installed and one outage happens during the lifecycle of the installation. The avoided outage cost was calculated using the Interruption Cost Estimate (ICE) Calculator (a tool designed to estimate interruption costs associated with reliability improvements) [185].

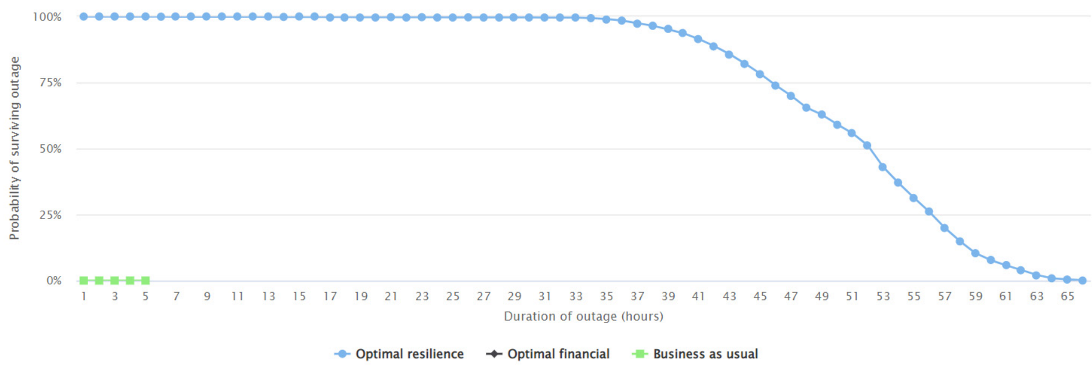

Figure 6. Outage simulation for a diesel engine as a storage-free dispatchable solution for critical power supply. Source: own elaboration.

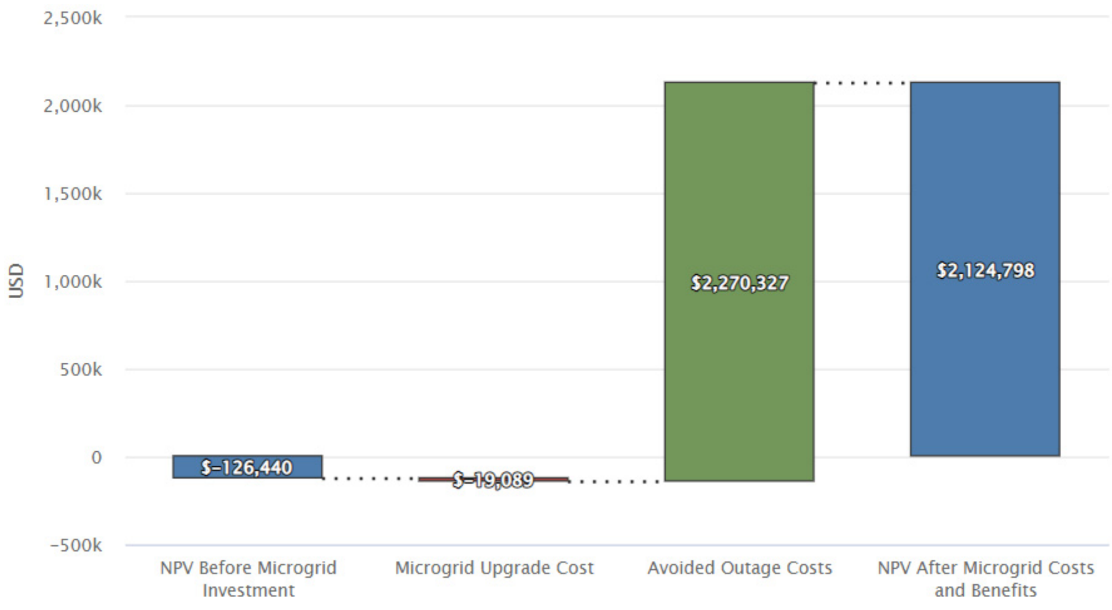

Figure 7. Resilience costs and benefits for a diesel engine as a storage-free dispatchable solution for critical power supply. Source: own elaboration.

3.6.2. Natural Gas Engine as Storage-Free Dispatchable Solution

The REopt Lite software developed by NREL was used to perform the energy resilience analysis assuming the following inputs:

- Outage duration (hours): 36 h;
- Critical load factor (%): 75%;
- Microgrid upgrade cost: 30% of system capital cost;
- Avoided outage costs: USD 3 per kWh.

As with the diesel generator case, the natural gas engine had a size of 354 kW to meet the proposed location critical load.

Since the nominal power (354 kW) is the same as the simulated power for the previously displayed diesel case, the system performance, the net load duration, and the outage simulation performance for the natural gas engine are identical to the ones presented in Figure 4, Figure 5, and Figure 7, respectively.

Figure 8 shows that, supposing an avoided outage cost of USD 3 per kWh and a microgrid upgrade cost of 30% of the system capital cost, the *NPV* after microgrid costs and benefits will be USD 1,930,083. In this analysis, an avoided outage cost of USD 3/kWh is enough to obtain USD 1,930,083 of revenue if this natural gas engine system is installed and one outage happens during the lifecycle of the installation.

