Systematic Review of Electric Vehicles, Resilience, and Evacuations

Working Paper (January 2024)

Mohammad Hossein Babaei[a, b]
Graduate Student Researcher
mbabaei@ualberta.ca
(Corresponding Author)

Dr. Stephen D. Wong[a, b]
Assistant Professor

[a] Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB, Canada

[b] Resilient and Sustainable Mobility and Evacuation Group, University of Alberta, Edmonton, AB, Canada

UNIVERSITY OF ALBERTA

RESUME Group
RESILIENT AND SUSTAINABLE MOBILITY & EVACUATION GROUP

Abstract

Disasters significantly impact communities, often require large-scale evacuations, and damage key infrastructure (e.g., power, transportation). With growing electric vehicle (EV) adoption and electrification of transportation, governments and utilities may face significant power challenges during a disaster, especially during the evacuation stage. Low states-of-charge, sporadic charging infrastructure, or power outages could significantly hamper safe and effective evacuations. Yet, EVs also offer possible resilience benefits to emergency response by more easily charging electronics (e.g., mobile phones, radios, vital medical equipment) or sending power back to the grid through vehicle-to-grid (V2G) technology. To understand this dichotomy, this paper focuses on the use cases, benefits, and drawbacks of EVs in disasters and evacuations through a systematic review of current literature, reports, and sources. Overall, this review discovered EVs show promise as modes of transportation and mobile energy supply units during disasters and emergencies. However, crucial challenges such as charging infrastructure locations, upfront cost of resilience technologies, and user behavior remain understudied. We recommend that more dedicated research, evaluation programs, and demonstrations be conducted to overcome EV shortcomings and guide more realistic implementation of EV benefits.

Keywords: Electric Vehicles, EVs, Resilience, Disasters, Wildfires, Power Outage, Evacuation

1. INTRODUCTION

The adoption rate of electric vehicles (EVs) has been steadily growing over the past decade as battery prices fall, production ramps up, and incentives increase. EVs comprised 14 percent of new car sales globally in 2022 (IEA, 2023). The steady adoption of EVs carries both challenges and novel opportunities, as EVs can act as both modes of transportation as well as energy storage and supply systems (Yang et al., 2020b). With continued acceptance and interest from consumers (Adderly et al., 2018), EV adoption is now faced with the challenge of meeting user needs apart from normal conditions, specifically during disaster scenarios. This includes access to charging infrastructure resilient to disasters such as large-scale power outages and wildfires (Rahimi & Davoudi, 2018). Risk-reduction measures, such as public safety power shutoff (PSPS) events in California, also pose an issue to EV adoption and resilience, requiring more research and resilient policies (Wong et al., 2022).

Focusing on possible benefits, EVs can act as energy storage devices that can potentially return power back to the grid for usage by other devices (Yang et al., 2020b). A community suffering from a loss of power can use EVs as mobile power sources (MPSs) by supplying power back to the grid, improving community resilience and long-term recovery (Lei et al., 2019). These challenges and benefits have yet to fully materialize as only a few anecdotal examples of EV use cases in disasters exist. In 2011 during the Japanese tsunami, EVs transported medicine to areas where oil refineries were destroyed but the electricity grid remained operational (Belson, 2011). Similarly, Pacific Gas and Electric utilized plug-in hybrid electric vehicles (PHEVs) to power evacuation shelters throughout California wildfires (Morris, 2015).

Despite these examples, most disaster plans or protocols do not require an analysis of EV needs during extreme events (Donaldson et al., 2020). Moreover, EV user behavior and the resilience of EVs during natural disasters have been relatively under-researched. Our objective in this paper is to address these gaps by providing an early understanding of the advantages of EV use in disasters as well as impediments to the safe and effective operation of these vehicles surrounding evacuations. We seek to answer the following questions:

1) What are critical EV barriers and challenges in disasters and evacuations?
2) What are the benefits and use cases for EVs in disasters and evacuations?
3) How should future research and practice consider the intersection of EVs, resilience, and evacuations for disasters?

To answer these questions, we conducted a systematic review of EV literature that focuses on resilience and/or evacuations. This paper is organized as follows. First, we elaborate on the various challenges faced by EVs currently. Second, we provide a detailed analysis of research into the benefits of using EVs in disasters through different strategies. A section is then dedicated to a review of policies surrounding EV use during disasters. We then provide a discussion on the key takeaways from our review and end with conclusions.

