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RESEARCH ARTICLE

Sizing and Life Cycle Assessment of Small-Scale Power Backup Solutions: A Statistical Approach

ARMIN ABDOLMOHAMMADI, ALIREZA NEMATI, MERIDIAN HAAS, AND SHIMA NAZARI, (Member, IEEE)
Department of Mechanical and Aerospace Engineering, University of California at Davis, Davis, CA 95616, USA
Corresponding author: Armin Abdolmohammadi (abdolmohammadi@ucdavis.edu)

ABSTRACT The increasing frequency of natural disasters, such as floods and wildfires, necessitates enhanced emergency management plans. Reliable backup power for critical infrastructure along evacuation routes is urgent. Using a case study approach, this study investigated small scale power backup solutions for a traffic light. We deployed a statistical approach to study the sizing problem for four alternative solutions: gasoline generator, battery pack, fuel cell system, and photovoltaic (PV) panels with a battery. Leveraging data from the State of California, we constructed probability distribution profiles to model power outage occurrence and duration and considered two representative high and low Global Horizontal Irradiance (GHI) locations. A Monte Carlo simulation, generating 10,000 power outage scenarios, was adopted to size the systems and evaluate their lifetime cost and Global Warming Potential (GWP). Following this approach allowed us to compare different systems and sizes based on the percentage of power outages that they can support, which is superior to sizing and analysis based on a single scenario. Our results show that the PV-battery system is the optimal choice, especially for areas with high GHI. The battery only option is a suitable choice only for short power outage scenarios, but increasing the battery size to cover prolonged outages will be both expensive and ungreen. Fuel cell systems, on the other hand, can be a better choice for the longest events; however, results show that, unlike the conventional belief, cheap gasoline generators can be comparable to fuel cell systems in terms of GWP due to the standby nature of power backup systems and the high CO2 emissions produced during the manufacturing process for fuel cell engine and hydrogen tanks. This study also explored additional factors for gasoline generators and fuel cells, such as PV panel shading, refueling cost and frequency, and the sensitivity of outcomes to component cost assumptions and variations.

INDEX TERMS Cost analysis, life cycle assessment, Monte Carlo, optimal sizing, power backup.

I. INTRODUCTION

Many critical infrastructures, from hospitals and data centers to telecommunication networks and emergency response systems, rely on a continuous and reliable supply of power. These vital operations necessitate uninterrupted energy or risk significant financial losses, compromised operations, and potential safety threats. In related applications, such as telecommunication towers, remote monitoring and control systems, and traffic lights, power backup solutions have been well-researched [1], [2].

A wide range of reliable power backup systems are available for consideration. Traditional solutions, such as gasoline or diesel generators, provide robust power generation capabilities but may be associated with fuel supply challenges and emissions concerns. Photovoltaic (PV) and battery systems have gained attention in recent years, with the ability to harness solar energy and store it for future use. These systems offer sustainability benefits and can be cost-effective in the long run [3]. Additionally, emerging technologies like Proton Exchange Membrane (PEM) hydrogen fuel cells present an innovative backup solution by leveraging hydrogen as a clean energy source. Given the diversity of power backup solutions and the wide range of their price and environmental impact,

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the most suitable option is not evident and depends on various factors.

There have been extensive studies on the sizing of renewable energy-based microgrids based on cost optimization. Notably, substantial research has explored the sizing of large, complex microgrids, often designed for remote area communities and high power demands in island mode [4], [5], [6], [7], [8]. Zhou et al. provide a review of the state of the art in microgrid optimal sizing [9]. Similar sizing problems have been solved for grid-connected PV-battery systems [10]. Such systems generally run constantly and are sized to provide the proposed power load for a given system.

Backup systems, however, must be sized differently and should rely on statistical analysis of power outage frequency and duration. Sizing studies for backup power generation frameworks have been performed for sizing PV with a fixed battery size [11], backup systems with a fuel cell and battery [12], and fuel cell and battery with an electrolyzer PV system [13]. Dual optimization problems have been introduced to size a backup battery and generator with a PV system, with the goal of minimizing cost and maintain reliability [14]. Yoo et al. independently proposed a methodology for sizing battery energy storage systems that is aimed at enhancing the integration of solar farms by incorporating system marginal price patterns, also referred to as market conditions [15].

The Life Cycle Assessment (LCA) of power generation systems has received substantial research interest. Smith et al. conducted an LCA that compared the environmental impacts of a Gasoline/PV/wind hybrid microgrid on Koh Jig Island, Thailand, with grid extension and home gasoline generators as alternative energy sources [16]. Mahmud et al. conducted a techno-economic operation and environmental LCA of a solar PV-driven islanded microgrid, focusing on the system's feasibility and sustainability for isolated communities [17]. It is important to note that research on power generation systems often reveals high environmental impacts associated with fossil fuel-based systems due to emissions during their operational ''use'' phase. However, power backup systems, due to their standby nature, may yield different environmental outcomes and therefore must be studied separately. Significant research has examined large-scale energy-generating systems. Varun et al. conducted a review of LCA for renewable energy systems in electricity generation. They emphasized the need to consider carbon emissions from renewable energy systems, even though they are generally more environmentally friendly [18]. Some studies have considered both the size and environmental impacts of energy systems. Tsai et al., explored the effectiveness of various hybrid renewable energy systems in island mode, focusing on the technical and economic viability as well as environmental impacts [19]. Jiménez-Vargas et al. introduced a novel approach for sizing microgrids, which integrated LCA of implementation and operation stages. Their methodology employed a multi-objective function inspired by the ReCiPe methodology [20].

Previous research has also explored various large-scale backup systems designed for high-demand scenarios, such as buildings or districts. However, there is a lack of comprehensive comparative analyses that consider multiple system options and their cost-effectiveness as the backup for small-scale systems. With the increasing environmental concerns, there is a growing need to integrate life cycle environmental impact analysis into the evaluation of backup systems.

This research is motivated by two key factors: the need to address the environmental impact of backup power systems and the upcoming bans on small gas generators in California, which are frequently used to support low-power systems [21], [22]. Additionally, in California, the increasing threat of power outages caused by wildfires has led to a greater emphasis on robust backup systems. Since wildfires can be caused by power line failures, frequent power shutdowns may become necessary during extreme weather conditions [23]. In such events, having operational signs and signals along evacuation routes is essential, leading to the installation of backup power systems at critical intersections in certain areas of California [24].

Traditionally, in the event of an extended power outage, portable gasoline or diesel generators have to be transported to the site of the these intersections. However, California's new legislation will ban the sale of new small gasoline generators in 2028 [25]; therefore, effective alternative backup systems must be considered to fill the gap. Recently, some fuel cell backup systems were installed in critical intersections such as Placerville, CA [26] and Santa Clarita, CA [27]. These backup systems provide several days of quiet operation, easy maintenance, and low emissions. Similarly, PEM fuels cells have been investigated as a backup power solution for remote cellular towers [28], [29].

A. CONTRIBUTIONS

This study investigates four backup systems, including gasoline generator, battery pack, fuel cells, and PV panels with battery, implemented as a microgrid at a three-way intersection in Placerville, California, where traffic light data were recorded. The novelty of this work lies within its statistical approach to sizing power backup systems. While stochastic approaches and Monte Carlo simulations have been previously utilized to generate daily demand profiles for battery sizing to do outage protection [30], this study introduces a novel application by generating outage scenarios for system sizing across multiple systems. Recognizing that power outages occur multiple times throughout the year with varying durations and start times, relying on a single outage scenario for sizing may not yield the most optimal solution. By utilizing real data to construct probability distributions of outage duration and start time, and employing a Monte Carlo approach, a diverse range of power outage scenarios

TABLE 1. Nomenclature section to the paper.

Variable	Description	Unit
I_h	Global horizontal irradiance	Wh/m^2
P_{GG}	Gasoline generator nominal power	kWp
η_{GG}	Diesel Generator efficiency	-
T_F	Diesel tank size	gal
SOF	State of fuel	–
η_{GG}	Gasoline generator efficiency	-
k_{GG}	Gasoline generator Consumption rate	Gal / kWh
x_{pv}	PV Surface	m^2
Q_b	Battery Capacity	kWh
η_b	Battery Efficiency	-
η_{pv}	PV efficiency	-
P_d	The energy demand	kWh
ζ	Battery state of charge	-
P_{FC}	Fuel cell nominal power	kWp
η_{FC}	Fuel cell efficiency	-
SOH	State of hydrogen	-
k_{FC}	Fuel Cell consumption rate	kg/kWh
m_{H_2}	Hydrogen Tank outlet	kg

reflecting the variability and unpredictability of actual events were generated. These scenarios were then utilized for sizing the considered power backup systems. To the best of our knowledge this approach towards sizing of backup systems is novel. Furthermore, this research addresses the critical need for an evaluation and comparison of backup power systems tailored to small-scale users and the integration of life cycle environmental impact analysis into the assessment of backup power systems.

