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ENHANCING COMMUNITY RESILIENCE: ELECTRIC SCHOOL BUS V2G AS PORTABLE ENERGY SOLUTION

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Abstract
This study investigates the potential of utilizing electric school buses equipped with vehicle-to-grid (V2G) technology as a portable energy solution to enhance community resilience during and after power outages caused by natural disasters and shortages. The first objective of this research is to advance our understanding of disaster resilience, particularly during the critical response period—from the onset of the disruption event to the stabilization of recovery efforts. The second objective is to translate fundamental insights gained from this understanding into practical applications. To achieve these objectives, the study encompasses various analyses. Firstly, economic losses resulting from power outages are quantified, providing insights into the broader impacts of energy disruptions. Additionally, the performance of power grid systems is evaluated to assess their resilience and effectiveness in responding to and recovering from adverse events. Furthermore, the study includes calculations for mobilization (response) time, crucial for assessing the timeliness and efficiency of emergency response efforts. Finally, the viability of employing electric bus V2G technology as an emergency power solution is thoroughly analyzed. This encompasses assessing factors such as response time, load recovery or supply, system performance pre- and post-recovery, and other resilience metrics. By integrating these multifaceted analyses, this research aims to offer comprehensive insights into the potential of electric school buses as a resilient energy solution for communities facing power disruptions.

Keywords Energy Resilience, Vehicle-to-grid (V2G) Technology, Sustainable Transportation.

INTRODUCTION

The energy sector's resilience in the face of natural disasters stands as a testament to its commitment to providing stable power supplies despite formidable challenges. Severe natural hazards often disrupt local energy distribution, affecting electricity supply and demand. At the community level, electricity is indispensable for critical functions such as emergency and healthcare services, information networks, transportation, and water management. Disruptions to these services can profoundly impact security, public health, and safety.

The United States has faced a myriad of natural disasters over the years, each posing significant challenges to the resilience of the power grid. Hurricane Irene in August 2011 brought widespread power outages along the East Coast, primarily due to downed power lines and infrastructure damage. Superstorm Sandy, occurring in October 2012, wreaked havoc on the northeastern United States, causing extensive damage to power infrastructure and resulting in prolonged outages. Similarly, the Derecho of June 2012 brought severe thunderstorms, leading to widespread power disruptions lasting over a week in some areas. Winter Storm Nemo, striking in

February 2013, brought heavy snowfall and strong winds to the northeastern states, causing significant damage to power infrastructure and prolonged outages. Hurricanes Harvey and Irma in August and September 2017, respectively, inflicted extensive flooding and wind damage in Texas and southeastern states, resulting in widespread and prolonged power outages. Additionally, wildfires in California in 2017, 2018, and 2020 caused significant damage to power infrastructure and led to long-lasting outages, exacerbated by intentional power shutdowns to prevent further fire risks. The polar vortex of 2014 brought extreme cold temperatures, straining the power grid and leading to outages in several states. Most recently, the Texas winter storm in February 2021 caused power grid failures and widespread blackouts due to severe winter weather conditions. These natural disasters underscore the vulnerabilities of the power grid to extreme weather events and the need for resilience-building efforts.

Despite these challenges, the energy sector has consistently demonstrated resilience by recovering and restoring power to affected communities. Strategic planning, robust infrastructure, effective emergency response systems, and investments in modernization and renewable energy have contributed to this resilience. Collaboration among utilities, government agencies, and communities has also played a vital role in facilitating rapid recovery and reliable electricity delivery. For instance, following the winter storm in 2021, stakeholders recognized the need for better coordination and communication to address vulnerabilities in the power grid during extreme weather events. As a result, utilities worked closely with state and local government agencies to develop comprehensive winterization plans for power plants, transmission lines, and other critical infrastructure. These plans included measures such as installing insulation, heaters, and de-icing equipment to protect equipment from freezing temperatures and ice accumulation. Additionally, energy regulators implemented new guidelines and requirements to ensure that power plants and utilities adequately prepared for extreme weather events. This included conducting winter readiness assessments, mandating regular inspections and maintenance of equipment, and providing incentives for investments in winterization measures. As a result of these collaborative efforts and lessons learned from the 2021 winter storm, the power grid in Texas was better prepared to handle similar extreme weather events in subsequent winters.

This study focuses on mobile emergency power solutions to enhance community resilience. Specifically, it investigates the potential of electric school buses equipped with vehicle-to-grid (V2G) technology to serve as renewable electricity generators and disaster relief resources during and after natural disasters. Electric school buses, with their high electricity storage capacity and limited operation during adverse events, are well-suited for this purpose. The study evaluates various factors including response time, load recovery or supply, system performance pre- and post-recovery, and other resilience metrics to assess the viability and effectiveness of electric bus V2G in enhancing community resilience. Winter Storm Uri (Texas 2021) data from authoritative sources is utilized to ensure practical applicability. While the focus is primarily on water-related events like hurricanes and floods, the findings are intended to inform disaster resilience practices applicable to various natural hazards. The research outcomes aim to support vulnerable communities nationwide in their planning and decision-making, particularly regarding federal and state-level investments such as the Infrastructure Investment and Jobs Act. Figure 1 illustrates the different stages of resilience and the proposed solution's role during the critical response period.

