Comparative Analysis of Backup Energy Solutions for Electric Vehicle Evacuations During Grid Failures

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***Abstract*— As the adoption of electric vehicles (EVs) continues to rise, securing reliable energy solutions to power EVs during evacuations caused by disasters, especially when the electric grid fails, becomes increasingly critical. This paper evaluates various backup energy options, including conventional fuels like diesel, natural gas, and propane, as well as emerging zero-emission technologies, such as electrochemical batteries and clean fuels, based on important metrics such as energy density and self-discharge rates. Additionally, the study estimates the land requirements for different backup energy solutions across various evacuation scales. The findings offer valuable insights for emergency planners and policymakers, helping to improve emergency preparedness.**

Keywords—electric vehicles, energy grid, energy storage, EV evacuation, lithium battery

I. Introduction

Each year, many evacuations are necessitated by natural disasters or human-induced crises [1], with most evacuees relying on private vehicles for transportation [2]. For example, approximately 90% of evacuees used their personal vehicles during Hurricane Irma in Florida [3].

Diesel and gas-powered generators have been employed to keep gas stations operational, enabling the refueling of gas-powered vehicles. However, with the ongoing transportation revolution driven by public policies [4] the adoption of electric vehicles (EVs) is expected to rise significantly in the coming years. This shift offers a new challenge: ensuring EVs can be reliably powered during evacuations, particularly when the electrical grid fails.

Several studies have already addressed the issue of powering EVs during evacuations. Feng et al. [5] analyzed the impact of Hurricane Irma and concluded that if a significant portion of vehicles had been EVs, the state would have encountered severe difficulties in powering them. They recommended increasing the deployment of energy storage technologies to mitigate this challenge. Similarly, Adderly et al. [1] underscored the need for more charging stations to overcome this issue.

In our previous study [6], we employed a pragmatic stochastic approach to estimate the energy needs of EV evacuations during grid failures. That study aimed to model the complex variables involved in an evacuation scenario, such as vehicle battery capacities, energy consumption rates, initial states of charge of the vehicles' batteries, and varying distances to safe zones. By treating these parameters as random variables with probabilistic distributions, we accounted for the uncertainties. For instance, the energy needed for each vehicle was calculated based on distance driven and energy consumption per kilometer, while a Monte Carlo simulation was applied to capture variations in key parameters, yielding the distribution of total energy needs. Then, based on the energy densities of lithium batteries (LiBs), the previous study calculated the required size of backup LiBs across different evacuation scenarios.

This study reviews backup energy solutions beyond LiBs, including both conventional and new technologies that would avoid emissions of carbon dioxide and other pollutants, consistent with the advantages of the EVs. We evaluate more than a dozen options for the needed energy storage based on their cost, efficiency, safety, maturity, and required area to meet the needs of various evacuation scenarios during a grid outage.

II. Methodology

We assume grid failure during an evacuation as the basis for our analysis. In this section, we introduce the backup energy technologies discussed in this paper and the metrics for evaluation. We review the total energy requirements calculated by our previous study for scenarios that vary the the initial charging condition for those vehicles [6]. These energy requirements are defined as the basis for analyzing the technologies in Section III.

A. Backup energy options

In this study, diesel, natural gas, and propane, collectively referred to as tri-fuels, serve as a baseline for comparison with newer alternatives, including electrochemical batteries and hydrogen (see Table 1). In Table 1, we found product datasheet(s) for all the technologies above row "iron-air batteries." While methanol and hydrogen gas are widely available, their datasheets typically do not include details about fuel tanks, which is why those fields are left blank in Table 1. Moreover, technologies such as compressed air and pumped hydro energy storage are excluded due to their geographical limitations [7]. Similarly, mechanical gravity storage solutions, such as water tanks and rocks, are omitted because of their low energy densities [8].

B. Metrics

Evacuations may involve areas where the size of backup energy systems becomes critical. Therefore, we analyze both volumetric and areal energy densities in kilowatt-hours per cubic meter (kWh/m³) and kilowatt-hours per square meter (kWh/m²), respectively. We estimate the areal density from the volumetric density by assuming a 2-m-high system with a total area up to twice that of the energy itself. Furthermore, this paper does not consider the speed of evacuations, or the power required, which may affect the choice of the technologies.