Section II describes the considered power backup systems, the optimization methodology, data gathering and scenario generation. Section III presents the LCA methodology, and Section IV reviews the results of sizing and cost sensitivity analysis.

II. SYSTEM AND METHODOLOGY

The primary focus of this study is cost assessment of different power backup solutions. We first describe each system and explain the associated costs. Next, we address the methodology used for sizing and optimization of these systems, and finally we detail the methodological framework for probabilistic evaluation of power outage data and the Monte Carlo simulation approach.

We conducted a cost assessment to evaluate the financial viability of different backup power systems by considering several cost components. the initial purchasing cost, C_{ip}, includes the cost of core components and storage units such as fuel or hydrogen tanks. Additionally, the cost of commissioning and installation, C_I, is also considered even though this remains a constant value that only depends on the considered system. Furthermore, operation and maintenance cost, $C_{O\&M}$, is accounted for the system's expected lifespan of 10 years. All the equipment costs, such as pipes, valves, and wires, are listed as equipment costs, C_{eq}. Other costs, such as fuel refilling and replacement cost, C_r, is taken into account. Finally, the savings, C_S, was considered for systems that have the potential to generate excess electricity and reduce the power intake from the grid. Annual and future costs were converted into present values using the Net Present Value (NPV). All values for these costs are listed and detailed in Table 3 These cost components were included in optimization framework to determine the optimal sizing and cost-effectiveness of the backup power systems.

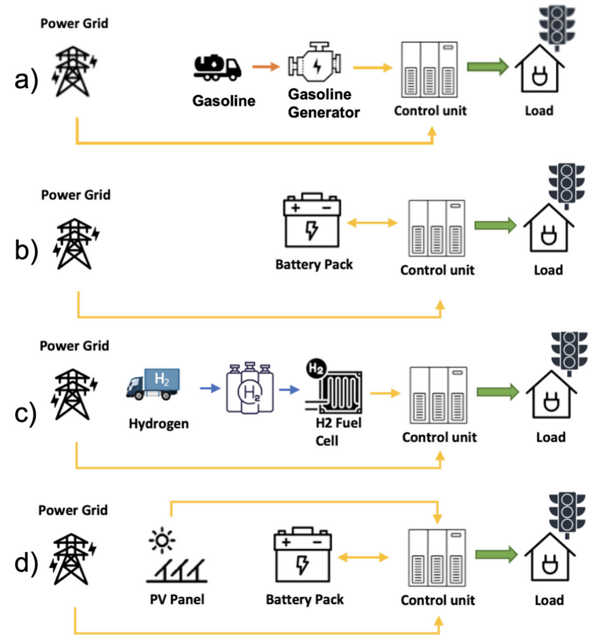

FIGURE 1. System schematics showing the main components of each backup system, the flow of fuel, hydrogen, electricity and demand for: (a) gasoline generator, (b) battery pack, (c) fuel cell, and (d) PV panels and battery.

A. POWER BACKUP SYSTEMS

1) GASOLINE GENERATOR

Gasoline generators are commonly used for backup power during outages due to their low cost. They offer portability and simple installation, making them suitable for temporary power needs. Nevertheless, they have significant operating costs (refueling and maintenance) and cause noise pollution. The negative environmental impact of these systems comes from tail pipe emissions, which are an additional concern that has caused some areas, such as California, to ban these systems in near future. In our cost assessment, the cost of a gasoline generator involves factors such as the initial purchase cost, the cost of an external gasoline tank per gallon, fuel cost, and equipment expenses that includes items such as pipes, valves, and cables.

2) BATTERY STORAGE SYSTEM

Battery backup systems are gaining popularity due to their zero emissions during the use phase and minimal maintenance requirements. These systems can be charged through the power grid, and operate silently. The costs consists of the initial cost of the battery cell and equipment, which includes an inverter and control system. Annual operation and maintenance costs includes regular maintenance and potential repairs. Replacement cost for the battery cells are included in the analysis to account for battery degradation equal to 80% of total capacity at the end of lifespan. In this study, we considered new batteries will be used for the purposes of power backup. However, acquiring used batteries, that will be available in the future due to the growing electric vehicle market, can substantially reduce costs.

3) PHOTOVOLTAIC WITH BATTERY PACK (PV-B)

The PV-battery system generates and stores electricity. This system is eco-friendly as it has zero emissions during operation. The cost breakdown for this system includes an initial purchasing cost for solar panels, batteries, installation, and commissioning costs. Battery replacement costs are considered due to battery degradation as previously explained. Equipment costs cover components, such as branch connectors, charger controllers, and DC/DC converters, ensuring a precise cost assessment.

This system can operate independently or in conjunction with the central grid, reducing energy costs. Surplus energy can be transmitted to the grid, promoting sustainable energy practices through net metering or feed-in tariffs. In California, the Net Energy Metering (NEM) 2.0 program [31], assumed in this study, allows solar panel owners to earn credits for excess electricity that they generate. The energy trade ratio is one to one under NEM 2.0 program, meaning that for every 1 kWh energy sent to the grid, the panel owner can use 1 kWh of energy from the grid at a later time. The compensation rate for surplus energy at the end of the contract year is typically lower than the retail rate [32]. The electricity costs of \$0.34 per kWh and a \$0.031 per kWh surplus energy selling rate [32] is considered in this study.

To determine the optimal sizing for photovoltaic panels in their various configurations, solar radiation data is employed. The data from the National Solar Radiation Database [33] gives the Global Horizontal Irradiance (GHI), I_h, for every 30 minutes. To account for variations in solar irradiance, we selected two representative locations with different Global Horizontal Irradiance (GHI) levels. The high GHI location is a traffic light at the intersection of Industrial Dr and Missouri Flat Rd in Placerville, CA (38.69, −120.82), which currently utilizes a hydrogen fuel cell, allowing us to conduct tests to get power demand information. Placerville has an average GHI of 5.35 kWh/day/m^2. For the low GHI location, we chose a site in San Francisco, CA (37.77, -122.46), which has an average GHI of 4.15 kWh/day/m^2. This selection enabled us to capture the effect of different GHI levels on the system sizing.

In California, some power outages are intentionally implemented to reduce wildfire risks [22], making the deployment of backup power systems in national parks and other wooded areas increasingly necessary. To evaluate the feasibility of using PV systems in these shaded environments, we conducted a shading study to assess the impact on PV panel performance. We introduced the shading ratio (SR), which quantifies the ratio of GHI in shaded versus unshaded conditions. This analysis helped us understand how shading affects the optimal sizing of PV-battery systems in such areas.

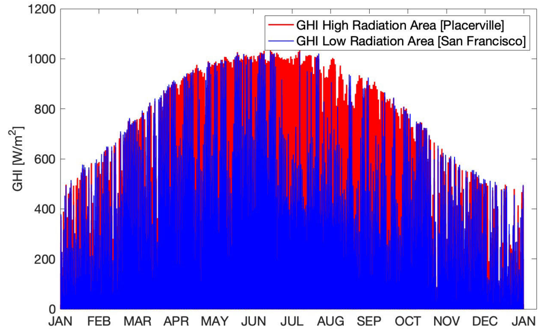

FIGURE 2. Global horizontal irradiance (GHI) data for two location of high and low radiation in California for the year 2021 [33].

To account for the impact of shading on PV panel performance, various shading scenarios were considered. The shading ratios (SR) of 25%, 50%, and 75% were used to simulate different levels of shading that PV panels might encounter due to obstacles such as buildings, trees, or temporary obstructions. The shading ratio (SR) represents the percentage of the GHI not available to the PV panel. This assumption is sufficient for our research as a more comprehensive approach necessitates including factors like the type of panel, cell arrangement, part of the panel covered, and the surface area of the shade, which are beyond the scope of this study. Previous research used LiDAR to assess tree-induced shading in urban areas, finding that trees can reduce direct radiation by 23% to 74%, with a 38% average reduction in total solar radiation received by residential rooftops [34]. The smoke generated by wildfires is another factor that diminishes the radiation reaching PV panels, consequently reducing their power output, as discussed in a study on radiation reduction and power drop in PV arrays by A. J. Ali et al. [35].