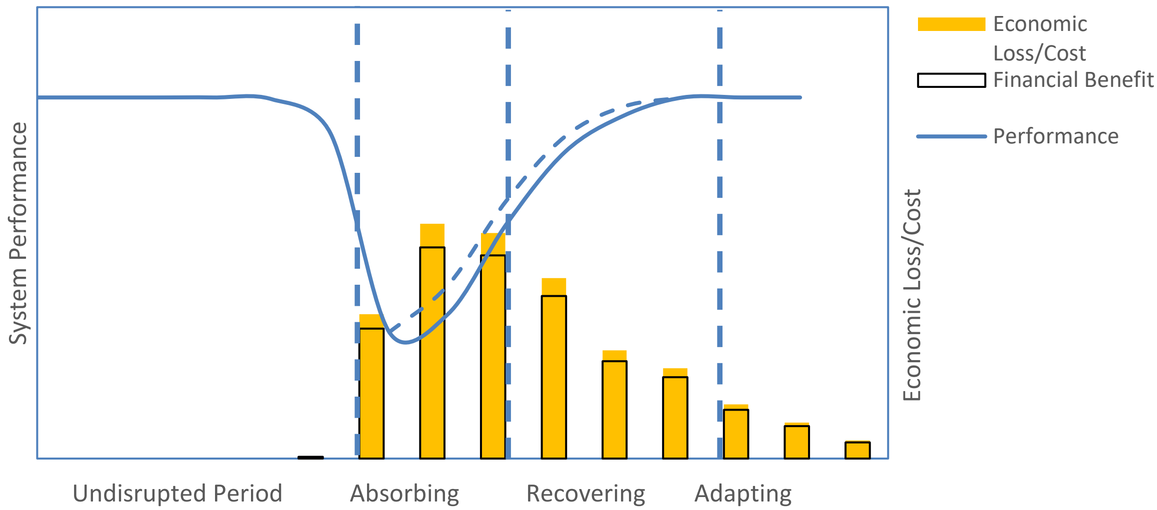

Figure 1: System Performance and Economic Impact Across Four Phases Post-Disruption

RESEARCH IMPORTANCE AND GOALS

The electricity infrastructure stands as a cornerstone of national energy security, essential for sustaining vital services such as healthcare facilities and emergency response systems. In recent years, governments and utility providers nationwide have intensified their focus on fortifying the grid against both natural disasters and man-made threats. However, prevailing wind loading design standards for electricity distribution often overlook the impact of severe wind events, aligning closely with community standards. A notable study led by atmospheric scientist Kerry Emanuel at the Massachusetts Institute of Technology has underscored the potential escalation in hurricane intensity in recent years, highlighting the increasing destructiveness of storms (Emanuel, 2021).

Recognizing the inevitability of such adversities, it becomes imperative to mitigate vulnerabilities within infrastructure systems and bolster their resilience. Enhancing resilience primarily entails two approaches: augmenting absorptive capacity to withstand adverse shocks, such as deploying underground powerlines in storm-prone regions and enhancing adaptive capacity to expedite system restoration and functionality post-disaster. This study focuses on the latter, aiming to capture critical data on restoration times and assess the efficacy of electricity infrastructure recovery.

A fundamental aspect of this endeavor lies in establishing a unified framework that correlates performance metrics, economic losses—both direct and indirect—and temporal factors. The significance of this research lies in its capacity to comprehensively evaluate the total economic impact of natural hazards on electricity infrastructure, encompassing physical damages, financial losses, functional impairment due to power and communication disruptions, and workforce interruptions. Central to this study is the development of an engineering-based loss estimation tool, enabling quantification of both direct and indirect economic losses and facilitating a standardized monetary assessment of system performance. The primary objective of this study is to enhance adaptive capacity by equipping systems with the resilience to adapt to disrupted conditions temporarily. This is pursued through two key research objectives: firstly, advancing understanding of disaster resilience during the critical response period—from the onset of the disruptive event to the stabilization of recovery performance—and secondly, translating novel insights garnered from research into practical applications. The urgency of these objectives is underscored by the prevalence of notable hurricane and water-related events along coastal regions and the occurrence of natural disasters nationwide, accentuating the pressing need for scientifically informed resilient measures.

The first objective involves integrating temporal factors into existing resilience metrics to scientifically gauge system performance during the response period. This entails assessing the efficacy of temporary power supply solutions—such as supplying power to essential devices and maintaining medication refrigeration—during emergency scenarios. The second objective delves into the potential of electric school bus vehicle-to-grid (V2G) technology as a disaster relief solution, paving the way for practical implementation and adoption. In essence, this research endeavors to contribute invaluable insights into bolstering the resilience of electricity infrastructure, thereby ensuring the sustained functionality and resilience of critical services in the face of adversities.

Addressing Gaps in Knowledge and Conceptual Framework

Since its inception by Holling (1973), the concept of resilience has undergone significant evolution within socio-ecological systems. Resilience, broadly defined, pertains to a system's capacity to absorb disturbance, reorganize, and retain its essential functions, structure, identity, and feedback amidst change (Walker et al., 2004). In the realm of power distribution systems, resilience manifests as the system's ability to anticipate and mitigate potential disasters, minimize load loss and component failure, and swiftly restore power through controlled reconfiguration (Phillips et al., 2020).

Historically, power systems have been regulated based on reliability metrics, traceable back to the Energy Policy Act of 2005, granting oversight authority to the Federal Energy Regulatory Commission. This legislation aims to ensure reliable operation, minimizing the risk of instability or cascading failures following sudden disturbances. Key reliability metrics, such as the system average interruption duration index and system average interruption frequency index, have been instrumental in assessing system reliability (Phillips et al., 2020). However, challenges persist in incorporating storm-related outages into reliability metrics across different jurisdictions (Congressional Research Service, 2018).

Recent contributions to resilience metrics, including those proposed by McJunkin and Rieger (2017), Phillips et al. (2020), and Li et al. (2020), have introduced nuanced approaches to evaluating system resilience. Despite these advancements, existing metrics often exhibit limitations, such as a neutral bias assumption in describing asset adaptive capacity and limited applicability as real-time operational metrics. Moreover, these metrics often lack precision in assessing system behaviors during specific disruptive events, necessitating a refined understanding of resilience stages and performance metrics.