2. METHODOLOGY

We conducted a systematic review on EVs, resilience, and evacuations using a keyword search for papers published between 2000 and 2023 on the peer-reviewed databases of Scopus, Taylor & Francis, and Transport Research International Documentation (TRID). The keyword string utilized to locate papers was as follows: (evacuation* OR route planning OR resilien* OR prepar* AND electric vehicle* OR alternate fuel vehicle* AND disaster* OR emergenc* OR wildfire* OR hurricane* OR tsunami* OR hazard* OR extreme weather event*. Focusing on titles and abstracts, the query provided 333 results across all databases which were screened for relevancy over multiple stages, resulting in 63 articles. Three articles were written in languages other than English and were omitted from the review, leaving 60 papers in total.

Our systematic review is limited by our choice in the publication databases and the restriction of English-only papers. We also excluded a significant amount of literature related to grid resilience, as articles did not have immediate transportation implications. Since EV resilience is an emerging area of research and practice, we may not have captured all current literature, especially reports and policy briefs from gray literature. The search string may also have failed to capture literature on the topic, especially those that discuss EV resilience or evacuations in the body of the article (as opposed to the title or abstract).

3. REVIEW OF EV CHALLENGES IN DISASTERS

Disasters can have widespread impacts on the power grid and related infrastructure, which can lead to power outages and reduce EV usability. This is particularly important since EVs tend to have shorter driving ranges than internal combustion engine (ICE) vehicles, which could alter how EV owners evacuate (Adderly et al., 2018). If grids do not adapt, evacuating EVs during disasters may become more difficult as adoption grows (Macdonald et al., 2021). Additionally, increased EV adoption can lead to stress on the power grid before, during, and after disasters. Research has found that an evacuation at 20% EV market penetration could cause dynamic and severe stress on the grid during a disaster such as wildfires, which can be further modulated by location and electric load within a region (Donaldson et al., 2022). The high demand for EV charging can negatively impact infrastructure, particularly transformers. This grid component can be excessively strained and potentially fail under emergency conditions, requiring demand response strategies to decrease these occurrences (Razeghi et al., 2021).

As electric storage systems (ESSs), the operation of EVs is limited by the capacity of their batteries and the insufficient coverage of the existing charging network (Rahimi & Davoudi, 2018). Sparse charging networks remain major obstacles to EV adoption, and their unreliability could significantly challenge EV-based evacuations. For example, EV owners may be unable to follow the same evacuation plans as evacuees with gas-powered vehicles (Adderly et al., 2018). With charging networks often left out of evacuation route planning, EVs are often not considered or planned for in evacuations (Purba et al., 2022). Moreover, the potential for flow bottlenecks at charging stations, resulting from EVs' longer refueling time, may require active oversight and the selection of charging station locations based on a variety of considerations, including traffic and population density (Li et al., 2022b), and not just operator profits. Consequently, adequate charging coverage may be lacking in certain disaster-stricken areas, which can lead to poor evacuation outcomes.

Beyond initial effects, the mass evacuation of electric vehicles can have long-term impacts on the grid. Feng et al. (2020) conducted research on evacuations during Hurricane Irma in Florida assuming an EV-majority fleet of evacuees. The study found that crucial refueling stations and the larger electrical grid outside of highly urbanized areas would not be able to support evacuating EVs, especially those that stop to recharge. In addition to the demand EVs will have on the network, traffic from all evacuating motor vehicles can impede the mobility of EV MPSs. As such, the transport and power networks are highly interdependent and disruptions in one can cascade and adversely impact the other (Hussain & Musilek, 2022).

Natural disasters may also cause failure in transmission devices, increasing the scale of power required and negatively impacting those residing within them (Maharajan et al., 2015). Communication infrastructure, control, and management strategies for EV discharge back into the grid are all key factors that must be considered in future strategies (Momen et al., 2020). The implementation of grid resilience strategies utilizing EVs should also ensure that the lifespan of these vehicles is unaffected by their use as electricity storage and transmission devices (Hussain & Musilek, 2022).

4. REVIEW OF EV BENEFITS AND USE CASES

This section will discuss the unique benefits of EVs in disasters and address approaches to remedy the aforementioned challenges.