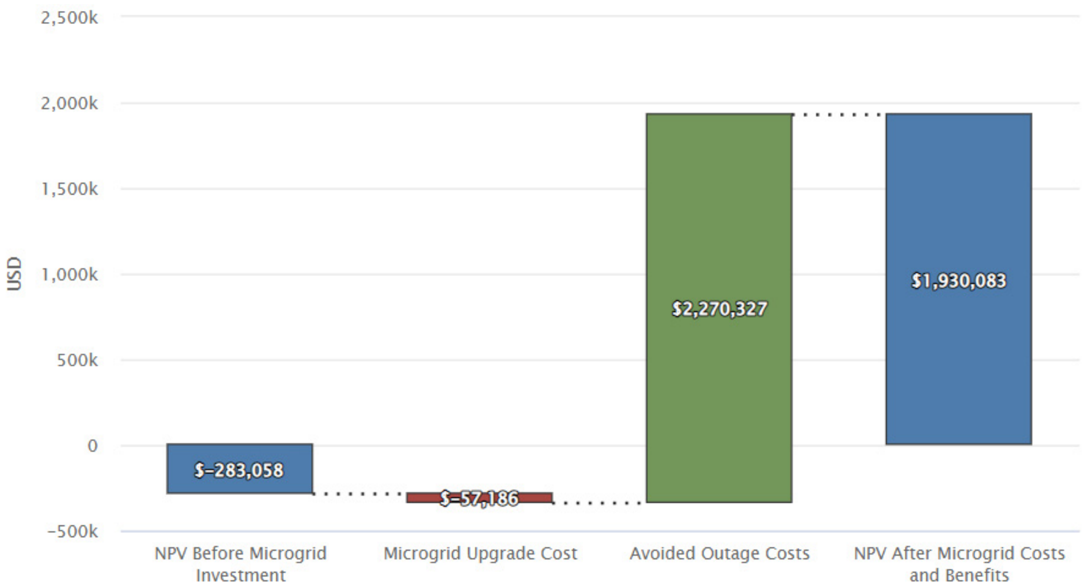

Figure 8. Resilience costs and benefits for a natural gas engine as a storage-free dispatchable solution for critical power supply. Source: own elaboration.

3.6.3. Biomethane Microturbine as Storage-Free Dispatchable Solution

The REopt Lite software developed by NREL was used to perform the energy resilience analysis assuming the following inputs:

- Outage duration (hours): 36 h;
- Critical load factor (%): 75%;
- Microgrid upgrade cost: 30% of system capital cost;
- Avoided outage costs: USD 3 per kWh.

As in the diesel and natural gas generator cases, a 354 kW power biomethane microturbine was selected to meet the critical load of the proposed site.

Since the nominal power (354 kW) is the same as the simulated power for the previously displayed diesel and natural gas cases, the system performance, the net load duration, and the outage simulation performance for the natural gas engine are identical to the ones presented in Figure 4, Figure 5, and Figure 7, respectively.

Figure 9 shows that, supposing an avoided outage cost of USD 3 per kWh and a microgrid upgrade cost of 30% of the system capital cost, the *NPV* after microgrid costs and benefits will reach USD 1,872,573. In this analysis, an avoided outage cost of USD 3/kWh is enough to obtain USD 1,872,573 of revenues if this effective biomethane microturbine system is installed and one outage happens during the lifecycle of the installation.

A positive *NPV* means that the backup system can not only protect the user from a resilience point of view but also bring revenue to the backup system owner because of the services provided to the power supply. It should be remarked that markets and tariffs are dynamic, and as such, the revenues obtained from supplying a range of ancillary services also vary during the time the installation is working. There are some regions where significant financial opportunities exist to reduce the cost of owning a backup generator. In any case, in those scenarios, where backup generators can supply auxiliary services, the economic results are better. As can be seen in this section, the auxiliary service revenues obtained in the case of an outage and the lower operating costs of the modeled backup systems can compensate for their higher capital cost. That said, and given regulation issues, in some cases, it is not possible to run diesel generators for purposes other than as backup generators. This could influence the choice of the type of generator.