While recognizing the multifaceted nature of resilience, encompassing both hard and soft factors such as collaboration and community engagement (Fox-Lent et al., 2015), this study primarily focuses on quantifiable aspects, with social and community components excluded from the present analysis. Definitions employed in this study delineate resilience as the system's ability to combat disruptive events effectively, with disruptive events defined as unwanted situations rendering the system susceptible to performance disruption. Additionally, key capacities integral to resilience, namely absorptive, adaptive, and restorative capacities, are defined to provide clarity in subsequent analyses:

- Resilience: The ability of a system to effectively combat (absorb, adapt to, or rapidly recover from) disruptive events (Mumby et al., 2014).
- Disruptive Event(s): An unwanted situation(s) that makes the system's normal performance level susceptible to disruption (Hu et al., 2008).
- Absorptive Capacity: 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: 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: The ability of a system to be repaired quickly and return to normal or improved operations and system reliability (Ouyang et al., 2012).
- Sustainable System: A system that can consistently meet its demands with sustainable inputs rather than using non-renewable sources (Karan and Asgari, 2021).

This research endeavor is necessitated by the inadequacies of existing resilience analysis frameworks in quantitatively evaluating electricity infrastructure resilience during the post-disaster recovery phase. While current measurement metrics serve as effective resilience assessment tools for systems engineers and managers, their generic nature and standardized forms limit their utility in evaluating system resilience during specific phases, such as recovery. To address this gap, this study proposes a focused approach centered on characterizing the adaptive processes within the energy sector and identifying key contributors to adaptive capacity building.

Figure 2 depicts these metrics and ratios, illustrating a hypothetical scenario surrounding Winter Storm Uri in Texas. Following the onset of freezing rain on Thursday, February 11th, 2021 (t0), power lines were compromised, leading to initial disruptions in electric service. As time progressed, the system experienced a significant decline in performance, marked by escalating power outages evolving from intermittent to prolonged. At the nadir of system performance (PD), proactive measures were initiated at td, including the mobilization of emergency operations to mitigate the crisis. The associated costs of these interventions (Ca) were estimated, with completion anticipated by ta, culminating in an overall enhancement of system performance and the attainment of a new operational threshold, Pa. Through a series of strategic investments and restoration endeavors, the gradual return to normalcy ensued, ultimately resulting in the restoration of essential services and the establishment of a new equilibrium, PR, post-crisis. The associated costs of these investments (Cr) were likewise accounted for in the overarching recovery efforts.

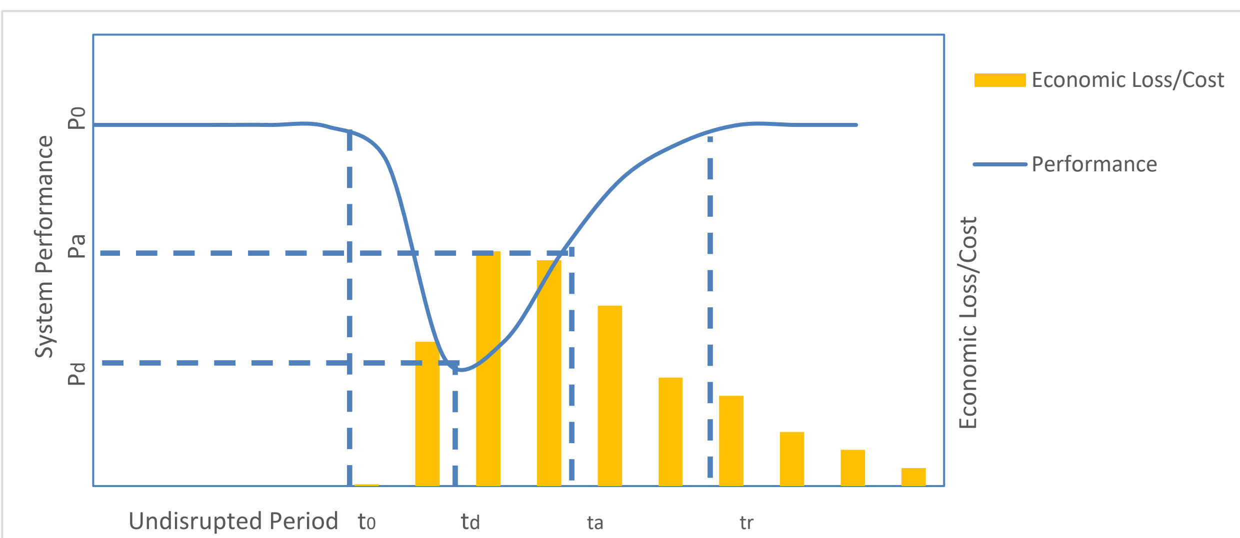

Figure 2: Temporal Evolution of System Performance and Response Strategies in the Aftermath of a Disruptive Event

This example underscores the significance of timely adjustments and investments in restoring system performance post-disaster, laying the groundwork for subsequent analyses. Building upon these insights, the proposal explores the viability of leveraging electric school buses equipped with vehicle-to-grid (V2G) technology to augment power supply during demand spikes or outages, further enhancing resilience in the electricity infrastructure.