4) HYDROGEN FUEL CELL SYSTEM (FC)

This system consists of a PEM fuel cell engine, hydrogen storage tanks, and various supporting parts. Although hydrogen fuel cells might be considered more environmentally friendly due to zero use phase emissions, they come with a relatively high initial cost compared to other backup systems. To calculate the cost of this system, we considered the initial purchase cost of the PEM engine and the hydrogen tanks which depends on system size and capacity. Installation costs for the hydrogen storage tank and hydrogen refilling expenses are also considered. The auxiliary equipment costs, such as piping, valves, and electrical components, are part of the equipment cost. Additionally, we included the operation and maintenance cost over the system's lifetime, covering periodic maintenance and repairs. Replacement costs were not considered for the fuel cell since we assumed a lifetime of

10 years for the PEM engines. Table 3 in Appendix provides the list of all considered costs for studied systems.

B. THE OPTIMAL SIZING PROBLEM

To find the optimal size for components of power backup systems, an optimization problem was formulated for each case. Decision variables include PV panels, batteries, fuel cells, generators and fuel storage size. To avoid repetition, the optimization problem for only one of the systems is provided: the PV-battery system with two decision variables. The results of the optimization problem provide the optimal size and quantity of components for each considered power outage event.

Photovoltaic with Battery P(PV-B): In the PV-battery system, the main goal is to minimize the total system cost, denoted as C_{total}. This cost includes the cost of main components, C_{pv} and C_b, multiplied by their system sizes, X_{pv} and Q_b. The cost function also include equipment costs, C_{eq}, and installation fees, C_I, as well as ongoing annual expenditures, including operation and maintenance, $C_{O\&M}$, and savings linked to electricity production based on NEM 2.0, C_S, which must be evaluated in terms of present value. The values used are listed in Table 3.

$$\text{Minimize}: \; C_{Total} = C_b Q_b + C_{pv} X_{pv} + C_{eq} + C_I + (C_{O\&M} - C_S)\frac{(1+r_d)^n - 1}{r_d(1+r_d)^n} \quad (1)$$

$$\text{subject to}: \; 0 \leq X_{pv} \leq X_{max} \quad (2a)$$

$$Q_b \geq 0 \quad (2b)$$

$$\zeta(1) = 1 \quad (2c)$$

$$\zeta_{min} \leq \zeta(i) \leq \zeta_{max} \quad i = 2, 3, \ldots, N \quad (2d)$$

$$\zeta(i) = \zeta(i-1) + \frac{p_b(i)\Delta T}{Q_b}\eta_b^{sgn(p_b)} \quad i = 2, 3, \ldots, N \quad (2e)$$

$$p_b(i) = p_{pv}(i) - p_d(i) \quad i = 2, 3, \ldots, N \quad (2f)$$

$$P_{pv}(i) \geq p_{pv}(i) \quad i = 2, 3, \ldots, N \quad (2g)$$

$$P_{pv}(i) = \eta_{pv} X_{pv} I_h(i) \quad i = 2, 3, \ldots, N \quad (2h)$$

Equation (2a) limits the size of the PV panels to be non-negative and smaller than a max value. This value is determined by the factors such as roof size and in this study it is set to 10 m^2. The inequality (2b) imposes a non negative battery capacity. Equation (2c) and inequality (2d) ensure that the initial state of energy is at 100% and it will stay within the boundary of 20% to 100% at all times. The equality constraint (2e) implements the state of energy dynamics for the battery in which $p_b(i)$ is the battery power at step i and η_b is the battery electro-chemical efficiency assumed to be 95%. ΔT is the step time discretization equal to 30 min in this study. The problem horizon, N, depends on the power outage duration. The equality (2f) imposes the conservation of energy in the system in which p_{pv} is the energy produced in the PV panels and p_d is the power demand. Inequality (2g) restricts the PV produced power to the maximum value possible to produce in the panels, P_{pv}, that is determined by the GHI value at each time step, $I_h(i)$, the size of the panels, X_{pv}, and the panel efficiency, η_{pv} computed in Equation (2h).

The net present value of future costs in (1) is calculated according to the method presented in [36]. For the corresponding annual costs, the total cost over the lifetime $P_{v,T}$ will be

$$P_{v,T} = \sum_{i=1}^{n} \frac{C_n}{(1-r_d)^n} \quad (3)$$

where C_n is the total cost in year n, and r_d is the real discount rate that is adjusted to eliminate the effect of expected inflation. We assumed a constant annual cost for the system over its lifetime similar to [37]. Additionally, we distribute the refueling and refilling cost evenly over the system's lifetime. With these assumptions, the present value over 10 years will be

$$P_{v,T} = C_{avg}\frac{(1+r_d)^n - 1}{r_d(1+r_d)^n} \quad (4)$$

in which C_{avg} is the average annual cost, which includes operation and maintenance cost as well as average replacement cost.

C. POWER OUTAGE PROBABILITY

The core of this study lies within the statistical approach deployed for sizing all the considered backup systems across a multitude of power outage scenarios. The Monte Carlo methodology enabled us to obtain a more optimal system size estimation based on the desired percentage of covered outages. Each power outage scenario is characterized by two parameters: outage duration and the start date and time.

For the start date and time of power outages, we used data from Bloomenergy [38], which sourced a power outage map for California. This data included blackout periods, times, locations, and the number of impacted customers, allowing us to generate probability distributions for specific months. For power outage duration, is derived from PG&E electric reliability report [39], which details major event days, outage duration's, affected customers, and restoration times. The data revealed a spectrum of outage duration, ranging from short disruptions of a few hours to more prolonged outages extending up to 96 hours. The distribution of these power outages in terms of month of the year and duration is shown in Figure 3.

The Monte Carlo simulation used in this study was designed to generate realistic power outage scenarios based on historical data and probabilistic modeling. The following are the specific parameters and assumptions used in the simulation:

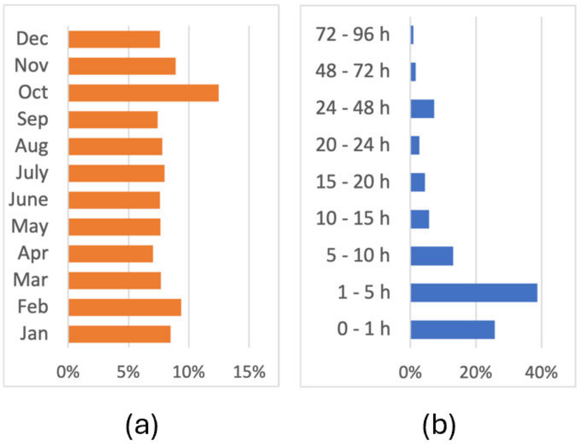

FIGURE 3. California power outage data for (a) Likelihood for each month [38] and (b) Events duration likelihood for major power outage events in California year 2021 [39].

- Power Outage Duration: Assumed to follow a probability distribution based on historical outage data from major events in California in 2021.
- Start Time of Power Outage: Assumed to occur at any time throughout the year, with probabilities associated with different months and times of day.
- Solar Radiation Data (GHI): Utilized GHI data from the National Solar Radiation Database, varying by location and time of year. GHI data for specific time spans were captured based on the start time and duration of generated power outages.
- Power Demand: The pattern of the power demand is known. In this study the power demand is assumed to be constant

These distributions and assumptions were used to generate 10,000 power outage scenarios. The process involved selecting starting points based on the probability of power outages occurring in each month, as in Figure 3a, and in the next step we determine the outage duration based on the probability distribution in Figure 3b.

To ensure the robustness and reliability of the 10,000 power outage scenarios generated, we employed several validation methods. Empirical CDFs for start time and duration were used to make a comparison between generated scenarios and historic data. Statistical validation using the Kolmogorov-Smirnov (K-S) and Mann-Whitney U tests were also employed that showed high p-values ($h = 0$, $p > 0.74$ for start time and $h = 0$, $p > 0.98$ for duration; $h = 0$, $p > 0.76$ for both tests), indicating no significant differences between historical and generated data.