4.1 Charging Infrastructure

Fast charging stations are instrumental in providing resilience to the grid during outages. Known as Level 3 chargers, they can supply high-voltage electricity unlike Level 1 and 2 chargers typically used for charging EVs at home (ChargeHub, 2023). Using these charging stations, vehicles equipped with bidirectional charging technology can send power back to the grid (Rahimi & Davoudi, 2018). This capability can also be provided in the form of a converter supplied at a station or installed in a home. A number of vehicle manufacturers highlight their electric vehicles' ability to provide electricity for the home during outages (Rahimi & Davoudi, 2018). The Ford Motor Company advertises the 2023 F-150 Lightning electric truck with the Ford Charge Station Pro, a home-installed charger and converter which provides bidirectional power flow for the vehicle, which allows it to power a home for up to ten days (Ford, 2023). Some research suggests equipping chargers with three-level converters (converters that use three voltage levels to boost bidirectional power flow), which increases transmission rates (Yamane et al., 2019). This can further facilitate the conversion of direct current (DC) power supplied to an EV back into alternating current (AC) power to resupply the network (Sayed & Gabbar, 2016).

Since charging infrastructure is vital for EV operation, research continues to focus on ensuring EVs have access to chargers during and after disasters (Purba et al., 2023). Placement and maintenance of charging stations should minimize the impact of natural disasters while maximizing charging convenience – an umbrella term that encapsulates factors such as EV battery capacities, range, and penetration with traffic demand (Zhang et al., 2022b). For operation during natural disasters and peak-price hours, ESSs in the form of batteries may be utilized in fast charging stations. The capacity of these storage systems is determined by such variables as the number, mileage, and arrival time of EVs as well as the amount of energy needed to charge each vehicle (Hussain et al., 2020). This information, coupled with the characteristics needed to study EV owner behavior (vehicle location, charge level, occupancy, return time etc.) can be used to provide a comprehensive, real-life study of resilience and evacuations (Liu et al., 2023b; Hussain & Kim, 2021).

Even when charging stations remain operational throughout a disaster, non-standardized charging ports can impede access for some EVs. Standardization of charging port infrastructure to ensure maximum interoperability is therefore essential (Hussain & Musilek, 2022), and highly connected to advances in vehicle-to-grid (V2G) technology. Policy and regulatory measures can prioritize both, better integrating EVs into grid operations (Razeghi et al., 2021).

4.2 Pre-Disaster Measures

Recent research has begun to identify pre-disaster measures that can reduce electricity demand, ready EVs, and/or conduct transportation responses. For example, research has identified how maximizing energy stored within both EVs and gas-powered vehicles prior to a disaster can help improve resilience (Gazijahani et al., 2022). Load curtailment is commonly suggested as a means of usage-control and preventing total loss of power. This entails limiting or entirely cutting the supply of power to non-essential purposes. Load curtailment can also be administered during outages in order to manage demand (Gazijahani et al, 2022; Candan et al., 2023) by categorizing loads into different classes. Despite the benefit of managing electric usage, load curtailment can be expensive as special equipment is required to implement the approach, which can lead to reduced productivity (Tian & Talebizadehsardari, 2021). Along with pre-charging and curtailment, EVs can be prepositioned at crucial locations along the grid in anticipation of damage (Lei et al., 2019). Early and rapid dispatch of EVs can help keep essential infrastructure functional (e.g., medical equipment). During the recovery period, organized and optimized dispatch can help minimize operational costs (Yang et al., 2020a).

Research has also found that mandatory and voluntary evacuation orders may require retooling when considering EVs, the grid, and congestion. Work by Erenoğlu et al. (2023) compared the rates of load restoration by dispatching EVs to microgrids in need while considering traffic congestion. Results found that the restoration rate was hampered by congestion, highlighting the importance of traffic considerations in planning power restoration to the grid. For coordination, research has suggested the development of a mobile application that would allow EV owners to input their desired evacuation time window (Li et al., 2022b).