Quantifying Power Grid Resilience

In this study, the resilience and sustainability of the power grid system are assessed using metrics developed by Francis and Bekera (2014) and Karan and Asadi (2018). Francis and Bekera's resilience metric integrates absorptive, adaptive, and restorative capacities alongside recovery time. Meanwhile, Karan and Asadi's integrated sustainability index incorporates various components of the power grid system. These metrics are crucial for evaluating the system's resilience to specific disruptive events based on the total recovery effort, which considers both recovery duration and costs (Vugrin et al., 2010). The following resilience metrics are employed:

- 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 = $\frac{t_{slack}}{(t_r - t_0)} \times \left(1 - \frac{C_r}{C_{aut}}\right) \times \frac{P_D}{P_0} \times \frac{P_a}{P_0} \times \frac{P_R}{P_0}$

Were

- 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 encompasses the period from the onset of the disruptive event to full system recovery (Nanab et al., 2014). This revised resilience metric, being dimensionless, facilitates comparative analysis. This research focuses on assessing the total economic impact of natural hazards during the recovery phase, including the costs incurred by unplanned power outages. Such outages, often caused by extreme weather events like hurricanes or winter storms, can range from brief interruptions to prolonged downtime, with corresponding economic repercussions factored into the overall assessment.

Quantifying the Economic Ramifications of Power Outages

To accurately assess the economic repercussions of power outages, this study integrates both objective and perception-based measures derived from datasets provided by the Environmental Protection Agency (EPA)'s Incident Action Checklist - Power Outages and the World Bank's Enterprise Surveys (WBES). Table 1 encapsulates the costs incurred by communities due to power outages, emphasizing the study's focus on households while acknowledging the significance of economic losses to commercial and industrial sectors.

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Table 1: Understanding Power Outage Impacts: Objective and Perception-Based Assessment

ITEM	MEASURE
Alternative Accommodation Evaluation	Combined Objective and Perception-Based Measure
Emergency Supply Evaluation	Objective Measure
Food Spoilage Consequences	Objective Measure
Lost Productivity Impact	Perception-Based Measure
Property Damage Estimate	Objective Measure

Objective measures encompass the frequency and duration of power outages, providing quantitative insights into outage occurrences and their durations. Perception-based measures, derived empirically, gauge commercial firms' perceived severity of power outages and their economic implications. These measures include the perceived value of losses attributed to outages and variables identifying electricity's impact as a constraint on business operations. Moreover, data on annual sales growth, employment growth, and labor productivity growth are considered to comprehensively evaluate the economic effects.

The economic impact of food spoilage resulting from power outages is assessed in Figure 3, drawing on dietary guidelines from the Food and Agriculture Organization (FAO) of the United Nations (UN) (Kennedy et al., 2011). Calculations are based on the recommended caloric intake for a household comprising one male adult, one female adult, and two children, estimated at 54,600 calories per week (or 7,800 calories per day). Utilizing average weekly consumption data, including approximately 38.5 ounces (1,092 grams) of meat, in conjunction with retail food prices provided by the Bureau of Labor Statistics, the economic losses incurred from food spoilage during power outages are quantified.

Extended power outages heighten the risk of food spoilage, particularly for perishable items like meat, dairy products, and fresh produce. The financial impact varies depending on the type of food, with premium cuts of meat or expensive seafood representing significant losses if spoiled during outages. Assuming a typical refrigerator loses 2-4 degrees Fahrenheit (1-2 degrees Celsius) per hour without power (Liddiard, 2017), the duration of power outages is a key determinant of economic losses associated with spoiled food, while the frequency of outages has a minimal impact.

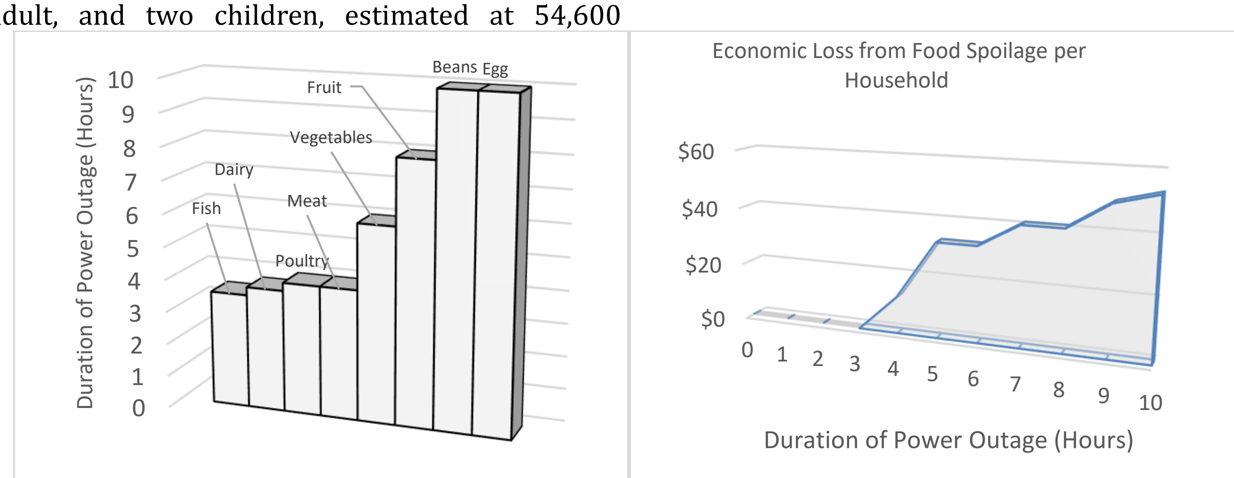

Figure 3: Economic Cost of Food Spoilage During Power Outage

During a power outage, it is crucial to have emergency supplies readily available to ensure safety and well-being. Medications, mobile devices, and cash are among the essential items often impacted during such events. Medications like antibiotics, insulin, and vaccines that require refrigeration are particularly vulnerable during power outages. To assess the cost of power outages on drugs and medications, a comprehensive list of commonly used refrigerated medications and their stability periods is compiled from the "Drug Stability Guidelines" published by the United States Food and Drug Administration (FDA 2008) and data provided by the Health Plan of San Mateo (HPSM) on the top 200 prescription medications in the United States in 2014. The average prices of these medications, along with their allowable temperature excursions and the duration for which such excursions are permissible, are taken into account. This information is then combined with estimates of the number of prescriptions in the United States in 2020, obtained from the National Institute of Health (NIH) as reported by Kosari et al. (2018). Figure 4 illustrates the estimated cost of power outages on the degradation of pharmaceuticals in the USA. It is important to note that most medicines and vaccines require storage within a temperature range of 36°F to 46°F (2°C to 8°C) from the time of manufacture until they are consumed by the end-user.