III. LIFE CYCLE ASSESSMENT (LCA)

In addition to optimal sizing, another objective of this study was to assess the Greenhouse Gas (GHG) emissions associated with the backup systems and report the total GWP for each system. The life cycle assessment methodology was employed to evaluate the environmental impacts of the systems throughout their entire life cycle. The methodology of this LCA study follows the four distinct phases outlined in ISO 14040:2006 [40]. The first phase is the goal and scope definition, during which the objective of the study is established.The scope of this paper was to carry out a comparative LCA for the four systems mentioned in terms of the equivalent carbon emission. The second phase is the inventory analysis, which involves defining the system boundary for the LCA study. This process includes identifying and quantifying the inputs and outputs associated with the backup system's life cycle which is shown in Figure 4 and discussed later on in this section. The system boundary includes processes such as raw material extraction and processing, manufacturing of system components, and modeling the use phase to account for related impacts.

The third phase is the impact assessment, where the environmental impacts are evaluated. In this study, the Tools for the Reduction and Assessment of Chemical and Other Environmental Impacts TRACI 2.1 [41] method was employed to assess the impacts. This method provides characterization factors for GHGs in terms of their equivalent carbon dioxide (CO2eq) emissions. It adopts a midpoint approach, which assesses the impacts earlier in the cause-effect chain.

The last phase aims to quantify and evaluate the environmental impacts of the backup systems, focusing specifically on their GHG emissions. Table 4 provides a comprehensive listing of the input flow quantities and proxy datasets utilized in this study, emphasizing the importance of reproducibility.

Given that a comparative analysis was conducted, transportation of the components was excluded with the exception of transporting required fuel to the site with a given pick up and drop off site to include the traveled distance. During the use phase, only the combustion of the gasoline generator and water usage for PV panel cleaning were taken into account. For the system's structure and housing, an aluminum cabinet was uniformly considered across all systems/scenarios. The electricity input was obtained from the 2021 California grid data set. The impacts from California grid electricity are reallocated based on the electricity produced by the PV panels, enabling a more accurate assessment of the systems' environmental performance. Installation processes, except for the PV plant installation, have not been considered due to a lack of data availability. Similarly, the end-of-life of the systems has been excluded from the analysis due to the diverse disposal options and associated assumptions, which could introduce additional uncertainties in the study. The data for this study were sourced from the Ecoinvent 3.6 database [42]. Transportation aspects were considered solely for transferring fuel to the system from a nearby distribution center. To estimate transportation distances, Google Maps data were used. For

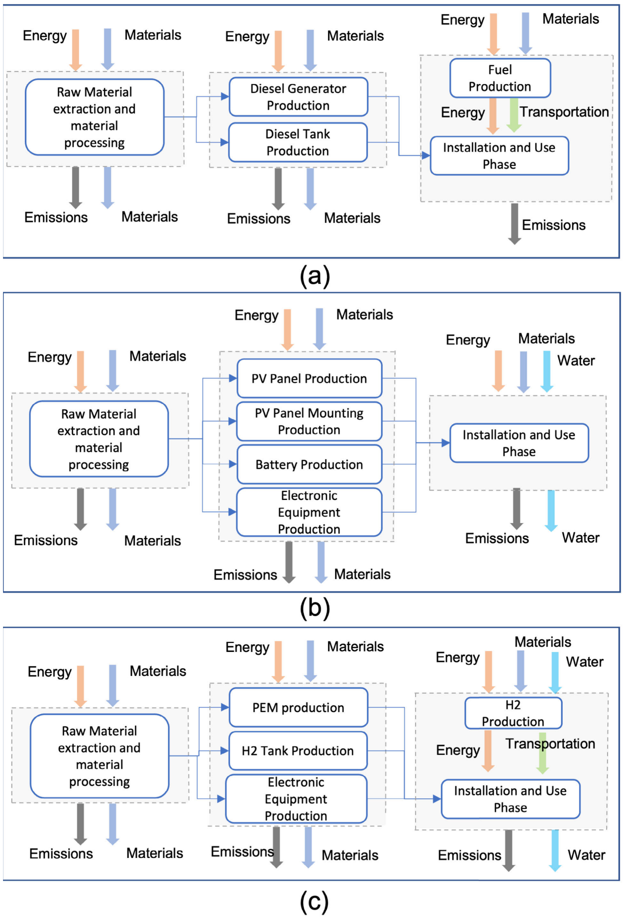

FIGURE 4. System boundary for LCA for systems: (a) gasoline generator, (b) photovoltaic and battery system, and (c) hydrogen fuel cell.

the analysis of resource extraction processes, aggregated data were utilized to assess their impacts on a single unit system (see Table 4).

Figure 4 provides an insight into the system boundaries adopted for the LCA study of our backup power systems. We present three systems out of the four, as they exhibit similarities, thus avoiding redundancy. Given the absence of specific data for a gasoline generator in the Ecoinvent database, we opted to use the data for a diesel generator as a suitable proxy. Figure 4a shows the system boundary for the diesel generator system, initiating with the extraction and processing of raw materials. This process is succeeded by the production of the generator itself and the requisite fuel. The last stage emphasizes the usage phase with a specific emphasis on the emissions arising from these activities.

Figure 4b illustrates the system boundary of a PV-battery system beginning with raw material extraction, the production of PV panels and batteries, and the manufacturing of ancillary electronic components. Here, we emphasize the installation and usage phase, corresponding only to emissions and water usage. Figure 4c, presents the system boundary of a hydrogen fuel cell system opting a proton exchange membrane and hydrogen storage (H2 tank production). The stages of the flow of this system will be the material extraction and processing, production of the parts and the energy and transportation in the use phase.

IV. RESULTS AND DISCUSSION

We have performed the optimal size of power backup systems explained in Section II-B for a traffic light with a 300W constant electric demand located in Placerville, California. Ten thousand power outage scenarios for two different locations of high and low radiation were generated as explained in Section II-A3. The method of generating power outage scenarios is explained in Section II-C.

The optimal size for each backup power system is first determined by solving an optimization problem, where the total cost of the system is minimized subject to constraints related to energy flow dynamics and variable limits. This process, as explained in detail in Section II-B, ensures that the system can effectively supply power during the generated power outages. Then in a secondary step, we simulated each of the sized systems for all of the power outage scenarios to determine the number of outages that this sized system can successfully support. The results were then sorted based on the covered power outage events.

The primary metrics used for comparing backup solutions are first the coverage percentage explained above. The initial cost and the total cost over the system's expected operational lifetime (10 years) are the other metrics. finally we will look at the GWP of each of the systems comparing the emissions of the power backup systems.

The benchmark to find optimal size thresholds for each system are the coverage of 90% and 99% of power outage scenarios. These thresholds were chosen to balance system reliability and cost-effectiveness. Figure 5 shows the corresponding life time cost of backup systems. In section II-B it was explained that the initial state of the fuel (gasoline, hydrogen) or state of charge of the battery is assumed to be 100%. For each system's cost analysis we assumed a 100 hour annual power outage to account for the cost of the fuel throughout one year.

The cost and GWP for these systems are shown in Figure 6 and the system size is reported in Table 2. Figure 6a compares the initial cost and life time cost of the systems that cover 90% and 99% of the simulated power outage scenarios while Figure 6b shows the initial and lifetime GWP for the same cases. The initial cost mentioned is the original cost required for the purchase, install and starting up the system. The life of all systems in this study is assumed to be 10 years. Figure 5 shows the cost of PV-battery system with different levels of shading, and Figure 8 showcase the lifetime total GWP of each system. In the following sections we analyze and discuss these findings in more detail.