We also discuss self-discharge or idle loss, the rate at which energy is lost from an energy system. Idle loss is significant when the energy system is not used daily and sits idle until an emergency evacuation occurs. For example, LiBs, with an idle loss of around 0.2%/day, may lose a significant amount of stored energy if left idle for extended periods. In contrast, flow batteries or conventional fuels like diesel and natural gas exhibit negligible idle loss during storage, making them more predictable for emergencies. Additionally, potential hazards such as thermal runaway in LiBs or the explosion risk of compressed hydrogen are also considered (see Table. 1).

Although cost is an important factor, its analysis introduces uncertainties that should be carefully considered when evaluating the cost data presented in Table 1, which are as follows:

1. The energy cost in \$/kWh is expected to decrease with the size of the system, making it complicated to compare costs of small systems with large ones.
2. Costs are expected to decrease with time; for example, the cost of LiBs has decreased by a factor of six in the past ten years [9].
3. Systems include more components than just the battery cells, such as inverters, thermal management systems, and other equipment. Therefore, it is critical to compare system-level costs rather than component costs
4. Companies may sell their products below the actual cost of manufacturing to gain market share, adding uncertainty to prices announced for projects. Nevertheless, the announced price for a completed project has less uncertainty that projected prices for theoretical projects.

C. Energy needs by electric vehicles

In this section, we briefly review the energy requirements for evacuating EVs based on the analysis in our previous study [6]. This information will be used in the results section to determine the land requirements of backup energy solutions. In our previous study [6], we analyzed three scenarios for the initial state of charge (SoC_0) of EVs, utilizing triangular probabilistic distributions:

- **i) Pessimistic scenario (SoC_0, mode=0.1):** Most EVs have a low state of charge at the time of evacuation.
- **ii) Average scenario (SoC_0, mode=0.5):** Most EVs have around 50% state of charge at the time of evacuation.
- **iii) Optimistic scenario (SoC_0, mode=0.9):** Most EVs are nearly fully charged at the time of evacuation.

We previously estimated that the average charging energy required by 1,000 EVs for a 100-km evacuation distance is 3.6 MWh, 1.3 MWh, and 0.8 MWh, for scenarios i, ii and iii, respectively [6].

III. Comparison of Backup Energy Candidates

Fig. 1 illustrates the range of volumetric and areal energy densities found for the backup energy solutions under study. As shown, traditional carbon-emitting fuels exhibit significantly higher densities than the clean technologies. Where pipelines are available, natural gas avoids onsite storage needs; however, in areas without pipeline access, the cost of establishing a connection can be significant. Diesel is typically stored in underground tanks and delivered by fuel trucks, which minimizes the area needed for energy storage. In contrast, propane is typically stored under pressure in above-ground tanks and swapped out as needed, increasing the area needed for a charging facility, though requiring much less space than the zero-CO_2-emissions storage technologies.

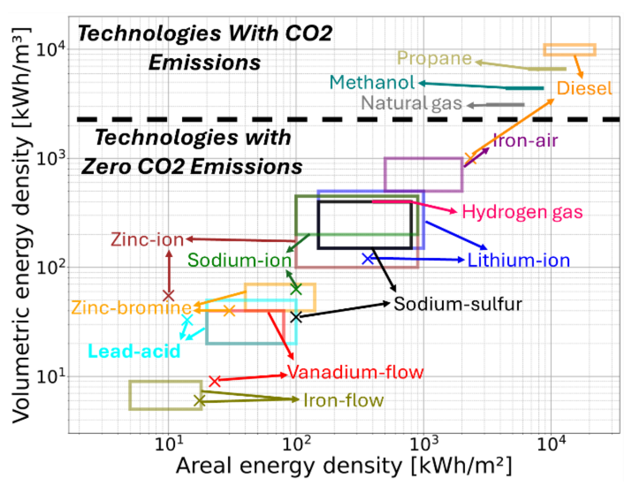

Fig. 1. Volumetric *vs* areal energy densities for candidate backup energy solutions. The X-shaped data points represent products for which datasheets are available, with performance usually less than the technology's potential.