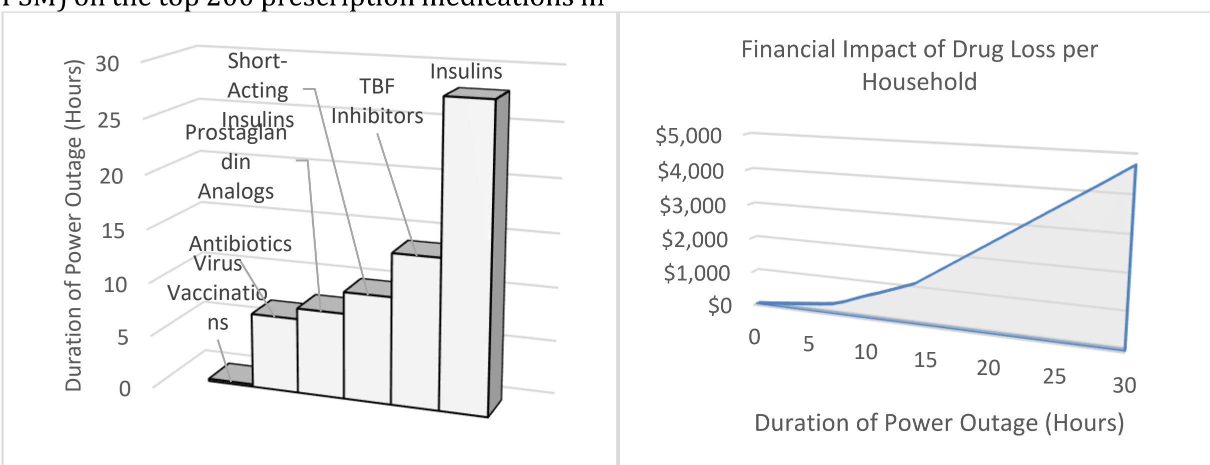

Figure 4: Impact of Pharmaceutical Losses Due to Power Outages

Productivity loss during a power outage primarily stems from the downtime experienced by businesses, leading to halted production, workflow interruptions, and missed deadlines. The extent of this loss hinges on the revenue generated by the affected business per hour or day. Industries vary in their reliance on uninterrupted power; for instance, data centers, financial institutions, hospitals, and critical infrastructure may suffer significant losses due to their essential operations. Conversely, businesses with lower power dependence or greater operational flexibility, such as construction and ground transportation, may experience relatively lower productivity declines. To estimate the cost of productivity loss per household during a power outage, we consider factors such as the industry's hourly rate, its reliance on power, and the number of employees. Figure 5 illustrates an approximate productivity loss cost during power outages, averaging $24/hr, although precise figures can vary depending on the specific circumstances.

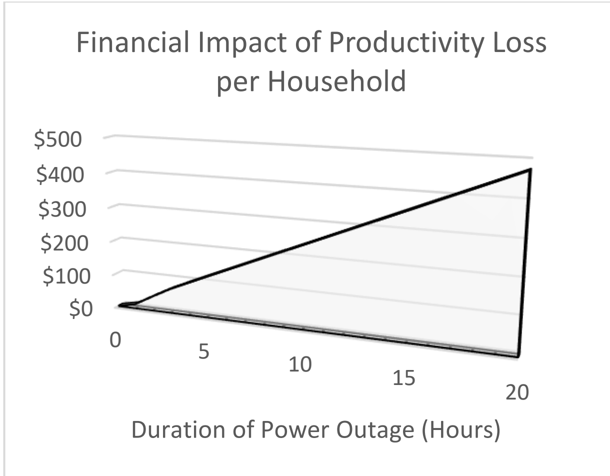

Figure 5: Impact of Productivity Losses Due to Power Outages

Power outages can result in property damage through various means, including electrical surges, frozen or burst pipes, flooding from sump pump failures, spoiled food, or damage from fires caused by alternative heating sources or candles. A reliable source of information for this study is a survey conducted by Baik et al (2018), which reported an average property damage cost of $211 for residential customers who experienced outages lasting more than 12 hours in the last two years.

During power outages, individuals or households may be compelled to seek alternative housing due to various reasons. This necessity can lead to additional expenses associated with renting temporary accommodations, such as hotel or motel costs, short-term rental fees, or the cost of staying with friends or family. Estimating the number of individuals seeking accommodation in hotels during a power outage is challenging and varies significantly based on factors such as the affected area's size, the effectiveness of evacuation measures, and the availability of alternative shelter options. It's worth noting that official statistics on the exact number of individuals staying at hotels during such events were not available at the time of the study.

Materials and Methods: Assessment of Power Grid System Performance

Evaluation of the performance of a power grid system is crucial to determine the extent to which energy production and supply meet demand. It is essential to consider both the frequency and duration of power outages in this assessment. While the supply-demand ratio provides valuable insights, it may overlook brief power outages lasting only a few seconds. However, studies supported by the U.S. Department of Energy have demonstrated that even temporary service interruptions (1-2 seconds) can have a significant impact, equivalent to 10-25 minutes of outage time (Campbell and Lowry 2012; LaCommare and Eto 2006; Lawton et al. 2003). To address this, a conservative approach adds 10 minutes to each momentary outage.

