MOBILE EMERGENCY POWER DURING AND AFTER NATURAL DISASTERS AND SHORTAGES

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Mobile emergency power during and after natural disasters and shortages

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Abstract

This study explores the potential utilization of electric school buses as an alternative emergency power source during power outages. With the increasing adoption of electric vehicles and advancements in energy storage technologies, repurposing electric school buses for emergency power generation presents a novel approach to addressing critical energy needs in times of crisis. This research investigates the technical feasibility, economic viability, and operational effectiveness of integrating electric school buses into emergency power systems. Through simulations and scenario analyses, the study examines the capacity of electric school buses to provide backup power over various durations, considering factors such as battery degradation, energy demand, and vehicle availability. Furthermore, the research evaluates the economic implications, including the cost-effectiveness of retrofitting and upgrading existing school bus fleets, and the potential revenue streams from participating in demand response programs and grid services. The findings of this study reveal that electric school buses have the potential to significantly enhance emergency preparedness and response capabilities. Although this alternative is technically feasible, it may not be financially justifiable for several reasons such as higher upfront costs, charging infrastructures, operational complexity, and the complexity of the policies and regulations involved in running the grid.

Keywords: Resilience, power outage, electric school bus, emergency power

Introduction

Every year, communities across the world suffer significant disasters from natural hazards such as droughts, earthquakes, fires, floods, hurricanes, and tornadoes. While these sorts of adverse events cannot be eradicated, their consequences can be less disastrous if communities reduce their vulnerabilities and increase their resilience. Further, as climate change and increasingly extreme weather events have caused a surge in natural disasters over the past 40 years, the need for improved sustainability and resilience of our homes is growing more pressing. Pursuing resilience-relevant research across the spectrum from fundamental to applied is critical for developing or assessing the alternatives for improving resilience of households, organizations, or jurisdictions. Nearly 1,700 people died in Pakistan after 2022 flooding and more than 16,000 died in Europe due to heat waves. There were several severe weather events recorded in 2022, including hurricanes, thunderstorms, hailstorms, tornadoes, floods, droughts, tropical cyclones, and windstorms. According to a recent report published by the National Oceanic and Atmospheric Administration (NOAA), the United States alone has sustained 323 separate weather and climate disasters since 1980 where total direct costs reached or exceeded $2.195 trillion. Figure 1 shows the top six years for the most costly events. As noted in the NOAA's report, 2021 was the seventh consecutive year (2015-2021) in which 10 or more separate billion-dollar disaster events have impacted the U.S. While the 1980–2021 annual average is 7.4 events, the annual average for the most recent 5 years (2017–2021) is 17.2 events.

Disaster Event Count

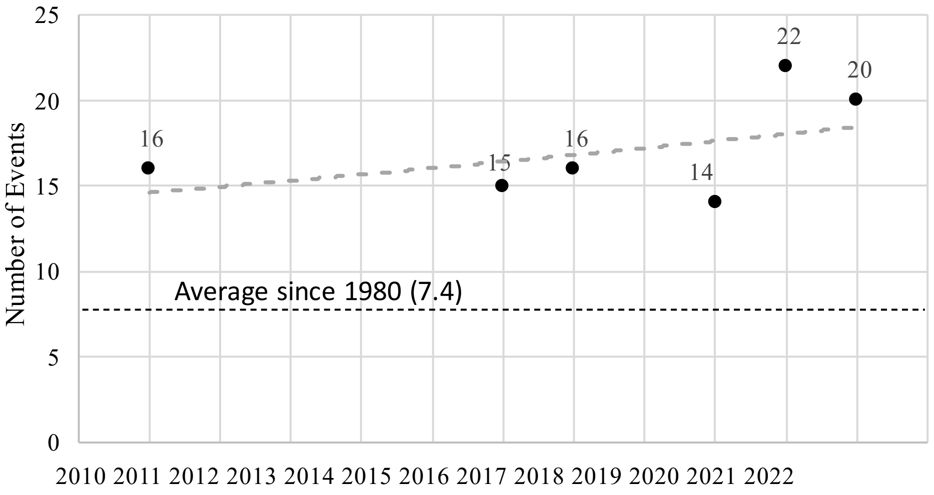


Figure 1: The top six high-cost extreme events in the United States from 1980-2021

Incorporating electric school buses as an alternative emergency power source presents a forwardthinking approach that aligns with the growing emphasis on sustainable and resilient infrastructure. By harnessing the potential of these vehicles, communities can enhance their ability to respond to emergencies while contributing to a more environmentally friendly and secure energy future. Electric school buses represent a distributed network of energy storage devices that are strategically located within communities. During power outages, these buses can be strategically deployed to provide power where it is most needed, reducing the reliance on centralized power generation and transmission. Electric school buses are equipped with sizable battery capacities to support their daily transportation needs. These batteries can be repurposed to supply electricity during emergencies, serving as a valuable reservoir of energy that can be tapped into to power critical facilities and services. Furthermore, electric school buses are often strategically located throughout communities, making them readily accessible during emergencies. Their swift deployment as power sources can aid in rapidly restoring essential services and supporting emergency response efforts.

Research Significance and Objectives

Electricity infrastructure is vital to the nation's energy security, supporting health-care facilities and emergency services, and virtually all economic activity depends on reliable electricity to function. Governments and utilities across the nation are increasingly focused on the need to maintain a hardened grid that is resilient in the face of natural disasters and man-made threats. One of the primary reasons for failures of transmission and distribution systems following severe wind events is that the current wind loading design standards for the distribution of electricity do not consider high winds, as such standards are aligned with those of communities. In a recent study led by the Massachusetts Institute of Technology, atmospheric scientist Kerry Emanuel suggests a possible increase in hurricane intensity in the recent decade and shows that storms are becoming more destructive (Emanuel 2021). While these sorts of adverse events will inevitably take place, it is thus necessary to reduce infrastructure systems' vulnerabilities and increase their resilience. Increasing resilience has two obvious solutions. First, we can take steps to increase the system's capacity (also called absorptive capacity) to absorb the impacts of adverse shocks (e.g., building underground powerlines in storm-battered areas). Second, we can reduce the time and money required to restore a system or set of systems to normal or pre-disaster levels of functionality (adaptive capacity). This study follows the second approach to capture information on restoration times and examines the rate of restoration of electricity infrastructure to establish performance goals and measure the ability of a community to recover from adverse events.