In addition to evacuation orders, educational measures with information on optimal practices can help prepare the public to conduct successful evacuations with EVs. One such practice is to refrain from fully charging EV vehicles during evacuations. Feng et al. (2020) found that Florida's current electrical grid could handle the increased load from evacuating EVs if drivers only partially charged their vehicles. Studies have also found that routinely maintaining a state-of-charge (SoC) of 20-80% is best for minimizing outages, but in practice, drivers may operate their vehicles outside of this range (Donaldson et al., 2022). The effective implementation of V2G technology is also contingent on the rapid response of willing participants which may vary based on factors such as weather conditions at the time of the disaster (Wu et al., 2022, Liu et al., 2023b). As such, EV drivers in disaster-prone regions may benefit from advanced information on charging procedures to help prevent outages and conduct safe evacuations within their regions.

4.3 Microgrids & EV Power Supply

Microgrids and EV power supply are extensively covered topics in research that considers resilience and EVs. A microgrid is a small grid that can sustain and manage its own electricity supply and demand within a region (Gouveia et al., 2013; Gholami et al., 2016). Microgrids can operate in either grid-connected or islanded modes. Grid-connected or networked microgrids can connect to and exchange with the larger grid or other microgrids within a community to improve overall system performance (Ali et al., 2020). Islanded microgrids can operate independently of the wider network during disasters and provide electricity within their own grid (Alizadeh & Jafari-Nokandi, 2023). A microgrid drawing power from microturbines, wind turbines, and energy storage systems in addition to EVs can produce enough power to be self-sustaining (Marami Dizaji et al., 2019). ESSs can enhance the operation of a microgrid by storing excess energy during normal conditions or periods of low demand, which can then be returned to the grid during a disaster or high-demand periods (Gouveia et al., 2013).

The operation of microgrids can be beneficial during both emergencies and normal periods (Razeghi et al., 2021). Under normal grid operation, EV owners can be incentivized to return power back to the grid using monetary compensation, thereby increasing supply and balancing peak demand periods (Hasan et al., 2021; Hussein & Musilek, 2022). Management of microgrids during emergencies can be divided into two categories. Here-and-now decisions consider the current state of microgrids and the distribution network for decision making, while wait-and-see decisions are based on real-time operation of microgrids considering uncertainties such as natural disasters (Ebadat-Parast et al., 2022; Gholami et al., 2016; Momen et al., 2021). Rigorous modeling of microgrids with uncertainties can help inform the desired operation of microgrids during disasters (Gholami et al., 2016).

Ideally, microgrids would draw from zero-emission power sources and enhance resilience by supplying the electricity demand of the community during disasters (Simental et al., 2022), though the use of back-up diesel-fuel generators often provides sufficient power during disasters (Ding et al., 2020). Within this context, EVs can connect to the grid using V2G technology and support bidirectional power flow, consequently supplying energy back into the grid, houses, or commercial buildings during outages (Wu et al., 2022; Hasan et al., 2021). Research also suggests that EVs can also help regulate the local grid, voltage control, and system reliability (Momen et al., 2020).

Microgrids can be supplemented with other technology to help bolster performance. A soft open point (SOP) can help rapidly isolate faults in networked microgrids and manage individual microgrid operations based on demand (Ding et al., 2020). Post-disaster, a grid can be broken up into multiple microgrids using sectionalizers, allowing easier service by EVs (Yadav et al., 2021). Furthermore, electricity supply can suffer from fluctuations and interruptions during disasters. This can be remedied through the use of EVs and PHEVs to generate and store power in a store-carry-forward scheme that aims to balance supply and demand (Yamamura & Miwa, 2014).

More closely related to EV power supply, EV clusters have also been suggested to restore and maintain electricity infrastructure such as substation transformers (Hussain & Musilek, 2022). If a microgrid generates power from sources other than EVs, the vehicles can be dispatched to restore critical loads at hospitals, waste treatment plants, and emergency response centers that may lie outside of the grid itself (Yang et al., 2019a). An on-call fleet of EVs has been suggested for this specific purpose as well, where vehicles are assessed based on their location and state of energy (SoE) and dispatched to critical locations during emergencies (Erenoglu et al., 2022).

Various approaches exist regarding when and where V2G technologies should be implemented to maximize EV power supply. One simulated approach placed bidirectional EV charging equipment in parking lots near residential or commercial districts, serving as gathering points and V2G connection points (Abdubannaev et al., 2021). These substations can be coupled with other power sources such as photovoltaic and diesel generators to supply additional power (Momen et al., 2021). Charging and discharging may also help avoid excessive demand from the grid during peak usage hours (Alizadeh and Jafari-Nokandi, 2023). Research by Yamagata et al. (2013) built a simulation to model parked EVs in central Tokyo which uses EVs to store photovoltaic energy in a bid to minimize the effects of an outage and provide the optimal amount of power to the area. These vehicles can also be deployed to supply power to other islanded microgrids if needed (Ali et al., 2020).