Moreover, as outage duration increases, the negative impact on performance may escalate, influenced by factors such as season, time of day, and day of the week. Preliminary data from previous studies on power outage costs or lost value were collected to understand this relationship (Balducci et al. 2002; Hashemi et al. 2018; Küfeoğlu and Lehtonen 2015; Reichl et al. 2013). Standardization and conversion of datasets were necessary due to variations in data collection methods, such as different outage periods or cost metrics.

In this study, the performance of a power grid system is quantified by the duration(s) of power supply disruption and characterized by three attributes: power supply, voltage, and number of outages. The following equation is developed to calculate system performance:

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

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 analyzed using this formula. Figure 6 illustrates the system performance during the first five days of Hurricane Irene (August 2011), Superstorm Sandy (October 2012), Winter Storm Nemo (February 2013), and Hurricane Harvey (August 2017). Resilience metrics from previous sections are utilized to measure the power grid's resilience during these natural disasters. The analysis of Winter Storm Uri (Texas 2021) will be further explored in the subsequent section to evaluate the feasibility of using electric bus Vehicle-to-Grid (V2G) technology as an emergency power solution. Remarkably low resilience index values were observed for Superstorm Sandy and Hurricane Harvey, primarily due to extended recovery periods. These findings underscore the need for improved strategies to expedite recovery timelines and address the complexities associated with such events.

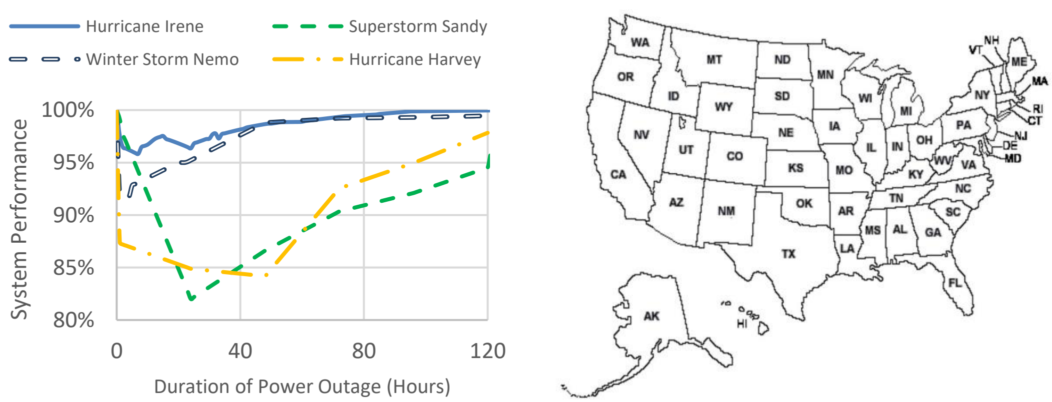

Figure 6 – (Left) Electrical network efficiency over duration, (Right) Resilience indicator following power disruption

Activation (Reaction) Period

Various natural phenomena impact the power grid differently. For instance, earthquakes inflict mechanical harm on heavy machinery (like generators and transformers) and fragile components (such as ceramics). Conversely, hurricanes and aquatic incidents can result in ground erosion and destruction of overhead power lines, all of which pose significant threats to electrical infrastructure assets. The time taken for recovery hinges on the equilibrium between repairs and resources. Difficulties in reaching damaged sites, caused by landslides or traffic congestion, can further impede restoration efforts. Restoration of power supply spans from a few hours to several months, with a more common range falling between 1 to 4 days.

Floods and hurricanes frequently lead to power disruptions. Erosion caused by floodwaters and landslides triggered by floods undermines the bases of transmission towers. When electrified equipment comes into contact with water, it can cause serious, and often explosive, damage, while inundated equipment requires time-consuming repairs due to moisture and dirt intrusion. Unlike earthquakes, early warnings are feasible for floods, enabling electric utilities to shut off power to facilities in flood-prone areas, thus mitigating damage. Recovery time is determined by the extent of necessary repairs and site access, which is contingent on the recession of floodwaters. Other factors influencing power grid recovery time post-natural disasters include the resilience of electric power utilities and the disruption of other critical infrastructure (primarily transportation and telecommunications), either directly due to the natural event or due to power supply loss.

This section evaluates the time and resources required to mobilize and deploy electric school buses for emergency response and communication restoration in disaster-affected communities. As depicted in Figure 7, the determinants impacting mobilization (response) time can be categorized into four groups: labor (bus drivers), proximity and accessibility to deployment sites, magnitude of the outage, and state of charge (SoC).

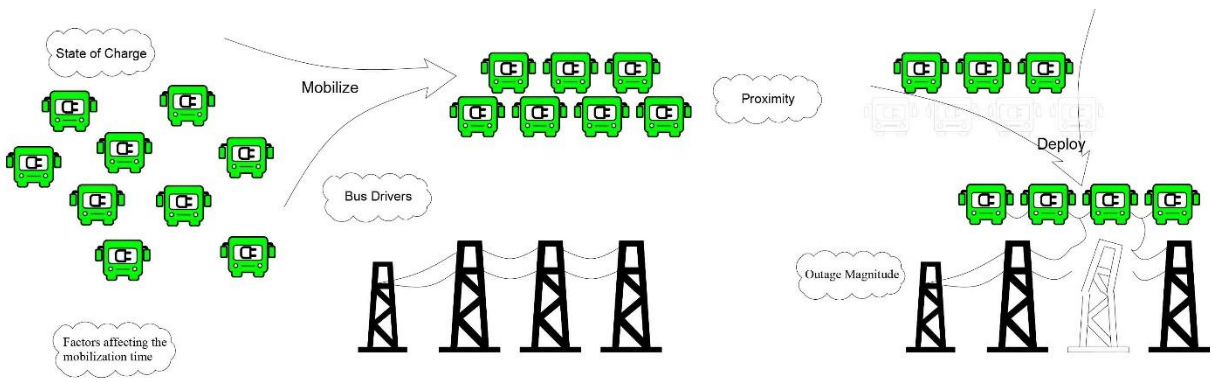

Figure 7 - Elements Influencing the Activation and Deployment of Electric School Buses