A common basis is needed to draw an analogy between performance, direct or indirect economic losses, and time. To this end, the **significance** of this study is its ability to capture the total economic impact of natural hazards on electricity infrastructure, from physical damage and financial losses to the effect of loss of functionality due to lack of power and communications, disruption of other lifeline utilities, or workforce disruptions, in addition to power restoration times. This study develops an engineeringbased loss estimation tool that can be used to measure both direct and indirect economic losses. This tool will enable us to mathematically determine the system's performance on a common basis of money. The main **goal** of this study is to increase adaptive capacity by providing a system with an opportunity to adapt itself temporarily to new disrupted conditions. The goal can be achieved through two research objectives; The first objective aims at advancing a fundamental understanding of disaster resilience during the critical response period (i.e., when the disruption event starts and when the recovery performance reaches a steady state), and the second objective is to ensure that fundamental new insights can be translated to practice. The recent notable hurricane and water-related events in coastal states along the Atlantic Ocean and the Gulf of Mexico and other natural disasters (e.g., tornado) occurring in all 50 states have heightened the nation's need to adopt more scientific and precise resilient measures. The **first objective** is to incorporate the time factor into the existing resilience metrics (including those developed by National Windstorm Hazard Reduction Program Strategic Plan) to measure the system performance during the response period scientifically. The objective will enable us to measure the effectiveness of using supplying temporary power as a solution for emergency scenarios to keep essential devices powered and medications refrigerated during the response period. The **second objective** is to investigate to what extent the use of electric school bus vehicle-to-grid (V2G) offers a disaster relief solution during an emergency. The objective will help us envision the path we need to take to facilitate the practical application of the electric bus V2G alternative.

Gaps in Knowledge

Since its introduction by Holling (1973), the concept of resilience has evolved considerably in the context of socio-ecological systems. Generally, the resilience of a system is defined as the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially still the same function, structure, identity, and feedback (Walker et al. 2004). In the context of power distribution systems, resilience can be measured as the ability of the system to anticipate a possible disaster, adopt effective measures to decrease the loss of load and system component failure before and during the disaster, and restore power quickly through controlled reconfiguration (Phillips et al. 2020).

To date, power systems are regulated based on reliability metrics. This dates back to the Energy Policy Act of 2005 where Congress gave the Federal Energy Regulatory Commission authority to oversee the reliability of the bulk-power systems. The purpose was to ensure a reliable operation where instability, uncontrolled separation, or cascading failures would not occur as a result of a sudden disturbance. Two main metrics are used to measure reliability; the system average interruption duration index and the system average interruption frequency index (Phillips et al. 2020). However, some jurisdictions consider storm-related outages as extreme events and thus, do not include them as inputs into the reliability metrics (Congressional Research Service 2018).

The most recent contributions to the resilience metric proposed include McJunkin and Rieger (2017), Phillips et al. (2020), and Li et al (2020). These metrics use a neutral bias assumption to describe the assets' adaptive capacity, which limits the ability to accurately model many assets. In addition, the metrics do not lend themselves well for use as real-time operational metrics. The existing methods can be used generically on a wide variety of systems and under different disruptive scenarios. The problem is that such studies face challenges in assessing system behaviors to a specific disruptive event because their metrics have not precisely defined around system performance. Most literature on resilience measurement and metrics focuses on specific sources of the system disturbance as generic techniques, and little attention has been paid to the unique requirements at each resilience stage.

The authors are aware of the fact that both hard and soft (e.g. collaboration, community engagement) factors play important roles in achieving resilience (Fox-Lent et al. 2015). However, some of these are very difficult to quantify and thus social and community components are not included in the present study. In this study, the following definitions are used:

- Resilience is the ability of a system to effectively combat (absorb, adapt to, or rapidly recover from) disruptive events (Mumby et al. 2014).
- The disruptive event(s) is an unwanted situation(s) that makes the system's normal performance level susceptible to disruption (Hu et al. 2008).
- Absorptive capacity is the degree to which a system can absorb the impacts of system disruption and minimize consequences with little effort (Vugrin et al. 2011) (e.g., battery capacity to overcome supply or production disruption).
- Adaptive capacity is the ability of a system to react to undesirable shocks by undergoing some adjustments (Kebede et al. 2016) (e.g., shift in the use of energy or other resources).
- Restorative capacity is the ability of a system to be repaired quickly and return to normal or improved operations and system reliability (Ouyang et al. 2012).
- A sustainable system is a system that can consistently meet its demands with sustainable inputs rather than using non-renewable sources (Karan and Asgari 2021).

This research is needed because the resilience analysis frameworks developed or proposed over the past few years failed to quantitatively evaluate the resilience of an electricity infrastructure system during the recovery phase after a disaster. These measurement metrics are generic, academic-wide models that function well as a resilience assessment tool for many systems engineers and managers. However, their broad scope and standardized form limit their usefulness as a quantitative model for evaluating the resilience of a system during a specific phase, such as the recovery phase. This gap necessitates a clear definition of system performance. A different approach is proposed in this study to overcome this problem, where the scope of the study is limited to characterizing the adaptive process of the energy sector and to identifying key areas that contribute to adaptive capacity building. The existing methods can be used generically in a wide variety of systems and under different disruptive scenarios. The problem is that such studies face challenges in assessing system behaviors to a specific disruptive event because their metrics have not precisely defined around system performance.

Figure 2 better illustrates these metrics and ratios. As a hypothetical example, consider the major events leading up to, throughout, and following Winter Storm Uri in Texas. On Thursday, February 11th 2021, freezing rain began at t_0. This disruptive event downed power lines and caused minor interruptions to electric service. After some time, we noticed a drastic reduction in the overall system performance (e.g., rolling power outages that transitioned to extended outages). When the performance of the system is at its lowest (P_D), we start making initial adjustments at t_d, such as mobilizing emergency operations. The cost of these adjustments is estimated at C_a and it takes t_a to complete them. Making these adjustments would result in an overall increase in the system's performance and brings the system to a new performance level, P_a. With the aid of several different investments and restoration activities, the power lines are gradually returning to normality and after some time, t_r, it may be able to restore most of its services, thereby achieving a new equilibrium, P_R. The cost of these investments is estimated at C_r.