4.4 Auxiliary Power Sources

In addition to EVs themselves, vehicles equipped with diesel generators or high-capacity batteries have been studied to help meet electricity demand (Ding et al., 2020; Gao et al., 2017; Momen et al., 2021). These vehicles are collectively known as mobile battery-carried vehicles (MBCVs) (Ding et al., 2020). Repurposed EV batteries can be utilized by mobile charging units as well as in stationary use cases such as energy storage systems as a backup source of power during disasters. Second-use batteries can come from EVs that suffer mechanical failures or accidents (Moore et al., 2020). They can also be sourced from battery swapping stations (BSSs), which are facilities used to swap depleted EV batteries with charged ones. Recently, BSSs have been studied to function as large electricity reserves for use in outages (Guo et al., 2021).

Photovoltaic generators (PVs) are another source of power that can be used alongside EVs. The combination of these two energy sources has been the subject of several studies. Simental et al. (2022) conducted a study on the cities of El Paso in Texas as well as Las Cruces and Holloman in New Mexico and determined that a combined EV/PV system used during a one-day outage during a summer heatwave can fully supply these areas with their electricity needs. Saitoh et al. (2013) proposed the creation of an islanded microgrid where small, distributed generators (DGs) such as EVs and PVs contributed to the operation of a functioning microgrid.

While PVs could increase the available energy and resilience of the grid, they also present challenges (e.g., voltage fluctuation). Smart inverters could resolve this issue by controlling voltage, but deployment can be expensive (Yadav et al., 2023). A virtual power plant – or VPP – can also be used to manage outages caused by disasters, whereby supply and demand for power are managed by a cloud-based software that dispatches EVs to actively help bolster the electricity needs of part of the community (Liu et al., 2023a; Maharjan et al., 2015). Since microgrid management by VPPs requires the active movement of EVs, traffic between two microgrids must be taken into consideration (Liu et al., 2023a).

4.5 Electric Buses

Battery electric buses can play vital roles during disasters (e.g., evacuating residents, powering essential resources), though challenges exist related to battery range, charging speeds, and infrastructure. One key advantage of electric buses in disasters over EVs is that buses can transport more individuals during an evacuation, significantly reducing grid demand (Zhang & Zhang, 2022) and congestion. When not used for evacuations, research has suggested that buses can help grid resilience (Li et al., 2022a). For example, electric buses could be connected to the grid at charging stations, acting as either storage systems or power sources depending on the circumstance (Li et al., 2021a). Work by Tessler & Traut (2022) found that effective electric emergency operations require resilient but cost-efficient charging infrastructure.

Scheduling electric buses for emergency power supply and transit comes with challenges, including the need for timely updates on road conditions and access to charging stations equipped with V2G technology. Cost-efficiency is another challenge, which can be optimized by comparing the cost of transportation with the benefit of critical load supply at any given station (Gao et al., 2017). The cost effectiveness of electric bus operations depends on the size of the fleet as well as the frequency and severity of the disaster (Li et al., 2022a). Three-level converters could be highly useful in discharging electric buses since they allow for power to be transmitted from the battery at a much higher speed (Sayed & Gabbar, 2016). In addition, electric buses' primary objective is to transport people, which may be limited in certain disasters given the limited range and available charging infrastructure of these buses. An optimization plan can help in this regard by minimizing total travel time while accounting for vulnerable populations (Zhang & Zhang, 2022).

4.6 Hydrogen Fuel Cell & Hybrid Vehicles

Similar to EVs, hydrogen-powered vehicles operate using electric motors but benefit from faster, grid-independent refueling (Dong et al., 2023). To ensure sufficient fuel, mobile hydrogen energy resources (MHERs) can be dispatched to refuel hydrogen distribution systems (Cao et al., 2023). Research suggests that hydrogen-powered buses and cars could provide power generation during outages using their electric motors (Dong et al., 2023).