TABLE 2. **The final results of the optimization for sizing of all of the systems including gasoline generator, battery, PV-battery for two different locations (high GHI regon: Placerville CA and low GHI region: San Francisco CA) and fuel cell.**

System	Coverage [%]	Components Size		Initial Cost [$]	Total Cost [$]	Initial GWP [kg CO2eq]	Total GWP [kg CO2eq]
Gasoline Generator	90%	1 kWp Gasoline Generator	5 Gallon Tank	2923	6496	5.53E+03	5.91E+03
	99%	1 kWp Gasoline Generator	10 Gallon Tank	3047	6619	5.58E+03	5.97E+03
Battery	90%	19 kWh Battery Capacity		9985	16344	6.14E+03	6.45E+03
	99%	36 kWh Battery Capacity		17635	27521	7.01E+03	7.49E+03
PV-battery							
High GHI Region	90%	4.3 kWh Battery Capacity	7.5 m^2 PV Panel	8181	5355	1.14E+04	1.08E+03
	99%	5.3 kWh Battery Capacity	7.5 m^2 PV Panel	8666	5840	1.15E+04	1.13E+03
Low GHI Region	90%	4.6 kWh Battery Capacity	9.6 m^2 PV Panel	8817	6955	1.31E+04	2.97E+03
	99%	6 kWh Battery Capacity	9.6 m^2 PV Panel	9457	7595	1.32E+04	3.05E+03
Fuel cell	90%	500 Wp Memberane	2 H2 Tanks	10050	15594	5.84E+03	6.01E+03
	99%	500 Wp Memberane	3 H2 Tanks	10550	16094	6.19E+03	6.36E+03

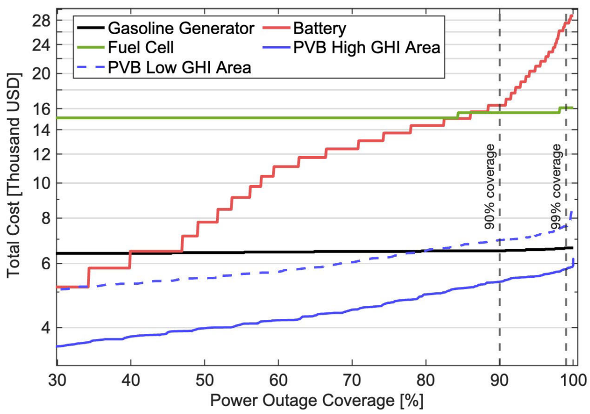

FIGURE 5. **Total cost of the systems (life time cost) versus coverage for all the systems, gasoline generator, fuel cell, battery, PV and battery, for two different locations of high and low GHI (Placerville, CA and San Francisco, CA).**

A. COST ANALYSIS

Here we explained the cost analysis in detail. All of the results are summarized in Table 2. The gasoline generator system stands out with its relatively low initial cost, approximately $3,000, making it an economically attractive option. There is a clear relationship between the gas tank size and the percentage of power outage coverage, which make this system easy to upgrade for prolonged outages with a low cost. Notably, the cost of gasoline is relatively low compared to the overall expenses, underlining the cost-effectiveness of this choice. When we consider the total cost over the system's lifetime, accounting for 100 hours of annual power outages, it totals around $7,000. The duration of annual power outages has minimal impact on the total cost because its primary influence is on the annual gasoline consumption, which has limited cost significance. Figure 6a shows that opting for 99% coverage is a wise choice for gasoline generators, particularly in scenarios with prolonged power outages.

Figure 5 shows that, in the case of battery backup systems, costs rise significantly as coverage percentages increase. For example, a 1 kWh battery can cover up to 35% of power outage events, while a 15 kWh battery is necessary to address 80% of outages. Achieving 90% coverage mandates a 19 kWh battery, incurring an expense of $16,500. However, to achieve 99% coverage, a 36 kWh battery is required, leading to a higher cost of $27,500. It is worth noting that the total cost increases substantially due to the larger battery capacities needed for extended outage coverage, making this system relatively expensive for prolonged power outages.

Shifting the focus to the PV-battery system, where cost variations are linked to different GHI level regions.The optimization process for sizing PV-battery systems in high GHI areas suggests smaller panel sizes, resulting in lower initial costs. Unlike other systems that only function as backups during outages, PV panels operate year-round, generating electricity continuously. This continuous operation allows the PV panels to generate electricity throughout the year, which can be sold back to the grid, providing additional financial benefits. In high GHI scenarios, looking

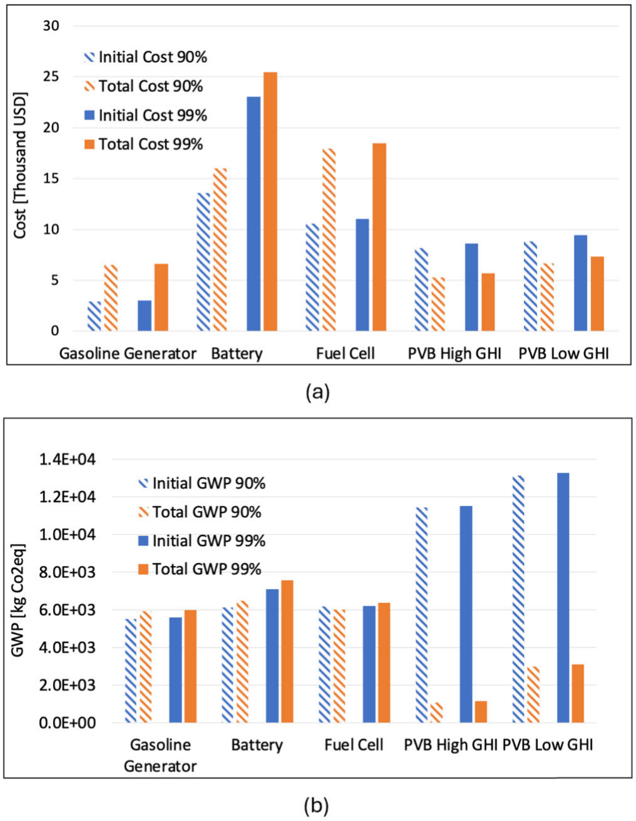

FIGURE 6. Optimal sizing and LCA results for systems that can cover 90% and 99% of power outages (a) initial and lifetime cost and (b) initial and lifetime global warming potential.

at 90% coverage, the configuration includes 7.5 m^2 of PV panels and a 4.3 kWh battery which costs $5,500 over the lifetime, while in low GHI scenarios, it comprises 9.6 m^2 of PV panels and a 4.6 kWh battery which costs $7,000. When aiming for 99% coverage, the system features the same PV panel size but integrates a 5.3 kWh and 6 kWh battery with the cost of $5,900 and $7,600 for high and low GHI scenario respectively. Note that life long cost of this system is lower than the initial cost. This abnormal case arises from the electricity generated by the PV array throughout its lifespan, effectively eliminating the need to purchase electricity from the grid. The PV panel size in the optimization solution is determined by the point at which the generated electricity, based on the GHI, is sufficient to cover both the system's costs through sending back electricity to the grid and also covering the energy needs.Furthermore, the disparity between the cost of electricity purchased from the grid compared to the sell back price based on NEM 2.0 [31] will determine the maximum size of the PV panel. Figure 5 illustrates the differences between high and low radiation scenarios, with higher costs associated with low radiation regions due to the larger PV panels. The lifetime cost of the PV-battery system emerges as relatively lower than battery and fuel cell systems, especially in high radiation regions, thanks to surplus electricity generation and the sell back to the grid.

Focusing on the effect of shading with different SR levels, as the SR value increases, the effective irradiance decreases, necessitating larger PV panel areas to generate the same amount of energy. For example, with an SR of 75%, the system might require a significantly larger PV array compared to a scenario with no shading to meet the same energy demand. This increased size of the PV array leads to higher initial costs due to the need for additional panels and associated infrastructure, which is reflected in the overall cost analysis of the PV-battery system. our results in Figure 7 show that, a 25% shading ratio cause an increase of up to 50% in total cost due to increase in the PV panel size to 9.5 m^2. This size remains consistent across various coverage percentages. However, with higher shading ratios, the PV panel size starts to fluctuate depending on the scenario, duration, and total GHI. Note that our optimization results for shaded scenarios show that for covering a small percentage of power outages up to 45%, it is not economical to deploy PV panels and the PV-battery system transitions into a battery-only configuration due to insufficient radiation and high cost of PV panels. As we progress to higher outage coverage percentages, the two lines representing SR = 50% and SR = 75% diverge, highlighting the key role of solar radiation on cost-effectiveness of PV-battery power backup systems.

Focusing on the fuel cell system, the result presented in Figure 5 shows the capability of a single hydrogen tank to cover 85% of power outages. Notably, two tanks supply a higher coverage threshold of 97%, while three tanks ensure a robust 99% coverage. The lifetime cost analysis highlights that fuel cell systems exceed initial costs, mainly due to the substantial expenses associated with refueling and hydrogen utilization during outages over the system's operational span. We considered hydrogen tanks with a capacity of 60L and a pressure rating of 300 bar, capable of holding 1 kg of hydrogen. The refueling cost is set equivalent to hydrogen needed for 100 hours of power outage per year. A more comprehensive analysis of the results, focusing on refueling frequency and associated costs for various annual power outage scenarios, is presented in Section IV-C. Furthermore, this analysis indicates that for a 99% coverage, three tanks suffice with a total system cost of $16,000. Alternatively, for 90% coverage, two tanks are similarly sufficient, with a total cost of $15,500. For detailed information about the assumed cost please refer to Table 3.