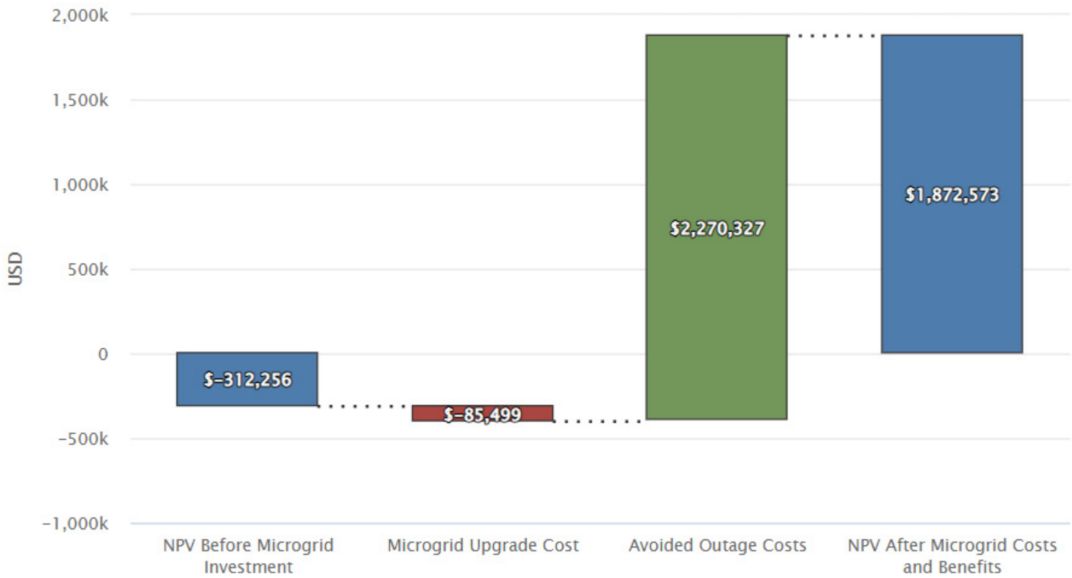

Figure 9. Resilience costs and benefits for an effective biomethane microturbine as a storage-free dispatchable solution for critical power supply. Source: own elaboration.

The increase in wildfires and extreme weather events requires a redesign of power systems to maximize resilience and reduce potential outages. This analysis shows that it is possible to greatly improve the reliability and resilience of a critical facility suffering a grid power outage by means of the integration of an optimally designed microgrid focused on maintaining a required critical load factor for an average outage duration. The results show that it is feasible to maintain up to 75% of the load factor in a 36 h duration outage event, obtaining a positive *NPV*. This provides a new design paradigm in which the design of a new building energy system can be integrated with an optimally resilient system and, at the same time, avoid the outage costs and obtain a positive economic outcome. The proposed methodology can be applied to many different scenarios worldwide, and it is necessary to remark that other non-accountable benefits—such as continuity in sanitary facility operation and the avoidance of food deterioration in food storage buildings—are obtained. It is necessary to remark that the results show that the integration of renewable energy generators such as biomethane turbines is economically and technically feasible, providing a resilient solution that contributes to decarbonization. Future research can focus on the development of fuel supply schemes that can maximize the fuel supply and storage reliability so that the studied facility can maintain the required fuel levels during the outages. In this sense, it is necessary to remark that the three studied fuels can be effectively stored on-site using diesel tanks, liquified natural gas systems, and biomethane tanks, reducing possible supply disruptions in case of a supply outage. Therefore, it is necessary to develop future research on fuel supply optimization that can ensure that the power generation requirements are assured and, at the same time, that the storage costs are minimal.

4. Conclusions

Power outages due to weather-related events and wildfires have increased during the last few years, and it is necessary to design resilient energy systems that can supply the required energy supply to critical buildings. This research presents the results of an optimal design scheme applied to critical buildings in order to reduce the effects of a power outage by ensuring that a high percentage of the critical load supply is maintained. A multi-scenario analysis for different microgrid systems with different power generators was performed using the REopt Lite tool. The results show that there are benefits resulting from the use of several backup systems configured to also obtain economic benefits by supplying ancillary services to the electricity grid. Although in most cases the electricity interruptions are not long, in areas that are prone to natural disasters, there is a greater likelihood of long-term outages, and specific strategies for this possibility must be considered. The use of backup generators to supply auxiliary services can significantly compensate for the necessary investment in such generators. A parametric analysis was performed for diesel, natural gas, and biomethane generators. The results show that the increased use of generators can also help to improve system reliability and that, to improve economic performance, as storage-free dispatchable solutions for critical power supply use expensive fuel, the optimal mode of operation would be one in which the generator is in operation regularly but for a small amount of time per day. In the research case studies presented here, diesel generators provide lower capital costs, which makes them a better choice than natural gas generators and biomethane microturbines. An important result is that it is possible to integrate renewable energy-driven generator systems in resilient microgrids. Biomethane microturbines are designed specifically for mission-critical loads, offer minimal maintenance, and are modular solutions with the highest reliability for the three technologies assessed. Considering that natural gas prices for industrial customers in the US are typically around 0.73 USD/MWh, biomethane's higher costs make this technology uncompetitive in the absence of government subsidies. It can be concluded that, depending on which is the preponderant design parameter (cost of capital, cost of operation, or reliability of the scheme), the storage-free dispatchable solution for the critical power supply to be selected will vary.

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Nomenclature

BTM	Biomethane microturbine
DG	Diesel generator
EFC	Electrical and fire codes
FTS	Failure to start
ICE	Interruption cost estimate
LCC	Lifecycle cost
NG	Natural gas
NGG	Natural gas generator
NPV	Net present value
O&M	Operation and maintenance
RNG	Renewable natural gas

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