Hybrid electric vehicles (HEVs) have also been studied as potential opportunities for power and transportation during disasters. HEVs use fossil fuels for their internal combustion engine (ICE), which operates in tandem with and recharges an electric motor. These vehicles can achieve ranges higher than that of traditional combustion engine vehicles (Abessi et al., 2020). Despite their range, HEV electric components are smaller and less capable than that of plug-in electric vehicles (PEVs), which reduces their effectiveness when supplying power (Rahimi & Davoudi, 2018). This further necessitates the use of sources such as solar panels and generators in addition to a PHEV (Abessi et al., 2020).

5. POLICY FOR EVS IN DISASTERS

Adequate adoption and use of EVs in disaster scenarios require effective policies that compel users to participate in employing EVs to contribute to community resilience. To increase control over charging and discharging times, time-of-use (TOU) prices could be introduced that further push consumers to recharge their vehicles at lower demand periods (Li et al., 2021b). In microgrid operations, shifting power consumption to align with low market prices can help the microgrids reduce the cost of energy (Marami Dizaji et al., 2019), especially in brownouts and rolling blackouts.

Policies should also consider equity for populations that are most vulnerable to natural disasters and their effects. Research has found that waiting times at assembly points and the severity of the effects of electricity deprivation differs from one community to another (Zhang & Zhang, 2022). An environmental justice index can help identify these communities and prioritize public and private interventions in areas with high environmental injustice (Ku et al., 2021). While proposed approaches such as renewable household generators and EV ownership help reduce both utility bills and carbon footprints, many approaches are unattainable for low-income households, who are often most severely affected by natural disasters (Lin et al., 2022).

A lack of knowledge surrounding EVs and their infrastructure also exists. To resolve this, research indicates that tools and guidelines could be developed for different officials and coordinators that help direct a safe and smooth evacuation process for EVs (Purba et al., 2022). Johnson et al. (2022) proposed a number of measures and tools in the Florida Alternative Transportation Fuel Resilience Plan for most types of vehicle fuels. After engagement with over 240 officials and affected parties, three tools were developed to help locate emergency facilities throughout the state, provide communication between electric vehicle supply equipment (EVSE) and emergency personnel, and plan possible evacuation strategies. In the Canadian context, Macdonald et al. (2021) simulated evacuations from Prince George, British Columbia. The study concluded that policymakers could increase the capacity and density of charging stations to help meet EV demand.

6. DISCUSSION

The goal of this research was to provide an early understanding of the state of research on EVs, resilience, and evacuations by identifying and analyzing relevant literature. This section will discuss each segment and highlight key takeaways relevant to the research questions.

6.1 Overcoming EV Deficits

The review found that EVs face multiple challenges stemming from their unique fuel source and refueling mechanism. Of all these obstacles, resolving charging station congestion received some of the least attention in the literature on the subject. At the same time, only a few studies focused on the evacuation of EVs (Feng et al., 2020; Li et al., 2022b; Purba et al., 2022). Despite this, the overarching problem of long charging times remains a key challenge that will require significant research from simulated *and* real-world cases.

In addition to charging time, the limited capacity of batteries also points to an understudied area of research. While increasing the density of the charging network helps mitigate the short range of EVs, research on methods to extend the range of EVs as a case for disaster resilience is rare. Frequent stops for refueling could hinder evacuations and recovery processes, including for maintenance fleets. Novel methods of recharging vehicles such as electrified road segments and inductive charging are also notably missing from our review.

Studies also tend to overlook the length of power outages. EVs will be unable to provide power throughout an extended power outage, essentially delaying the inevitable loss of power for the user. While the usage of other sources of power alongside EVs is often suggested (Abessi et al., 2020; Sayed & Gabbar, 2016; Momen et al., 2021; Yadav et al., 2021), these recommendations depend on the interconnection of users to a larger grid. This leaves out those who cannot or choose not to connect to a larger network, such as those living in remote or rural locations. Within this general issue, ongoing public safety power shutoff (PSPS) events in California could cause additional challenges, especially as these pre-planned shutoffs could reduce EV travel. Research has found that power loss is a key influence on travel behavior (Wong et al., 2022).

The upfront cost of EV resilience measures and infrastructure is not sufficiently discussed, and very few papers mention end-user cost as a consideration (Hussain & Musilek, 2022; Zhang et al., 2022b). EVs are generally more expensive than gas-powered cars, and the infrastructure and resources needed to take full advantage of their resilient capabilities during disasters require investments that many drivers may not be able to justify. Future research can investigate methods to provide essential resilience components that are more affordable and accessible.