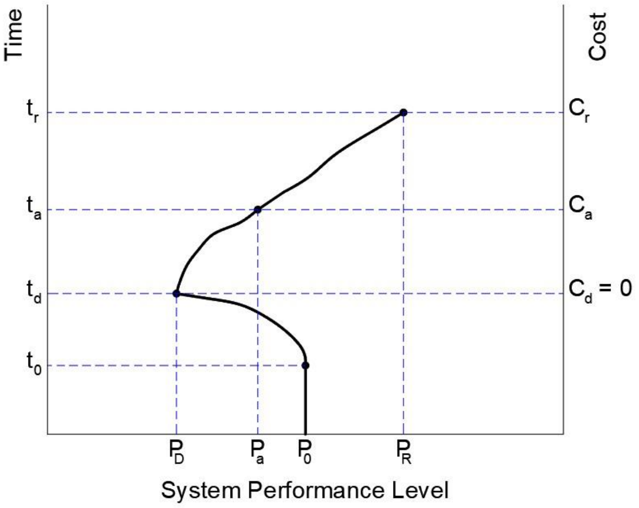


Figure 2 – Time and cost dimensions of system performance under unwanted disruptive situations

A common way to ensure consistent electrical access while restoration workers are trying to restore power is with onsite backup generation or with renewables and battery storage. Backup systems can be powered by renewable energy sources like solar and wind power or by generators that run on fuel like gasoline, propane, or diesel. Today, most of the nation's nearly half a million school buses run on diesel fuel. This situation is likely to change as billions of new federal dollars will become available for school districts across the country to transition to electric school buses. If every yellow school bus currently in operation were replaced with an electric bus equipped with the right vehicle-to-grid (V2G) technology, this would add enough capacity to store electricity and support health-care facilities and emergency services during the restoration phase. This proposal will assess the viability of electric school buses for providing additional power during unexpected demand spikes or emergency power during outages.

Measuring the Resilience of a Power Grid System

To quantitatively measure resilience and sustainability, the metrics developed by Francis and Bekera (2014) and Karan and Asadi (2018) are used in this study. Francis and Bekera proposed a resilience metric that incorporates the three resilience capabilities (absorptive, adaptive, and restorative) and the time to recovery. Karan and Asadi (2018) developed an integrated sustainability index that incorporated components of the power grid system. These components each consist of different sub-components (e.g. transportation fuel for the energy component) that make up an integrated system. The resilience of a system to a specific disruptive event can be determined by total recovery effort, which is a function of the duration of recovery and the recovery costs (Vugrin et al. 2010). The following resilience metrics are used and the integrated resilience metric is proposed to measure the resilience as a function of the duration of recovery and the recovery costs:

- Absorptive capacity resilience metric, $R_{abs} = \frac{P_D}{P_0}$
- Adaptive capacity resilience metric, $R_{adp} = \frac{t_{slack}}{(t_a - t_0)} \times \left(1 - \frac{C_a}{C_{aut}}\right) \times \frac{P_a}{P_0}$
- Restorative capacity resilience metric, $R_{res} = \frac{t_{slack}}{(t_r - t_a)} \times \left(1 - \frac{(C_r - C_a)}{C_{aut}}\right) \times \frac{P_R}{P_0}$
- Integrated resilience metric, $R = \frac{t_{slack}}{(t_r - t_0)} \times \left(1 - \frac{C_r}{C_{aut}}\right) \times \frac{P_D}{P_0} \times \frac{P_a}{P_0} \times \frac{P_R}{P_0}$

Where

- P_0 is the original stable performance level
- P_D is the performance level immediately post-disruption and before any recovery efforts
- P_a is the performance level after initial adjustments have been made
- P_R is the performance at a new stable level after recovery efforts have been exhausted
- t_0 is the start time of the disruptive event
- t_a is the time to complete initial adjustments
- t_r is the time to final recovery
- t_{slack} is the maximum amount of time post-disaster that is acceptable before recovery ensues (varies based on system's function)
- C_a is the cost needed to complete initial adjustments
- C_r is the recovery cost
- C_{aut} is the cost of full automation so systems can perform continuously with no or with minimal human assistance

The slack time can start from the time of the appearance of the shock due to a disruptive event until the time of full recovery of the system (Nanab et al., 2014). The revised resilience metric is dimensionless and thus can be used in a comparative manner. Figure 3 shows how this project frames the resilience of an electricity infrastructure system during the recovery phase after a disaster in the context of time and cost. The scope of this research task is limited to the total economic impact of natural hazards during the recovery phase. This also includes the amount of money an unplanned power outage costs a community. A power outage (or a loss of electrical power) due to extreme weather like hurricanes, tornadoes, thunderstorms, or winter storms could be extremely short (just a few minutes) or could last for days, depending on the cause and severity of the damage. The economic loss due to the power outage is added to the cost of temporary power sources to calculate the total economic impact of natural hazards on electricity infrastructure during the recovery phase.

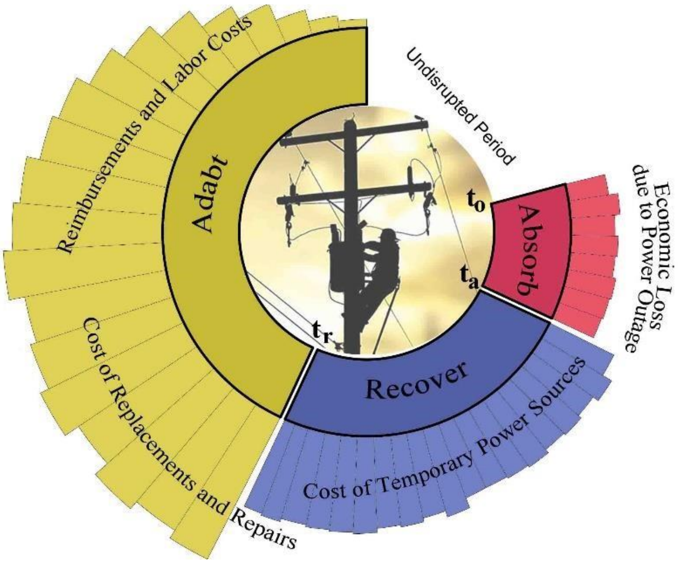


Figure 3 – Total economic impact of natural hazards on electricity infrastructure

Measuring the Economic Impact of a Power Outage

The time-dependence of the economic loss due to the power outage is considered by calculating the effects of power outages on households using the datasets derived from the Environmental Protection Agency (EPA)'s Incident Action Checklist - Power Outages and World Bank's Enterprise Surveys (WBES). Table 1 summarizes the power outage costs to the community. The extents of power outages are depicted by objective measures characterizing durations and frequencies of power outages and by perception-based measures reflecting commercial firms' perceived severity of power outages. The significance of the economic loss due to a power outage on commercial and industrial sectors is acknowledged, however, the scope of this study is primarily centered around households.