Comparing studied systems in terms of cost, both fuel cell and battery only system are substantially more expensive compared to gasoline generators. for prolonged outages, the fuel cell system is better choice in terms of cost comparing to batteries and it is also also supported by the study from Rodriguez et al. [43]. The study by Wang et al. also highlights that batteries are not ideal for prolonged outages at cellular base stations due to their limited capacity and accelerated degradation during deep discharges [44]. PV-battery system on the other hand, especially if installed in high GHI areas can be more cost effective over their life time. The lower accessibility of hydrogen fuel and relatively high refueling cost impacts the life time cost of these systems significantly, nevertheless, this analysis will change as hydrogen becomes more accessible in future. Furthermore, it is predicted that the cost of both batteries, hydrogen fuel and fuel cell systems will decrease in future. These changes will make these systems more competitive in upcoming years in terms of lifetime cost [45].

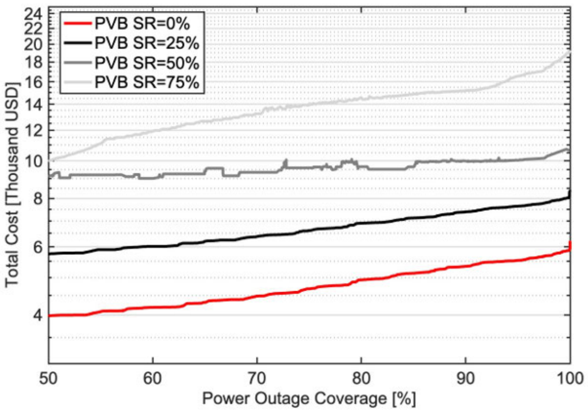

FIGURE 7. **Total cost (lifetime cost) of the PV-battery system subject to different shading ratios of 25%, 50% and 75% (high radiation area).**

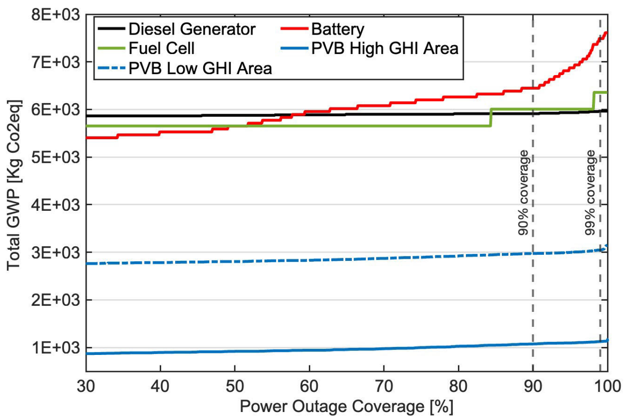

FIGURE 8. **Total GWP of the systems (impacts of the production, installation, use phase for 10 years of life time) per coverage for all the systems, gasoline generator, fuel cell, battery, PV and battery for two different locations of high and low radiation (Placerville, CA and San Francisco, CA) using Ecoinvent 3.6 LCI Data Set [42] and TRACI 2.1 [41].**

B. ENVIRONMENTAL IMPACT ANALYSIS

Figure 6b compares the initial and lifetime environmental impacts of the studied systems capable of covering 90% and 99% of the power outages, and Figure 8 illustrates the total GWP of each system relative to their power outage coverage. The gasoline generator exhibits a relatively low GWP when compared to many other alternatives. It is important to note that, as power outage coverage expands, any changes in the environmental impact are minimal primarily due to the consistent generator technology with varying tank sizes that have relatively low impacts. A closer examination of the total GWP reveals a slight increase from 5500 kg CO2eq to 6000 kg CO2eq, primarily attributed to gasoline consumption during outages over the 10-year operational span. These findings highlight that backup gasoline generators, which are mainly idle throughout their lifespan, have relatively comparative environmental impacts due to very low annual fuel consumption requirements.

The results for the battery system show a rise in the environmental impact as the battery size increases, mainly attributed to battery production. GWP numbers provided in Table 2 also confirms that the battery system increases from 6500 kg Co2eq to 7500 kg Co2eq for total GWP with an increase in battery size, from 19 kWh to 36 kWh capacity.

Moving on to PV-battery system, the results presented in Figure 6b reveal that the initial GWP of the PV-battery system is the highest among all the systems especially in regions with lower solar radiation due to the solar panel requirements. It resulted in an initial GWP of about 13,000 kg CO2eq, compared to 11,000 kg CO2eq in high radiation areas. Nevertheless the environmental impact of PV-battery systems shows a significant reduction, dropping lower than other alternative systems. This drop is attributed to the continuous electricity generation of the PV-Battery systems and their potential to transfer the surplus electricity back to the grid. When accounting for the reallocation of electricity from the grid, the total GWP drops to approximately 10,300 kg CO2eq for high radiation locations and 10,100 kg CO2eq for the low radiation region. The power generation ability positions PV-battery systems as an environmentally friendly choice, especially in high-radiation regions.

As shown in Figure 6, when considering 90% coverage, the PV-battery system exhibits the lowest environmental impact followed by the fuel cell system and the gasoline generator. This trend remains relatively consistent for 99% coverage, with only minor fluctuations. Gasoline generators and hydrogen fuel cells exhibit similar emissions trends due to their standby operation. Both systems required additional equipment like aluminum cabinets and steel tanks, leading to comparable initial emissions. While the fuel cell system produces no direct operational emissions, the production of hydrogen does contribute to its overall emissions. In contrast, the gasoline generator's operational phase includes emissions from gasoline production and combustion. Despite these differences, the total GWP for both systems is relatively close, with the gasoline generator having slightly lower overall emissions than the fuel cell system when considering both initial and operational phases

The environmental impact of the fuel cell system increases as additional tanks are required, whereas the impact of the gasoline generator remains relatively stable despite the utilization of a larger tank. This shift is attributed to the high GWP of hydrogen tank production. In contrast, the battery system's impact escalates significantly due to the necessity of a larger battery size for higher coverage rates. Consequently, for prolonged outages, due to the high battery impact, using a fuel cell system can be more environmentally friendly. For short outages, however, batteries are a viable choice.

C. THE IMPACT OF REFUELING AND YEARLY POWER OUTAGE HOURS

As mentioned, the transportation of fuel to the power backup system site can influence the life time cost and the optimal size of storage. In this section we take a closer look into the impact of refueling frequency on fuel storage requirements.The approach for accounting for refueling costs and frequencies for gasoline generators and fuel cells involves integrating additional parameters including the number of refueling events N_r and the refueling ratio R_r. N_r represents the number of refueling attempts made within a year, particularly relevant for backup systems located in remote areas with difficult access for refueling. This value is determined by factors such as the cumulative annual outage duration, the rate of power consumption, and the size of the fuel storage unit. R_r represents the cost of a refueling event relative to the cost of the storage unit. A higher R_r suggests more expensive refueling events, incentivizing the installation of larger storage tanks.

We considered a range of total annual power outage durations from 100 to 500 hours per year, leading to varying annual fuel utilization and associated costs. For hydrogen and gasoline tank costs and refueling ratios, the storage unit cost for gasoline was assumed to be $20 per gallon, normalized to a 10-gallon tank costing $200, based on the average market price at the time of this research. Refueling costs for gasoline generators ranged from $16 to $80 per refueling event, based on transportation costs provided by suppliers. This price range, combined with the fuel tank cost of $20 per gallon, corresponds to refueling ratio R_r values of 0.8 to 4. For hydrogen fuel systems, a tank cost of $500 per tank was assumed. Due to the less widespread use of hydrogen fuel, refueling costs were assumed to range from $50 to $400 per refueling event. This price range, combined with the hydrogen tank cost of $500 per tank, corresponds to R_r values of 0.1 to 0.8. All cost assumptions are based on available market data and supplier information at the time of the research. By integrating these parameters into the optimization framework, the optimized parameter for the number of refueling events N_r is determined and presented in Figure 9.

Analyzing Figure 9a, we observe that for R_r values up to 4, the recommended gasoline tank size for covering 100 hours of annual power outage (as assumed in the previous sections) is 10 gallons. However, as the outage duration increases to 500 hours, the recommended tank size also increases, reaching up to 40 gallons. This is notably four times the size recommended by the optimizer in Table 2, which suggests 5 gallons for 90% coverage and 10 gallons for 99% coverage.