6.2 Building Realistic Strategies

The potential for EVs to aid in evacuations and disaster scenarios is covered well by research in this review. This indicates that opportunities do exist for smart and effective utilization of EVs during disasters. However, a large portion of the analyzed research focuses on grid resilience, while incorporating the auxiliary use of EVs (Wu et al., 2022; Ebadat-Parast et al, 2022; Momen et al., 2021; Ding et al., 2020). Consequently, grid resilience is elevated above transportation and EV resilience. As a result, more focus is put on the use of EVs as an on-call fleet to power the larger grid, leaving opportunities for future research to study options that focus more on EV users and their choice. Additionally, while some papers suggest a grouping of vehicles could be used to supply power (Cao et al., 2023; Hussain & Musilek, 2022; Yamagata et al., 2013), most research solutions do not study the number of vehicles needed to achieve the intended results. Since different actions and energy demands require varying numbers of EVs, further research can be conducted to study optimal strategies for different EV adoption patterns and fleet mix.

Resilience strategies are often not discussed within research on charging infrastructure or operations. Studies place a strong emphasis on the continued operation of charging stations throughout disasters (Purba et al., 2023; Tessler & Traut, 2022; Zhang et al., 2022b), but strategies for their continued operation seldom extend beyond their strategic placement to reduce the likelihood of damage. This can conflict with planning that emphasizes charging station accessibility during disasters. As such, there is room for future research to further study all facets of charging infrastructure placement and to develop independent solutions to ensure charging stations continue to provide service to EV users.

Importantly, our review found that user behavior is highly understudied in EV research on evacuations. While several papers advocate for improving EV technology and increasing charging infrastructure density to accommodate all possible EV user actions (Adderly et al., 2018; Feng et al., 2020; Purba et al., 2022), other work focuses on directing user behavior in line with optimal outcomes and performance (Zhang & Zhang, 2022; Li et al., 2022b). In both cases, EV driver behavior is left out, widening the research gap on EV resilience in critical scenarios. Few papers cover EV driver choices and willingness to participate in demand response events (Donaldson et al., 2022; Liu et al., 2023b). The participation of resident-owned EV fleets is more difficult to coordinate and more heavily relies on the willingness of users to partake in the proposed measures. This includes challenges related to demand response programs that can shift electricity demand (e.g., smart charging). While smart charging programs can be useful in disaster events, they require sufficient consumer opt-in and are affected by the program design and demographic characteristics (Wong et al., 2023). Future research can focus on the behavior of individual EV users to further optimize the better align societal goals, driver actions, and infrastructure.

Finally, despite the availability of EV technology for analysis (especially in the last five years), our review found minimal evidence of real-world experiments, data, or observations of EVs in disasters and evacuations. Anecdotal evidence is also largely missing from the literature, which can inhibit policy implementation and reduce the sharing of lessons learned. Testing EV strategies in real-life demonstrations or collecting data directly from EV drivers or auto companies will help future research uncover technical or logistical problems that may not come up in theory or simulated methods.

7. CONCLUSIONS

This literature review analyzed the main challenges facing the use of EVs during disaster scenarios and identified that a lack of charging infrastructure is one of the largest ongoing issues. This, coupled with the short range of EVs, was found to limit the mobility and utility of electric vehicles in disaster scenarios. The long charging time of EVs compared to internal combustion engine vehicles can create congestion at charging stations, irregular charging patterns, and unexpected behavioral patterns. In addition, policies and planning were found to neglect EVs in disasters.

Along with these challenges, the review identified that EVs can act as mobile energy storage and transmission system, especially in a power outage event. Combined with proper measures and infrastructure, EVs and electric buses can be used in tandem with or in place of other power generation devices to supply power to communities via microgrids and grid management. The full utilization of these capacities requires the inclusion of alternate fuel vehicles into a holistic approach to disaster management and the conscious deployment of infrastructure with these emergency scenarios in mind. With both challenges and opportunities, multiple new avenues have opened for research using a variety of approaches (e.g., simulated, empirical, behavioral, etc.). As the adoption of EVs continues to rise, more research and practical evaluation of EVs can help guide the development of resilient, electrified transportation.