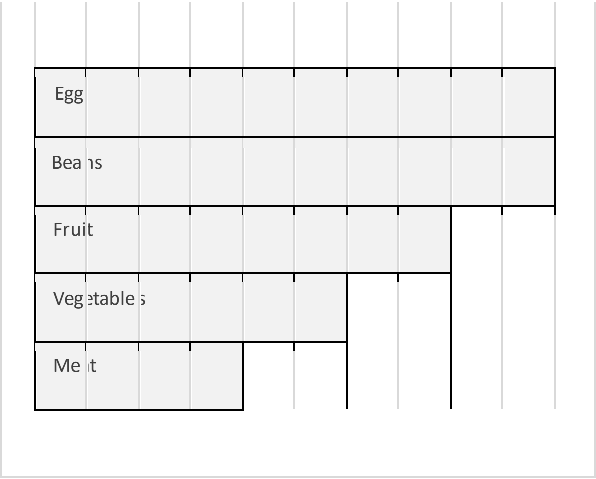
Table 1: Effects of power outages using objective and perception-based measures

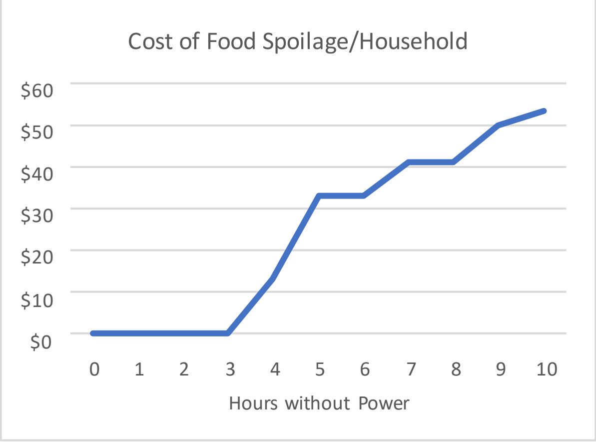
ITEM	**MEASURE**
Spoiled food (in the case of an extended power outage)	Objective measure
Emergency supplies	Objective measure
One day of lost productivity	Perception-based measure
Property damage	Objective measure
Alternative housing/workplace	Objective & perception-based measures

The objective measures cover frequency/number of power outages in a typical day, duration of power outages in a typical power outage incident measured in hours, and total duration of power outages per day. The perception-based measures that are used through an empirical analysis cover the perceived value of losses due to power outages and identification variables on whether electricity constitutes a major constraint for business operation. The data from the annual sales growth, employment growth, and labor productivity growth are considered.

The economic loss of food spoilage due to the power outage is summarized in Figure 4. The calculations are based on the dietary information provided by the Food and Agriculture Organization (FAO) of the United Nations (UN) (Kennedy et al., 2011). The amounts of calories needed for a household consists of one male and one female adult, and two children is estimated to be 54,600 cal/wk (or 7800 cal/day). The recommended average weekly intake amounts for the household are used in the calculations (e.g., weekly estimate of approximately 38.5 ounces (1,092 grams) of meat). The amounts are combined with the average retail food prices in the U.S. published by the Bureau of Labor Statistics to calculate the economic loss of food spoilage due to the power outage summarized in Figure 4.

The longer the power outage lasts, the higher the likelihood of food spoilage. Perishable items like meat, dairy products, and fresh produce are more susceptible to spoilage, particularly if the outage extends for several hours or days. Type of food: Certain types of food are more expensive and thus have a higher financial impact when spoiled. For example, premium cuts of meat or expensive seafood can represent significant losses if they spoil during a power outage. It is assumed that a refrigerator typically loses about 2-4 degrees Fahrenheit (1-2 degrees Celsius) per hour without power (Liddiard 2017). The frequency/number of power outages in a typical day does not impact the economic loss of spoiled food and only the total duration of power outages per day contributes to the cost.





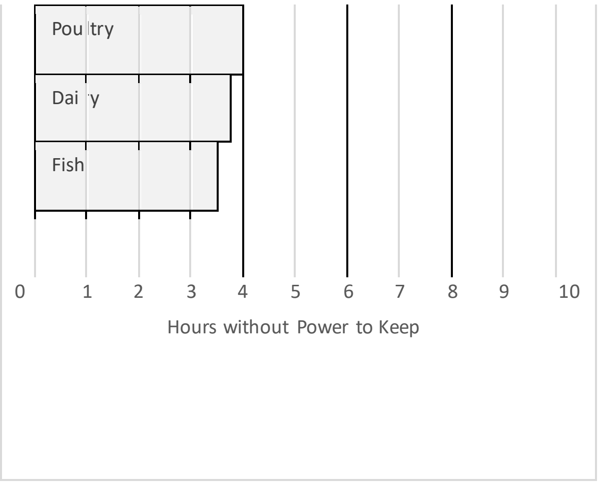


Figure 4 – Economic impact of food spoilage due to the power outage

During a power outage, it's essential to have emergency supplies on hand to ensure safety and wellbeing. Medications, mobile devices, and cash are some commonly impacted supplies during power outages. Medicines like antibiotics, insulin, and vaccines that require refrigeration typically become endangered when a power outage happens. To estimate the cost of power outages on drugs and medications, a list of commonly used refrigerated medications and their length of stability are adopted from the "Drug Stability Guidelines" published by the United States Food and Drug Administration (FDA 2008) and the information gathered by the Health Plan of San Mateo (HPSM) on the top 200 prescription medications in 2014 in the United States. The average price of the medication and their allowable temperature excursions and the length of time such excursions are permitted are taken into consideration. This data is combined with the estimated number of prescriptions in the United States (2020) obtained from the National Institute of Health (NIH) as reported by Kosari et al. (2018). Figure 5 shows the estimated cost of power outages on the degradation of pharmaceuticals in the USA. Most medicines and vaccines require a storage temperature range of 36°F to 46°F (2°C to 8°C) from the time of their manufacture to when the final consumer utilizes them.