TABLE 1. SUMMARY OF BACKUP ENERGY OPTIONS PERFORMANCE

Technology	Energy density				Cost [$/kWh] (excluding taxes and installation)	System power cost [$/kW] and duration	Self-discharge [%/day]	Hazard
	Technology		Available product					
	Volumetric [kWh/m^3]	Areal [kWh/m^2]	Volumetric [kWh/m^3]	Areal [kWh/m^2]				
Diesel and propane	7000-11000	7000-22000	1000[a] (Diesel generator)	2340 (Diesel generator)	The cost depends on the fuel tank size	100-600[b]	No self-discharge	Flammable fuel
Natural gas at 250 bar	3000	3000-6000	No need for onsite storage where pipelines are available	No need for onsite storage where pipelines are available	The cost depends on the fuel tank size	100-600[b]	No self-discharge	Flammable fuel
Lead-acid battery	20-50 [10]	20-100	33[c]	14	50-150 [11]	500-1500[d] (10hr) [12]	0.3-1 [12]	Corrosive; Can generate explosive gases
Lithium-ion battery	150-500 [13]	150-1000	56-184[e,f]	160-570 [14,15]	System cost: 240 [14]; Cell cost: 140 [16]	970[g] (4hr)	0.2 [12]	Thermal runaway can ignite
Zinc-bromine flow battery	40-70 [17]	40-140	40[h]	30 [17]	800 [18]	9600[i] (12hr)	<0.01 "When the system is on hibernation feature [17]"	Nonflammable
Iron flow battery	5-9 [19]	5-18	5-7[j]	14-21 [19]	125 [20]	1250[k] (10hr)	<0.01 [21]	Nonflammable
Vanadium flow battery	20-40 [22,23]	20-80	9[l]	23	>280 [24]	>2800[d] (10hr) [24]	<0.01 [23]	Nonflammable
Sodium sulfur battery	150-400 [25,26]	150-800	35[m]	100	-	-	<0.01 [27]	Liquid sodium burns on contact with air
Zinc-ion battery	100-450 [28,29]	100-900	55[n]	10	<100	<1200[o] (12hr) [30]	1%/hour at 100% state of charge [31]	Nonflammable
Sodium-ion battery	200-450 [32,33]	100-900	63[p]	100	40-80 [34]	240-1440[d] (6-18hr) [35]	0.03-0.2 [36]	Mostly not flammable
Iron-air battery	500-1000 [37]	500-2000	-	-	20 [38]	2000[q] (100hr) [38]	-	Nonflammable
Methanol	4400	4400-8800	-	-	The cost depends on the fuel tank size	-	No self-discharge	Flammable fuel
Hydrogen gas (at 150 bar)	400	400-800	-	-	The cost depends on the fuel tank size	-	No self-discharge	Flammable fuel

[a] GENERAC MOBILE [b] Advertised prices, no installation [c] MEDIPRODUCTS standalone system [d] Cost is for a module in 2024 [e] TESLA MEGAPACK [f] LG [g] Includes inverters and thermal systems based on a 1MW (4MWh) system in 2024 [h] REDFLOW [i] Cost includes only battery modules and is for a 10kWh system in 2024 [j] ESS INC [k] Cost includes only battery modules and is an estimation by the US Advanced Research Projects Agency-Energy [l] StorEn Technologies [m] NGK INSULATORS, LTD [n] Eos [o] This was a target cost of battery modules for 2022 [p] Northvolt [q] Cost includes only battery modules and is a target for a product with a close construction

Table 1 compares the energy candidates, with color coding from dark green (best) to red (worst) to indicate relative performance. This analysis shows that fossil-fuel generators have a clear advantage for high energy density and low cost. The fossil-fuel technologies are rated "red" for their flammability, but today's energy system routinely addresses this. Viewing both Fig. 1 and Table 1, among the carbon-free options, iron-air batteries demonstrate comparatively higher energy densities. However, no datasheets were found for iron-air battery products. For the electrochemical batteries for which datasheets were available (represented as X-shaped data points in Fig. 1), LiB systems exhibit the highest volumetric and areal densities. While iron flow batteries are reputed to have very low energy density, the data sheet we found for this product suggests that the products are doing well at approaching the theoretical maximum.

IV. BACKUP ENERGY SIZE FOR 6 EVACUATION SCENARIOS

This section leverages the results from our previous study [6], as discussed in Section II, along with the energy densities of the backup energy candidates of available products reviewed in Section III (X-shaped data points in Fig. 1), to determine the land requirements of each candidate for the six evacuation scenarios. Fig. 2 shows the area up to twice that of the system itself (shown by the uncertainty bars). For the tri-fuel options, the diesel generator datasheet used in Fig. 2 (referenced in Table 1) represents a complete system, including the fuel system within a container. As diesel tanks are typically installed underground, the area shown in Fig. 2 is an overestimate and could be reduced by underground installation. In contrast, propane tanks are generally installed above ground, as mentioned in Section III. Therefore, the range indicated for diesel in Fig. 2 may be also applied to propane, with minor adjustments due to differences in energy density (that is the reason why we have shown propane and diesel together in Fig. 2). Natural gas, typically supplied via pipelines, is excluded from Fig. 2 as it does not require onsite storage.