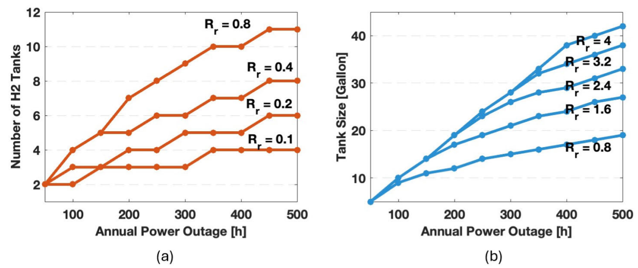

FIGURE 9. Fuel storage size versus annual power outage duration for different refuelling ratio of (a) gasoline generator system and (b) fuel cell system.

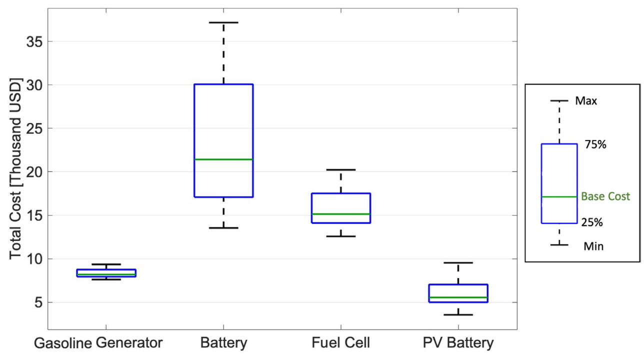

FIGURE 10. Comparative cost sensitivity analysis among different backup power systems capable of covering 90% of power outages. The cost of major system components are varied from 50% to 200% of assumed baseline cost.

For the hydrogen fuel cell system, the hydrogen tank cost of $500 per kg of hydrogen is assumed. If we look at the results of the in Figure 9b we can see that, for refueling ratios of 0.1 to 0.8, at 100 hours of power outage, the number of hydrogen tanks is in the range of 2 to 4. For the same scenario without considering the refueling, the results are 2 tanks for 90% coverage and 3 tanks for 99% coverage as reported in Table 2. For longer power outages of up to 500 hours per year, the number of hydrogen tanks goes up to 11 for R_r of 0.8 equivalent to $400 of refueling cost.

This analysis revealed that the optimal size of fuel storage varies significantly depending on the specific context, including the refueling costs and outage duration.

For instance, in the case of gasoline generator systems, the recommended tank size ranges from 10 to 50 gallons, highlighting the importance of considering accurate cost and power outage duration. Similarly, for hydrogen fuel cell systems, the number of required tanks can range from 2 to 11, demonstrating the wide range of cost outcomes. Ultimately, the decision making process regarding fuel storage size must account for a multitude of factors, including system requirements, cost considerations, and operational constraints.

D. SENSITIVITY ANALYSIS RESULTS

In this section, we present a cost sensitivity analysis to understand the impact of varying component costs on our results, accounting for price differences among suppliers, locations, and potential future cost changes. Component costs were varied within a range from 50% to 200% of their base values, as listed in Table 3, with increments adjusted in steps of 10%. The optimization algorithm was rerun for each cost set to assess if changes affected optimal system sizing. Results were compiled into a box plot to visualize the impact of cost fluctuations on system desirability, helping to determine if cost changes favored one system over another.

Figure 10 presents the associated variation in the lifetime cost of the studied systems in a box plot. The green line shows the base cost. The cost of the gasoline generator remained stable with a minimum of $7,200 and maximum of $9,400. In contrast, the battery system demonstrated, a high cost variation with minimum of $13,500 to a maximum of $37,200 and median of $23,000, which points out that the main cost of this system is the battery cell cost. Fuel cell, having a middle going trend, with minimum of $12,500 up to maximum of $20000 has some cost overlap with battery system. The PV-battery system with a minimum of $3,500 have the lowest total cost among the backup options and with maximum of $9,500, it has an overlap with gasoline generator. The PV-battery system with a median of $6,000, comparing to gasoline generator with median of $8,300 came out as an overall better option.

Overall, the battery system showed the greatest variation in total cost. This result was mainly driven by the cost of battery cells. The fuel cell system displayed moderate cost variability with its costs partially aligning with those of the battery system. The PV-battery system had the lowest cost across the systems with some overlap with the gasoline generator. The gasoline generators maintained the narrowest cost range, which is attributed to their lower generator and fuel costs.

V. CONCLUSION

In this study, we conducted a thorough comparative analysis of four distinct small-scale power backup systems designed for critical but low-demand applications such as traffic lights on evacuation routes. The considered options include gasoline generator, battery pack, PV-battery system, and fuel cell. We evaluated these options based on cost-effectiveness and environmental impact over a 10-year operational period. Our findings are summarized as follows:

- PV-battery systems are the most environmentally and economically sustainable choice, particularly in areas with high solar irradiance. Their ability to generate electricity and potentially contribute to the grid significantly lowers both their environmental footprint and lifetime costs. Nevertheless, their performance can be severely affected by shading, leading to higher lifetime costs under significant shading conditions.
- Gasoline generators remain a competitive option due to their low upfront costs and minimal operational emissions for power backup purposes where the system is mostly on standby during its lifetime.
- Battery backup systems were found to be efficient for short-duration power outages compared to fuel cells and gasoline generators. However, our analysis revealed that these systems will become expensive and less eco-friendly when scaled up for longer outages due to the expensive battery cells and the associated greenhouse gas emissions during the manufacturing phase.
- Our investigation showed that fuel cell power backup systems offer a cost-effective solution for extended outages compared to battery-only setups. Nonetheless, the environmental impacts and financial costs of manufacturing hydrogen tanks and fuel cell engines make them less appealing and more costly than gasoline generators when a large number of tanks are installed.

There are several research directions for future exploration. Accounting for other environmental factors, such as temperature and smoke, are valuable areas for future study. The performance of batteries, PV panels, and fuels cells are all impacted by temperature due to the required cooling/heating for the unit and the overall influence of the temperature on the system performance; for example, the available capacity of battery systems can be significantly reduced in subzero temperatures. Furthermore, the effect of smoke caused by wildfires can substantially reduce energy generation in PV panels and therefore impact the optimal size and cost effectiveness of the systems. Research should also explore the future trends of cost for fuel cells engines, PV panels, batteries, and the availability of hydrogen fuel and the significance of these changes in the optimal power backup option for the considered small scale systems. A possible future direction is utilizing extensive historical data on power outages can pave the way for developing predictive models using machine learning approaches. These models could effectively capture annual trends as well as seasonal and monthly variations.

Additionally, there is significant potential for further exploration in environmental impact assessments. Future studies can have broader range of environmental impacts, including resource depletion, water usage, and ecological toxicity, to provide a more in dept assessment of different backup solutions. Moreover, examining emissions in greater detail and including end-of-life considerations could be pursued in the future. Conducting size optimization algorithm with primary focus on the environmental impacts is also worth investigating.

ACKNOWLEDGMENT

The authors acknowledge the use of Artificial Intelligence (AI), specifically ChatGPT by OpenAI [46], for enhancing the clarity and flow of their manuscript. They utilized ChatGPT to review their text for grammar accuracy, clarity, and coherence. It is important to note that all results, figures, and graphs presented in this work were produced without AI assistance.

APPENDIX

TABLE 3. The table of all the costs used in the optimization algorithms. The costs are all extracted and averaged from the market of (or to be delivered to) Northern California in 2023.