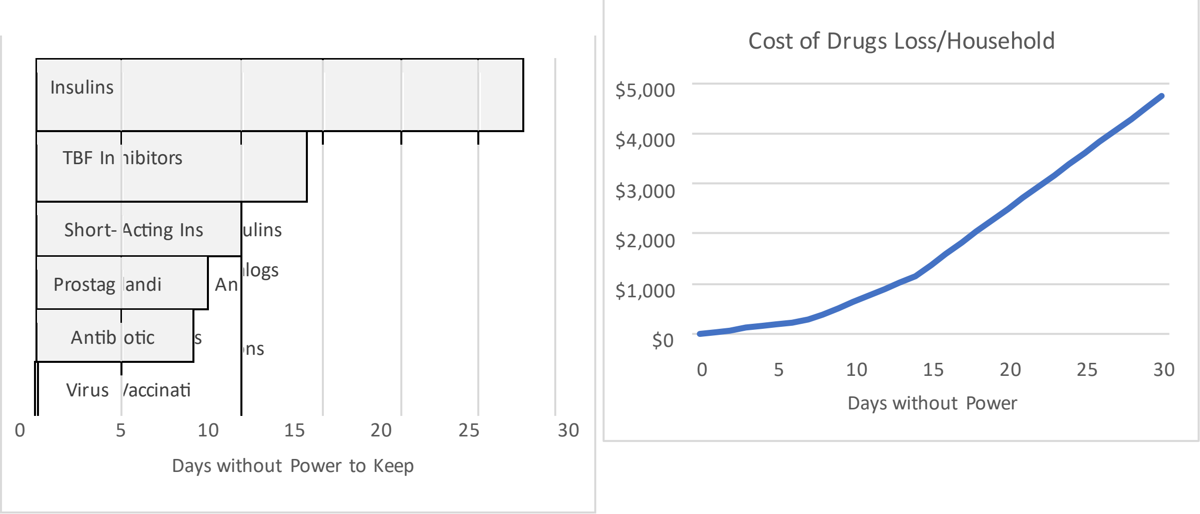


Figure 5 – Economic impact of drug loss due to the power outage

The primary factor contributing to productivity loss during a power outage is the downtime experienced by businesses. This downtime can result in halted production, interrupted workflow, and delayed or missed deadlines. The cost of downtime depends on the revenue generated per hour or per day by the affected business. There is no doubt that different industries have varying levels of dependency on uninterrupted power supply. For example, data centers, financial institutions, hospitals, and critical infrastructure may incur substantial losses due to power outages, considering the critical nature of their operations. On the other hand, businesses with lower power dependency or more flexibility in their operations may experience comparatively lower productivity losses such as construction and ground transportation . Thus, the cost of productivity loss due to power outage per household is estimated based on the hourly rate of the industry, its dependency on power, and the number of people working in the industry. Figure 6 shows an approximate cost of productivity loss due to power outages (with an average of $24/hr) although it is challenging to provide an exact cost as it can vary from case to case.

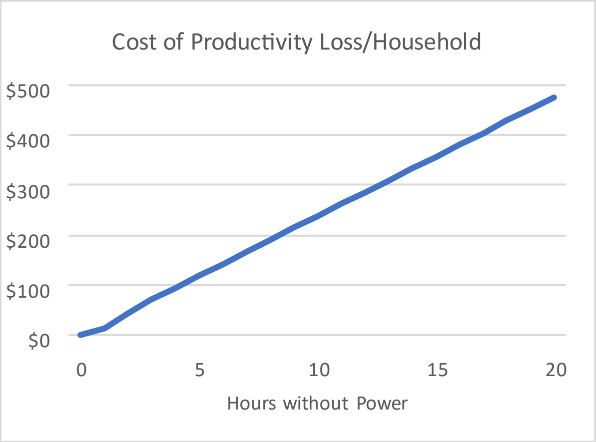


Figure 6 – Economic impact of productivity loss due to the power outage

Power outages can lead to property damage in various ways, such as electrical surges, frozen or burst pipes, flooding from sump pump failures, spoiled food, or damage from fires caused by alternative heating sources or candles. The only reliable source of information found for this study is related to a survey conducted by Baik et al (2018). The cost of property damage due to large-scale power outages to residential customers is reported to be an average of $211 for those who had experienced an outage for more than 12 hours in the last two years.

In some situations, the power outage forces the people to find alternative housing. If individuals or households need to seek alternative housing during a power outage, they may incur costs associated with renting temporary accommodation. This can include expenses such as hotel or motel costs, shortterm rental fees, or the cost of staying with friends or family. The number of people seeking accommodation in hotels during a power outage cannot be estimated since it varies significantly depending on factors such as the size of the affected area, the effectiveness of evacuation measures, and the availability of alternative shelter options. It is important to note that official statistics on the exact number of individuals staying at hotels during such events were not available at the time of the study.

Performance of a Power Grid System

Measurement of the system performance should indicate to what extent the energy production and supply meet the demand. It is necessary to take into account both the frequency and the duration of the power outage to measure the performance. The supply-demand ratio does not reflect the brief power outages lasting for a few seconds. However, the survey studies supported by the U.S. Department of Energy showed that the impact of temporary service interruptions (1-2 seconds) is approximately equal to 10-25 minutes outage (Campbell and Lowry 2012; LaCommare and Eto 2006; Lawton et al. 2003). A conservative approach to considering the outage frequency would be to add 10 minutes to each momentary outage. Furthermore, as the length of the outage increases, the negative impact of reduced performance could become greater. This impact depends not only on the duration, but also the season, time of day, and even day of the week are contributing attributes. The research team collected some preliminary data from prior power outage cost or lost value studies to understand this relationship (Balducci et al. 2002; Hashemi et al. 2018; Küfeoğlu and Lehtonen 2015; Reichl et al. 2013). Because the datasets were gathered differently (e.g., 1/3-1-4 hr outage periods versus 1-4-8-24 hr outage periods or $ per interruption versus $/KWh), a relative cost and linear interpolations are used to standardize and convert them. In this study, the performance of a power grid system is measured by the time period(s) the power supply is disrupted and characterized by three attributes: power supply, voltage, and number of outages. The following equation is developed to calculate the performance of the energy system:

$$P = \int_{t_{out}}^{t_{slack}} \frac{E_S \times V_S}{E_D \times V_D} - \frac{(N_{out} \times t_{eqv})}{t_{slack}}$$

Where

- P is the system performance
- E_S is the amount of power supply
- E_D is the amount of power demand
- V_s is the voltage in the electricity supply
- V_D is the desired electricity voltage
- t_{eqv} is the equivalent time period with similar impact on the performance per power outage (e.g., 10 minutes)
- t_{out} is the duration of the power outage
- N_{out} is the total number of power outages

The performance of the power grid during six major natural disasters since 2011 is measured using the above formula. Figure 7 shows the system performance during the first five days for Hurricane Irene (August 2011), Superstorm Sandy (October 2012), Winter Storm Nemo (February 2013), and Hurricane Harvey (August 2017). The metrics developed in the previous sections are used to measure the resilience of the power grid for these natural disasters. Winter Storm Uri (Texas 2021) is analyzed and will be used in the next section to assess the viability of using electric bus V2G as an emergency power solution. In the analysis, it has been observed that the resilience index for Superstorm Sandy and Hurricane Harvey has yielded remarkably low values. This discouraging outcome can be primarily attributed to the excessively long periods it took for these cases to achieve final recovery. Despite initial optimism and efforts to address the issues, the extended duration of their recovery processes has significantly affected the overall index. Such prolonged delays have not only highlighted the inherent complexities and challenges associated with these cases but also underscored the urgent need for improved strategies and interventions to expedite the recovery timeline.