As shown in Fig. 2, for smaller evacuation scenarios involving 1,000 vehicles, the required land for all systems remains less than that of a football field. However, as the scale of evacuation increases to 1 million EVs, the land required by some technologies becomes comparable to the area of Vatican City. At this large scale, the required land for LiBs remains approximately the size of a football field, while the baseline technologies of diesel or propane fuels would require an area roughly equivalent to a basketball court. Diesel or propane fuel generators' compactness and ability to operate with minimal onsite infrastructure make them advantageous for efficient deployment during emergencies, especially in space-constrained urban settings. Conversely, while LiBs and other electrochemical storage options require larger land areas, they align better with sustainability objectives due to their zero-emission operation. Fig. 2 helps select high-density, scalable energy storage options for different scenarios, depending on space and emission constraints.

V. Conclusions

This paper addressed the challenge of powering electric vehicles (EVs) during evacuations when the electric grid fails, focusing on backup energy options. The findings underscore that, in the absence of strict emission constraints for emergency situations, conventional tri-fuels outperform other technologies due to their higher energy density (and thus lower land requirements) and cost-effectiveness (it should be noted that the economic attractiveness of natural gas depends on the availability of supply pipelines). Among carbon-neutral technologies, several promising candidates have emerged. Iron-air, lithium-ion, zinc-ion, sodium-ion, sodium-sulfur batteries, and compressed hydrogen show competitive energy densities, though lithium-ion batteries stand out due to their commercial maturity, with a wide range of products and demonstrated implementations.

Additionally, the study evaluates the land requirements for the analyzed backup energy solutions for evacuation of 1k and 1M EVs. Conventional fuels of propane and diesel generators require an area roughly equivalent to a basketball court for evacuations involving up to 1 million EVs over a 100 km distance. In contrast, lithium-ion batteries, as a zero-emission alternative, require approximately a football-field-size area, while other carbon-neutral technologies may require significantly larger areas, potentially as large as Vatican City, depending on the initial state of charge assumptions of the vehicles.

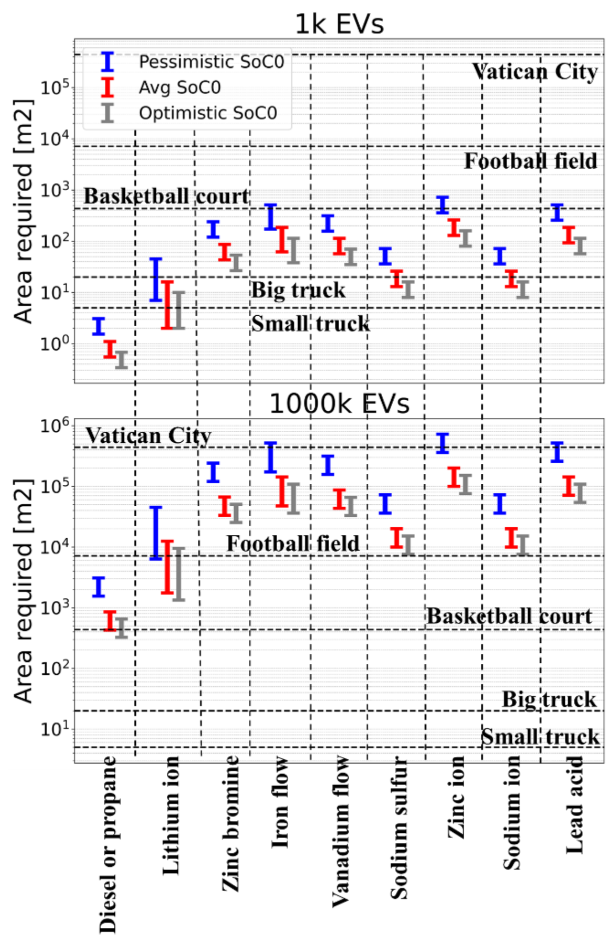

Fig. 2. The estimated area required by candidate commercially available energy systems for the evacuation of 1k and 1000k EVs over a 100 km distance (d_mode = 100 km) for the three SoC_0 scenarios. The required area is calculated to be up to twice that of the energy system itself as indicated by uncertainty bars (based on Table 1 product areal energy densities).

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