Components	Symbol	Functional Unit	Cost	Unit	Production/Use phase GWP [kg Co2eq][1]	Weight [Kg/unit]	Transport GWP [kg Co2eq][2]	Note
				Gasoline Generator System				
Gasoline Generator	C_{GG}	1 kWp	1000	$/Unit	4.10E+02	15	6.95E-01	Assumed same as a Diesel Generator
Fuel : Gasoline	C_F	1 Gallon	4.7	$/Gallon	2.02E+00	3.78	1.75E-01	refilling equal to 100 hours of power outage required
Cabinet	C_{eq}	1 Cabinet	800	$/Unit	5.04E+03	450	2.09E+01	450 kg Aluminium Cabinet
Fuel Tank	C_T	1 Gallon	20	$/Gallon Tank	9.01E+00	1.25	9.58E-02	Linearized over 20 Gallon Gas Tank, 25 kg
Maintenance	$C_{O\&M}$	-	300	$/year	-	-	-	
Installation	C_I	-	1000	$	-	-	-	Per setup
Refueling	C_r	-	50-200	$/refueling event	-	-	-	
				Battery				
Battery	C_B	1 kWh Capacity	450	$/ Unit	5.08E+01	6.67	3.09E-01	
Inverter	C_{eq}	1 kWp	100	$/Unit	9.30E+01	18.5	8.57E-01	part of equipment cost
Cabinet	C_{eq}	1 Cabinet, 200 kg	800	$/Unit	5.04E+03	450	9.27E+00	part of equipment cost
Equipments (Charger, Cables, etc)	C_{eq}	-	350	$/Unit	1.81E+01	0.5	2.32E-02	1/2 kg of electronics
Maintenance	$C_{O\&M}$	-	250	$/year	-	-	-	
Installation-Comission	C_I	-	1000	$	-	-	-	Per setup
				Photovoltaic Panel				
PV Panel	C_{pv}	$1m^2$	200	$/Unit	2.64E+02	12	1.20E+01	
Mounting	C_{eq}	$1m^2$	40	$/Unit	4.01E+01	18.5	1.85E+01	per 1 m^2 of Panel
Equipments (Charge Controller, Cables ,etc)	C_{eq}	-	300	$	1.81E+01	0.5	2.32E-01	
Maintenance	$C_{O\&M}$	-	50	$/year-panel	-	-	-	per 1 m^2 of Panel
Installation-Comission	C_I	-	2000	$	4.97E+02	-	-	Per setup
				Hydrogen Fuel cell				
Hydrogen PEM	C_{FC}	1kWp	8200	$/Unit	1.02E+02	10	4.64E-01	
Hydrogen Tank	C_T	1 Tank	500	$/Unit	3.49E+02	80	3.71E+00	1 Tank: 60L, 300 bar, 1kg H2
Fuel: Hydrogen	C_{H2}	1 kg	16	$/kg H2	2.69E+00	1	4.64E-02	
Cabinet	C_{eq}	1 Cabinet, 450 kg	800	$/Unit	5.04E+03	450	2.09E+01	
Equipments (Pressure regulator, Pipes, etc)	C_{eq}	-	350	$	1.81E+01	0.5	2.32E-01	1/2 kg electronics
Maintenance	$C_{O\&M}$	-	500	$/year	-	-	-	
Installation-Comission	C_I	-	3800	$	-	-	-	Per setup
Refueling	C_r	-	200-500	$/refueling event	-	-	-	

[1]The GWP corresponding cradle to gate

[2]Transportation of 500km is considered and the corresponding weight of each component

TABLE 4. Life Cycle Inventory from Ecoinvent 3.6 [42].

Flow	Inventory Proxy Dataset in Ecoinvent 3.6	Notes	Region	Method u-so / agg	TRACI 2.1 GWP	Unit
Diesel Generator [p]	Diesel-electric generating set, 18.5 kW {GLO} | market for | Alloc Rec, S	Unit Size: 1 kWp Diesel Generator Assumed same as Diesel generator Lifetime: 10 years Replacements : None	GLO	agg	4.10E+02	kg Co2 eq
Gasoline production [kg]	Gasoline mix at filling station	Unit : 1 kg of Gasoline Mix	US	agg	5.71E-01	kg Co2 eq
Diesel Fuel Burned [MJ]	Diesel, burned in Diesel-electric generating set, 18.5 kW {GLO} | market for | Alloc Rec, S	Unit : 1 kg Diesel Mix Assumed same as Gasoline Mix	GLO	u-so	9.69E+00	kg Co2 eq
Steel - Gasoline Tank [kg]	Steel, chromium steel 18/8 {GLO} | market for | Alloc Rec, S	Unit : 1 Gallon Gasoline Tank Mass : 31 kg / 15 Gallon Tank	GLO	agg	9.01E+00	kg Co2 eq
Photovoltaic Panel [m^2]	Photovoltaic panel, single-Si wafer {GLO} | market for |Alloc Rec, S	Unit : $1m^2$ PV Panel Lifetime: 10 years Replacement : None	GLO	agg	2.64E+02	kg Co2 eq
Photovoltaic plant [kWp]	market for photovoltaic flat-roof installation, 3kWp, single-Si, panel, mounted, on roof	Unit : $1m^2$ PV Panel Installation of Photovoltaic Panels in a plant	GLO	agg	7.46E+03	kg Co2 eq
Photovoltaic Mounting System [m^2]	market for photovoltaic mounting system, for slanted-roof installation	Unit : $1m^2$ PV Panel	GLO	agg	4.01E+01	kg Co2 eq
Battery [kg]	Battery, Li-ion, rechargeable, prismatic {GLO} | market for | Alloc Rec, S	Unit: 1kWh Battery Capacity Life time: 10 years Replacement : 1/2 of Cells over lifetime	GLO	agg	5.08E+01	kg Co2 eq
Inverter[p]	market for inverter, 0.5kW	Unit : 0.5kW Inverter	GLO	agg	4.65E+01	kg Co2 eq
Electronic Components[kg]	market for electronics, for control units	Unit : 1 kg of Electronics	GLO	agg	3.61E+01	kg Co2 eq
Electricity [kWh]	Electricity grid mix - CAMX , consumption mix, to consumer, <1kV	Unit : 1 kWh	US	agg	3.65E-01	kg Co2 eq
Fuel cell [kWp]	Fuel cell, stack polymer electrolyte membrane, 2 kW electrical, future {GLO}| market for | Cut-off, S	Unit Size: 1 kWp PEM Lifetime : 10 years replacements: None	GLO	agg	1.02E+02	kg Co2 eq
Hydrogen [kg]	Hydrogen at refinery	Unit : 1kg of H2	US	agg	2.69E+00	kg Co2 eq
Compressor	market for air compressor, screw-type compressor, 4kW	Unit: 4 kW compressor	GLO	agg	7.06E+02	kg Co2 eq
Steel - H2 storage [kg]	Steel, chromium steel 18/8 {GLO}j market for j Alloc Rec, S	Unit : 1 Tank 1kg H2 Capacity Mass : 80 kg / Cylinder	GLO	agg	3.48E+02	kg Co2 eq
Aluminium - Outdoor Cabinet [kg]	Aluminium frame profile, powder coated (EN15804 A1-A3)	Unit : 1 Cabinet 450 kg Mass : 200-450 kg (Empty Cabinet) / Cabinet	GLO	agg	3.48E+02	kg Co2 eq
Transportation	Transport, combination truck, average fuel mix	Unit : Tonne-km	US	agg	9.27E-02	kg Co2 eq

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ARMIN ABDOLMOHAMMADI received the Bachelor of Science degree in mechanical engineering from the Sharif University of Technology, Tehran, Iran, in 2019. He is currently pursuing the Ph.D. degree in mechanical and aerospace engineering with the University of California at Davis, Davis. His research interests include system dynamics, controls, and robotics, with a particular emphasis on optimal control in automotive applications. He has been involved in research at the UC Davis Control, Optimization, Robotics, and Electrification Laboratory (CORE Lab), since 2023.

ALIREZA NEMATI received the B.Sc. degree in mechanical engineering from Shiraz University, in 2008, and the M.Sc. and Ph.D. degrees in mechanical engineering, in 2010 and 2017, respectively. He was a Postdoctoral Researcher with Qingdao University, for two years, and became an Assistant Professor with Qingdao University, in December 2020. Since September 2022, he has been a Research Scientist with the University of California at Davis, Davis. His research interests include control, optimization, and robotics at various scales, including the development of traditional robots and control algorithms as well as the study and evaluation of nanorobots.

MERIDIAN HAAS received the B.S. degree in mechanical engineering from the University of Idaho, in 2021. She is currently pursuing the Ph.D. degree with the University of California at Davis, Davis. She is also with the CORE Laboratory. She is specifically focused on sustainable engineering design and analysis. Her research interests include electrification technology, optimization, and control design, particularly for electric off-road vehicles.

SHIMA NAZARI (Member, IEEE) received the B.S. and M.S. degrees from the Sharif University of Technology, Tehran, Iran, in 2009 and 2012, respectively, and the Ph.D. degree in mechanical engineering from the University of Michigan, in 2019. She is currently an Assistant Professor of mechanical engineering with the University of California at Davis, Davis. Prior to this position, she was a Postdoctoral Researcher with the Model Predictive Control Laboratory, UC Berkeley. Her research interests include optimal and data-driven control with applications for automation, electric vehicles, and transportation systems.