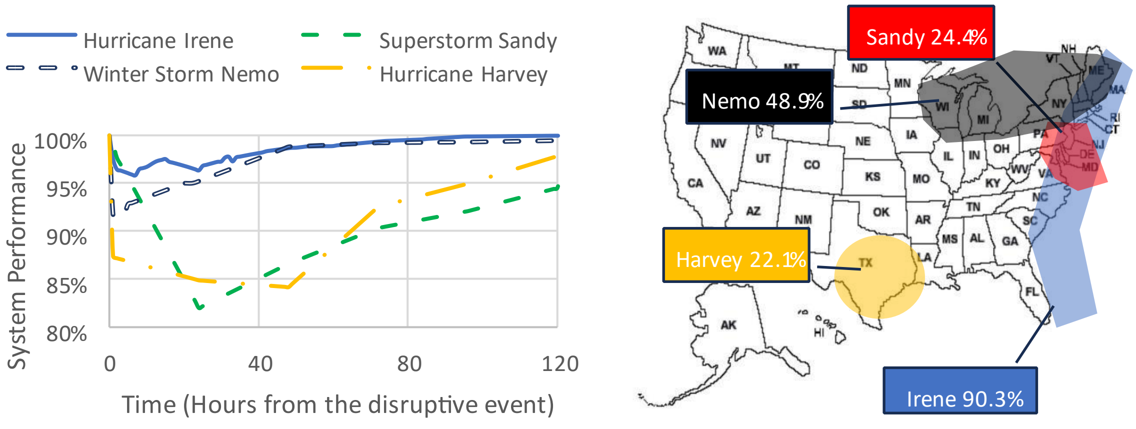


Figure 7 – (Left) Power grid performance over time (Right) Resilience index due to the power outage

Mobilization (response) time

Different natural hazards affect the power grid in different ways. For example, earthquakes cause inertial damage to heavy equipment (such as generators and transformers) and brittle items (for example ceramics). However, hurricane and water-related events can cause ground failure and damage overhead power lines, all can be devastating to electric infrastructure assets. Recovery time is driven by the balance of repairs and capabilities. Poor access to damaged facilities, due to landslides or traffic congestion, can also delay repairs. The time to restore power supply ranged from a few hours to months, but more frequently from 1 to 4 days.

Floods and hurricanes are commonly associated with power outages. Erosion due to the floodwaters and landslides triggered by floods undermine the foundations of transmission towers. Serious, and often explosive, damage may occur when electrified equipment comes in contact with water, while moisture and dirt intrusion require time-consuming repairs of inundated equipment. In contrast to earthquakes, early warning is possible, and enables electric utilities to shut off power to facilities in flood zones, therefore minimizing damage. Recovery time was driven by the number of needed repairs, and site access as repairs cannot start until floodwaters have receded. Other factors affecting the power grid recovery time in the aftermath of natural disasters include the resilience of electric power utilities, and the disruption of other critical infrastructure (mainly transportation and telecommunications), either as a direct result of the natural event, or because of the loss of power supply.

This section examines the time and resources needed to mobilize and deploy electric school buses to respond to emergencies and help restore communications in disaster-stricken communities. As shown in Figure 8 the factors affecting the mobilization (response) time fall into four groups; labor (bus drivers), proximity and access to the deployment location, magnitude of the outage, and the state of charge (SoC).

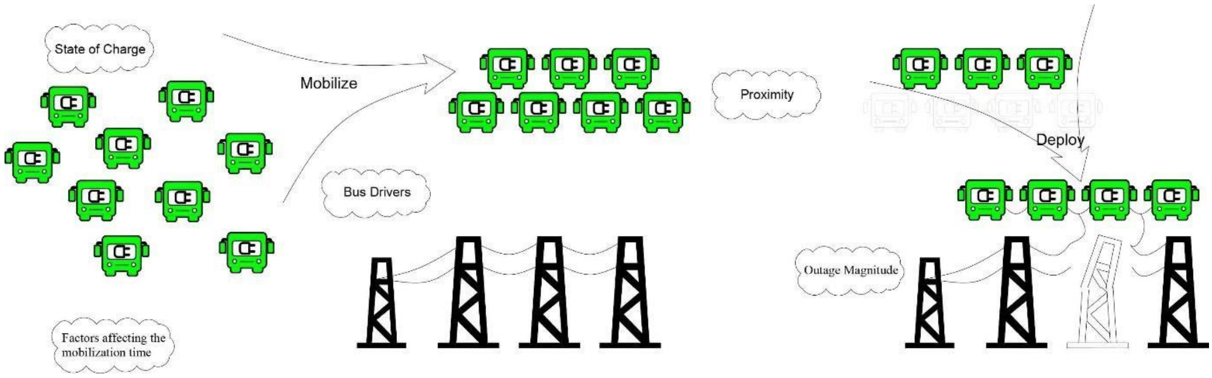


Figure 8 – Factors affecting the mobilization and deployment of electric school busses

Viability of using electric bus V2G as an emergency power solution

In theory, any electric vehicle, provided with right hardware and software, could be capable of sending power back to the grid. However, two features unique to school buses – as opposed to other electric vehicles, even including transit buses –make them particularly well-suited to V2G applications: 1) predictable and limited schedule; electric school buses operate for an average of only four to five hours per day and are mostly idle during weekends, school holidays, and emergency situations, 2) large battery sizes; while battery capacity in personal (light-duty) EVs is rarely higher than around 100 kWh, the battery packs in electric school buses range from 100 to 200 kWh, which could roughly power the equivalent of five operating rooms for more than eight hours, and a single operating room for 43 hours. This section analyzes the costs of the V2G equipment and labor the mobilization and deployment require, appraising whether the use of electric school buses is a good public investment decision based on an economic viability analysis.

Viability assessment here includes the description of the V2G equipment that will be required, the technology to be used, the power storage and outputs to be provided, and the identification of the endusers. Capital, operating, and maintenance costs are estimated over the recovery phase, as well as any revenue expected to be generated. Table 2 lists the main equipment needed to successfully create a vehicle to grid storage and explains how the estimate was made. This equipment includes electric vehicle supply equipment (EVSE), power discharging meter equipment (PDME) such as energy management gateway, smart meter, and grid control indicator. Other operating costs depend on the mobilization and recovery times and obviously the outage magnitude.

Table 2: Costs associated with V2G usage as an emergency power solution

ITEM	COST	ESTIMATE SOURCE
EVSE	$8501	An average of twenty different vendors producing EVSE for an AC Level 2 (supply power 208/240VAC/20-100A with 16-80A continuous)
PDME	$379	An average of fifteen different vendors manufacturing or supplying PDME in the USA
Software	$139	The cost of software is estimated based on the equipment estimates because equipment and its software are often sold together (1.5% of EVSE and 3% of PDME).
Mobilization/Operating Time	($114 x t + $0.3 x d) x min(power outage, No. of buses x SoC x battery pack)	Average rental price of $92 for a school bus and hourly rate of $22 for a bus driver, t is the utilization time (hr), average of $0.2 per kWh, an equivalent MPG of 10 for school buses, d is the travel distance (mile), both the power outage and the SoC x battery pack are measured in kWh

The cost of acquiring and establishing the physical infrastructure and equipment are considered capital costs. These costs are incurred upfront and are independent of how the electric school buses are utilized. On the other hand, operating costs are ongoing expenses that are dependent on the level of consumption or usage of the school buses. These costs depend on the include items such as travel distance for the deployment, recovery time, and the travel distance. Understanding the distinction between capital costs and operating costs is crucial for financial planning and decision-making.