Results: Feasibility of Employing Electric Bus Vehicle-to-Grid (V2G) as an Emergency Power Alternative

In principle, any electric vehicle, given the appropriate hardware and software, could potentially supply power back to the grid. Nonetheless, two distinctive attributes specific to school buses - unlike other electric vehicles, including transit buses - render them particularly suitable for V2G applications: 1) their predictable and restricted schedules; electric school buses typically operate for an average of merely four to five hours per day and remain mostly inactive during weekends, school breaks, and emergency situations, 2) their substantial battery capacities; while battery size in personal (light-duty) EVs seldom exceeds around 100 kWh, the battery packs in electric school buses range from 100 to 200 kWh, which could power roughly the equivalent of five operating rooms for over eight hours or a single operating room for 43 hours. This section scrutinizes the expenses associated with V2G equipment and labor required for mobilization and deployment, evaluating whether employing electric school buses constitutes a prudent public investment decision based on an economic viability assessment.

The viability assessment entails delineating the requisite V2G equipment, the technology involved, the power storage and outputs to be provided, and identifying end-users. Capital, operational, and maintenance costs are estimated over the recovery phase, along with any projected revenue. Table 2 enumerates the principal equipment necessary to establish vehicle-to-grid storage and elucidates how the estimation was derived. This equipment encompasses electric vehicle supply equipment (EVSE), power discharging meter equipment (PDME) such as energy management gateways, smart meters, and grid control indicators. Additional operational costs are contingent on mobilization and recovery times, as well as the extent of the outage.

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 the 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 procuring and establishing the physical infrastructure and equipment is considered capital expenditure, incurred upfront and irrespective of how the electric school buses are utilized. Conversely, operational costs constitute ongoing expenses contingent on the level of consumption or usage of the school buses, including factors such as travel distance for deployment, recovery time, and the travel distance. Grasping the distinction between capital and operational costs is imperative for financial planning and decision-making. The following equation is devised to evaluate the efficacy of utilizing electric school buses as an emergency power solution:

$$E = \frac{\int_{t_0}^{t_r} \frac{No.of\ busses \times SoC \times Battery\ Pack}{(E_D - E_S)}}{Captial\ Costs + Operating\ Costs}$$

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 formula can be illustrated using the following example: Winter Storm Uri caused approximately 32,800 households in Conroe, TX, to lose power for an average of 14 hours. The estimated power outage magnitude for this scenario is assessed to be 812,550 kWh. With an average battery capacity of 150 kWh, SoC of 100%, and 1382 available electric school buses, for every $10,000 spent, the system performance is estimated to increase by 0.018%.

Notably, over eighty-four percent of the total cost is attributed to V2G equipment. Excluding these capital costs, the system performance could potentially increase by 0.114% for every $1000 spent. If all of Conroe's city had electric school buses available and utilized them during Winter Storm Uri, the system performance could increase by 25%, necessitating an investment exceeding fifteen million dollars solely for V2G equipment.

Data related to Winter Storm Uri (Texas 2021) from the National Hurricane Center and the National Weather Service is employed to evaluate the viability of employing electric bus V2G as an emergency power solution. Since the magnitude of power outages caused by these storms is known, it is feasible to compute the system performance during the outage with and without leveraging electric bus V2G alternatives. Utilizing this alternative enhances the absorptive capacity of system resilience as shown in Figure 8. While the power grid experiences a significant decline to around seventy-five percent after the initial 24 hours, the utilization of electric school buses has the potential to increase performance by four percent. In absolute terms, this is equivalent to over half a million households. However, if power restoration takes longer, relying on electric bus V2G as an auxiliary power source may be less efficient.

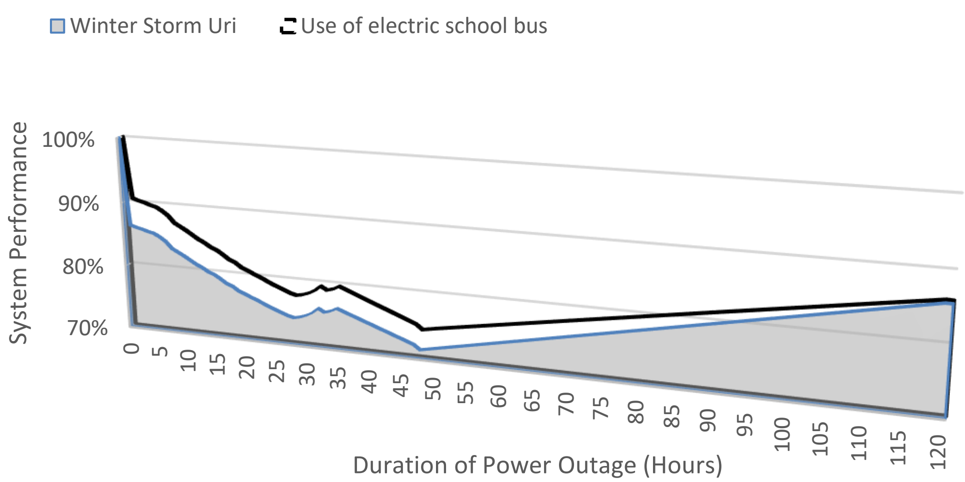

Figure 8 - Performance of Texas Power Grid Throughout Duration of Winter Storm Uri

DISCUSSION

The electrical system, encompassing generation, transmission, and distribution, is under a diverse ownership structure. Publicly owned utilities and cooperatives, numbering around 2,900, contribute 15% of net generation, 12% of transmission, and nearly 50% of the nation's electric distribution lines. Independent power producers, approximately 2,800 in number, account for 40% of U.S. net generation. The Federal Government possesses 9 power agencies, responsible for 7% of net generation and 8% of transmission. Additionally, 211 Electric Power Marketers handle about 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 delineates how the federal government, states, jurisdictions, and citizens should respond to disasters and emergencies. In scenarios involving power outages or shortages, typically caused by hurricanes and major wind events, electric utilities bear the responsibility of repairing damaged electricity infrastructure and reinstating services. Often, electric utilities engage in mutual assistance—voluntary partnerships with other electric utilities—to leverage additional resources beyond those of the affected utility for restoring electricity. Mutual assistance enables affected electric utilities to augment their workforce by borrowing restoration workers from other companies. These restoration workers, comprising both company employees and contractors, are accompanied by specialized equipment to aid in restoration efforts.

This study acknowledges the intricate nature of the policies and regulations governing the grid. It involves various stakeholders, including generator operators, transmission owners, and, from a systemic perspective, independent system operators or regional transmission organizations (ISOs and RTOs). These entities monitor system loads and voltage profiles, operate transmission facilities, direct generation, define operating limits, develop contingency plans, and implement emergency procedures. Reliability coordinators, such as NERC (North American Electric Reliability Corporation), are pivotal in developing and enforcing reliability standards, monitoring the bulk power system, assessing future adequacy, and auditing owners, operators, and users for preparedness. The complexity is further compounded by the disparities in rules existing among school districts, state, and local governments.

CONCLUSION

In summary, the utilization of electric school buses as a contingency power source during power disruptions offers a promising and inventive remedy. These buses' multifunctionality serves not only as a dependable mode of transportation for students but also as a resilient alternative power provider for communities during crises. By harnessing their substantial battery capacities, electric school buses can bridge energy deficiencies in emergencies, supplying vital electricity to critical facilities like shelters, medical centers, and communication hubs. Operating on predictable and constrained schedules, these buses possess ample battery size to cater to emergency power needs of over 10 households. This environmentally conscious and sustainable approach not only curtails greenhouse gas emissions but also bolsters community readiness and resilience. While additional exploration, strategic planning, and infrastructure advancement may be necessary to fully exploit this potential, embracing electric school buses as emergency power sources signifies a forward-looking strategy towards fostering more resilient and environmentally friendly societies.

In terms of technical considerations, leveraging electric school buses as a supplementary power source presents both opportunities and obstacles. To implement this concept, buses need to be equipped with bidirectional charging capabilities, enabling them to both charge and discharge electricity to the grid or residences. This requires installing sophisticated charging infrastructure at schools or designated hubs, with estimated costs of up to $10,000 per school bus. Integrating electric school buses into the grid requires meticulous planning to ensure smooth coordination. Advanced smart grid technologies are imperative to efficiently manage the bidirectional flow of electricity. This entails implementing systems to regulate power flow, synchronize with the main grid, and manage demand fluctuations during outages. Additionally, advanced monitoring and control systems are crucial to prioritize energy distribution to critical facilities and maintain overall grid stability. The complexity arises from various factors, including adapting the buses' battery management systems to perform optimally in both transportation and power supply modes. Rigorous safety protocols must be enforced to prevent unauthorized access to bus batteries and ensure secure connections to the grid or residences.

Establishing standardization and regulations is imperative to govern the technical specifications and safety standards of power-sharing systems involving electric school buses. Collaboration among electric utilities, transportation authorities, and relevant regulatory bodies is essential to streamline implementation and overcome potential challenges. Despite these intricacies, utilizing electric school buses as a supplementary power source offers significant advantages, including bolstered grid resilience, alleviated peak demand stress, and potential cost savings. It's crucial to compare this alternative with other small-scale options like portable generators or solar systems with batteries. With ongoing technological advancements and infrastructure development, this innovative approach has the potential to play a pivotal role in shaping a sustainable and resilient energy future. However, meticulous planning, investment, and collaboration are essential to fully realize its potential in practical applications. While electric school buses' bidirectional charging capabilities make them technically feasible as a mobile power source during outages, their financial justification faces several challenges:

- Electric school buses entail higher upfront costs mainly due to the expense of battery technology, which constitutes a significant portion of the vehicle's total cost.
- The limited utilization of electric school buses as mobile power sources during infrequent power outages in certain regions can hinder the justification for their higher initial investment.
- The implementation of bidirectional charging infrastructure at schools or designated hubs increases the overall cost, although these costs can potentially be offset over time through savings on fuel and maintenance.
- Utilizing electric school buses as power sources involves complex planning and coordination with utilities and grid operators, entailing additional costs due to the intricacies of integrating them into the grid and managing demand fluctuations during emergencies.
- Alternative solutions like stationary energy storage systems or backup generators may offer more cost-effective and efficient options for addressing power outages and providing emergency backup power, particularly in areas where power outages are infrequent.
- The financial viability of using electric school buses as mobile power sources depends on local incentives, grants, and regulatory policies, which can significantly impact their cost-effectiveness without adequate support.

Despite the financial hurdles, it is crucial to recognize the broader advantages of electric school buses, including decreased emissions, enhanced air quality, and long-term operational cost reductions. Furthermore, with ongoing advancements in battery technology and increased production scales, the costs associated with electric buses are projected to decline, rendering them more economically feasible in the future. Ultimately, the financial viability of utilizing electric school buses as mobile power sources will hinge on various factors such as the local energy scenario, governmental backing, technological progressions, and the frequency of power interruptions in specific regions.

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Author Contributions

Dr. Ebrahim Karan conceptualized and designed the study, conducted the research, performed the data analysis and interpretation, and wrote the manuscript.

Conflict of Interest

The author declares no conflict of interest.

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