The following equation is developed to assess the efficiency of using electric school buses as an emergency power solution.

$$E = \frac{\dfrac{No.\ of\ busses \times SoC \times Battery\ Pack}{\int_{t0}^{t^r} (E_D - E_S)}}{Captial\ Costs + Operating\ Costs}$$

Where

- E is the efficiency of using electric school buses and is calculated as the ratio of system performance improvement or increase in a value per dollar spent.
- E_S is the amount of power supply during the outage (without using electric school buses)
- E_D is the amount of power demand at normal condition
- t_r - t_0 measure the duration of the power outage

- N_{out} is the total number of power outages

The application of the above formal can be shown using the following example. Winter Storm Uri caused around 32,800 households in Conroe TX to lose power for an average of 14 hours. The estimate power outage magnitude for this scenario is estimated to be 812,550 kWh (Kemabonta 2021). With an average of 150 kWh battery capacity, SoC of 100%, and available 1382 electric school buses, for every $10,000 spent it is estimated to increase the system performance by 0.018%. Please note that more than eighty-four percent of the total cost is associated with the V2G equipment. Without these capital costs, it is possible to increase the system performance by 0.114% for every $1000 spent. If all the city of Conroe had electric school buses available and those buses were utilized during Winter Storm Uri, the system performance could increase by 25%. This requires more than fifteen million dollars investment only for the V2G equipment.

Winter Storm Uri (Texas 2021) related data from the National Hurricane Center and the National Weather Service is used to assess the viability of using electric bus V2G as an emergency power solution. Since the magnitude of the power outage caused by these storms are known, it is possible to calculate the system performance during the outage with and without using electric bus V2G alternative. The use of this alternative contributes more to the absorptive capacity of system resilience. While the power grid falls sharply to around seventy five percent after the first 24 hours, the use of electric school buses can potentially increase the performance by four percent. In terms of the total numbers, this is equivalent to more than half a million households. However, if it takes longer to restore the power supply, it will be less efficient to rely on electric bus V2G alternative as an auxiliary source of power.

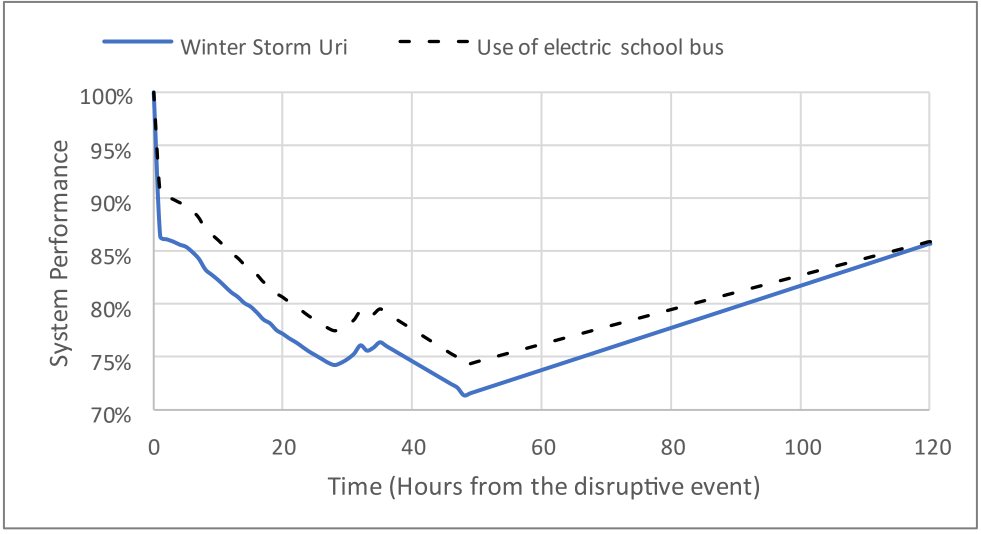


Figure 9 – Texas power grid performance over time during Winter Storm Uri

Complexity of existing policies and regulations

The electric system, which includes generation, transmission, and distribution, is owned by a mix of entities. About 2,900 publicly owned utilities and cooperatives account for 15% of net generation, 12% of transmission, and nearly 50% of the nation's electric distribution lines. Approximately 2,800 independent power producers account for 40% of the U.S. net generation. The Federal Government owns 9 power agencies with 7% of net generation and 8% of transmission. And 211 Electric Power Marketers account for approximately 19% of sales to consumers.

A review of the National Response Framework developed by the Department of Homeland Security and the Strategic Plan for the National Windstorm Impact Reduction (NWIRP) program indicates how the federal government, states, jurisdictions, and citizens should respond to disasters and emergencies. In

the case of a power outage or shortage (commonly caused by hurricane and major wind events), electric utilities are responsible for repairing damaged electricity infrastructure and restoring services.
Electric utilities often use mutual assistance—voluntary partnerships with other electric utilities—to bring in additional resources beyond those of the affected utility to help restore electricity. Electric utilities affected by a major outage are thereby able to increase the size of their workforce by borrowing restoration workers from other companies. When called upon, a company will send skilled restoration workers, both company employees and contractors—along with specialized equipment to help with the restoration efforts of a fellow company.

This study recognizes the complexity of the policies and regulations involved in running the grid. There are generator operators and transmission owners. But from a system perspective, one of the most critical entities is the independent system operator or regional transmission organizations (ISOs and RTOs). They monitor system loads and voltage profiles; operate transmission facilities and direct generation; define operating limits and develop contingency plans; and implement emergency procedures. Reliability coordinators also play an essential role. For instance, NERC (North American Electric Reliability Corporation) develops and enforces reliability standards; monitors the bulk power system; assesses future adequacy; audits owners, operators, and users for preparedness. Adding to this complexity is the inconsistency in the patchwork of rules existing at the school districts, as well as among state and local governments. Figure 10 illustrates the interconnected stakeholder roles in owning, maintaining, operating, and interacting with power systems and jurisdictions.

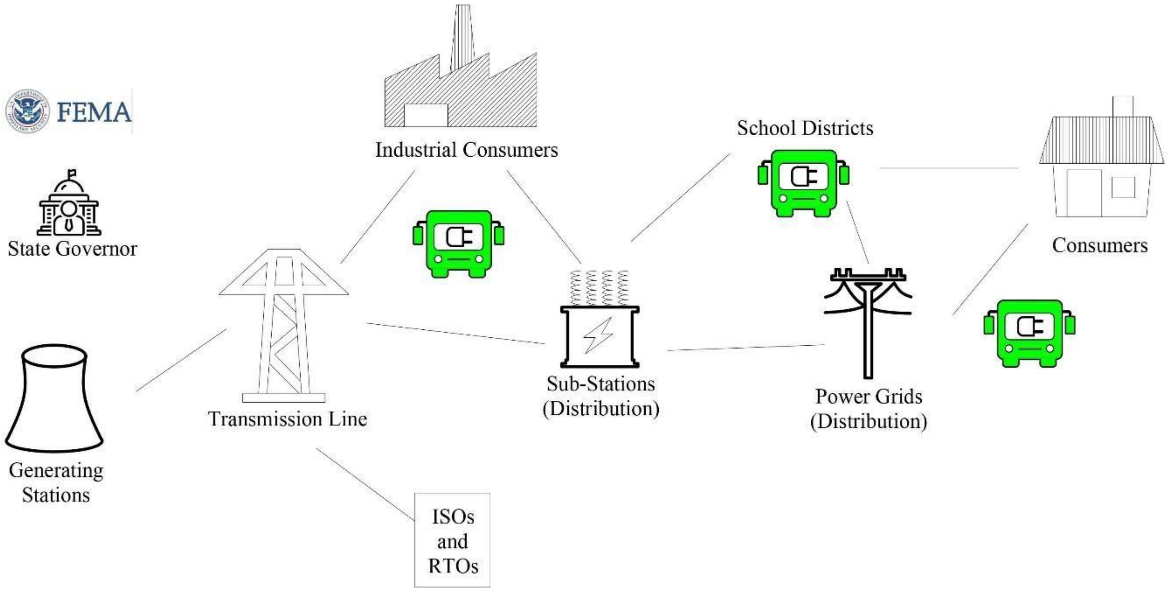


Figure 10 – Stakeholders in disaster recovery of an electricity system

Conclusion

In conclusion, utilizing electric school buses as an emergency source of power during a power outage presents a promising and innovative solution. The dual-functionality of these buses not only serves as a reliable means of transportation for students but also offers a resilient backup power supply for communities in times of crisis. By leveraging their large battery capacities, electric school buses can help bridge the energy gap during emergencies, providing essential electricity to critical facilities such as shelters, medical centers, and communication hubs. The vehicles operate on predictable and limited schedules and their large battery size will provide enough power for more than 10 households (if they use power for emergency needs). This eco-friendly and sustainable approach not only reduces greenhouse gas emissions but also enhances community preparedness and resilience. While further research, planning, and infrastructure development may be needed to fully realize this potential, embracing electric school buses as emergency power sources signifies a forward-thinking approach towards building more resilient and greener societies.

The technical aspects of using electric school buses as an auxiliary source of power show both potential and challenges. The hardware required for implementing this concept involves adapting the buses with bidirectional charging capabilities, allowing them to not only charge but also discharge electricity back into the grid or directly to homes. This necessitates the installation of sophisticated charging infrastructure at schools or designated hubs, capable of handling high-power output, that could cost to $10,000 per school bus.

Connecting electric school buses to the grid demands careful planning to ensure seamless integration. Advanced smart grid technologies would be essential to manage the bi-directional flow of electricity efficiently. This includes implementing systems to regulate power flow, synchronize with the main grid, and manage demand fluctuations during power outages. Additionally, advanced monitoring and control systems would be crucial to prioritize energy distribution to critical facilities and maintain overall grid stability. The complexity arises from various factors, such as adapting the buses' battery management systems to perform optimally in both transportation and power supply modes. Safety protocols should be rigorously implemented to prevent unauthorized access to bus batteries and to ensure secure connections to the grid or homes.

Furthermore, standardization and regulations must be established to govern the technical specifications and safety standards of these power-sharing systems. Collaboration between electric utilities, transportation authorities, and relevant regulatory bodies is vital to streamline implementation and address potential challenges.

Despite these complexities, leveraging electric school buses as an auxiliary source of power offers tremendous benefits, including enhanced grid resilience, reduced peak demand stress, and potential cost savings. It is important to compare the use of electric school bus V2G alternative with other small-scale (household-level) alternatives such as portable generators or solar systems equipped with battery. With ongoing advancements in technology and infrastructure, this innovative approach has the potential to play a crucial role in shaping a sustainable and more resilient energy future. However, careful planning, investment, and collaboration will be key to successfully realizing the full potential of this concept in practical applications.

The use of electric school buses as a mobile power source is technically feasible due to their bidirectional charging capabilities, which allow them to discharge electricity back into the grid or directly to homes during a power outage. However, while the concept is technically possible, it may not be financially justifiable for several reasons:

- High upfront costs: Electric school buses generally have higher upfront costs compared to conventional diesel or gasoline buses. The additional expense is primarily attributed to the cost of battery technology, which represents a significant portion of the vehicle's overall cost.
- Limited utilization: Electric school buses would only be used as mobile power sources during power outages, which might not occur frequently in some regions. This limited utilization of their power-sharing capabilities can make it difficult to justify the higher upfront investment.
- Charging infrastructure: Implementing bidirectional charging infrastructure at schools or designated hubs adds to the overall cost. While these costs can be offset over time through savings on fuel and maintenance, the initial investment can still be a barrier.
- Operational complexity: Utilizing electric school buses as power sources requires careful planning and coordination with utilities and grid operators. The complexity of integrating these mobile sources into the grid, ensuring safe power distribution, and managing demand fluctuations during emergencies can be challenging and may involve additional costs.

- Alternative solutions: There are alternative ways to address power outages and provide emergency backup power, such as stationary energy storage systems (e.g., battery banks) or dedicated backup generators. These options may offer more cost-effective and efficient solutions for emergency power needs, especially if power outages are infrequent.
- Incentives and regulations: The financial feasibility of using electric school buses as mobile power sources can vary depending on local incentives, grants, and regulatory policies supporting their adoption. Without such support, the cost-effectiveness of the concept may be further challenged.

Despite the financial challenges, it's essential to consider the broader benefits of electric school buses in terms of reduced emissions, improved air quality, and long-term operational cost savings. Additionally, as battery technology continues to advance and production scales increase, the costs of electric buses are expected to decrease, making them more financially viable in the future. Ultimately, the financial justifiability of using electric school buses as mobile power sources will depend on a combination of factors, including the local energy landscape, government support, technological advancements, and the frequency of power outages in a given area.

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