ACKNOWLEDGEMENTS

This research was funded by University of Alberta's Future Energy Systems (FES), which was formed from the Government of Canada's Canada First Research Excellence Fund.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: S. Wong, M. Babaei; data collection: all authors; analysis and interpretation of results: all authors; draft manuscript preparation: all authors. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

Abdubannaev, J., Lu, S., Ai, X., Sun, Y., Makhamadjanova, N., & Khasanov, M. (2021). Investigate the use of electric vehicles to improve resilience for active distribution network system. *2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2)*. https://doi.org/10.1109/ei252483.2021.9713572

Abessi, A., Shirazi, E., Jadid, S., & Shafie-khah, M. (2020). Sustainable and resilient smart house using the internal combustion engine of plug-in Hybrid Electric Vehicles. *Sustainability*, *12*(15), 6046. https://doi.org/10.3390/su12156046

Adderly, S. A., Manukian, D., Sullivan, T. D., & Son, M. (2018). Electric vehicles and natural disaster policy implications. *Energy Policy*, *112*, 437–448. https://doi.org/10.1016/j.enpol.2017.09.030

Ali, A. Y., Hussain, A., Baek, J.-W., & Kim, H.-M. (2020). Optimal operation of networked microgrids for enhancing resilience using Mobile Electric Vehicles. *Energies*, *14*(1), 142. https://doi.org/10.3390/en14010142

Alizadeh, M., & Jafari-Nokandi, M. (2023). A bi-level resilience-oriented islanding framework for an active distribution network incorporating electric vehicles parking lots. *Electric Power Systems Research*, *218*, 109233. https://doi.org/10.1016/j.epsr.2023.109233

Belson, K. (2011). *After disaster hit Japan, electric cars stepped up.* The New York Times. https://www.nytimes.com/2011/05/08/automobiles/08JAPAN.html

Candan, A. K., Boynuegri, A. R., & Onat, N. (2023). Home Energy Management System for enhancing grid resiliency in post-disaster recovery period using Electric Vehicle. *Sustainable Energy, Grids and Networks*, *34*, 101015. https://doi.org/10.1016/j.segan.2023.101015

Cao, X., Cao, T., Xu, Z., Zeng, B., Gao, F., & Guan, X. (2023). Resilience constrained scheduling of mobile emergency resources in electricity-hydrogen distribution network. *IEEE Transactions on Sustainable Energy*, *14*(2), 1269–1284. https://doi.org/10.1109/tste.2022.3217514

ChargeHub. (2023, May 29). *Definitive guide on how to charge an electric car*. ChargeHub. https://chargehub.com/en/electric-car-charging-guide.html

Ding, T., Wang, Z., Jia, W., Chen, B., Chen, C., & Shahidehpour, M. (2020). Multiperiod distribution system restoration with routing repair crews, mobile electric vehicles, and soft-open-point networked microgrids. *IEEE Transactions on Smart Grid*, *11*(6), 4795–4808. https://doi.org/10.1109/tsg.2020.3001952

Donaldson, D. L., Alvarez-Alvarado, M. S., & Jayaweera, D. (2020). Power system resiliency during wildfires under increasing penetration of electric vehicles. *2020 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*. https://doi.org/10.1109/pmaps47429.2020.9183683

Donaldson, D. L., Alvarez-Alvarado, M. S., & Jayaweera, D. (2022). Integration of electric vehicle evacuation in Power System Resilience Assessment. *IEEE Transactions on Power Systems*, 1–12. https://doi.org/10.1109/tpwrs.2022.3206900

Dong, Y., Zheng, W., Cao, X., Sun, X., & He, Z. (2023). Co-planning of hydrogen-based microgrids and fuel-cell bus operation centers under low-carbon and resilience considerations. *Applied Energy*, *336*, 120849. https://doi.org/10.1016/j.apenergy.2023.120849

Ebadat-Parast, M., Nazari, M. H., & Hosseinian, S. H. (2022). Distribution system resilience enhancement through resilience-oriented optimal scheduling of multi-microgrids considering normal and emergency conditions interlink utilizing multi-objective programming. *Sustainable Cities and Society*, *76*, 103467. https://doi.org/10.1016/j.scs.2021.103467

Erenoglu, A. K., Sancar, S., Terzi, I. S., Erdinc, O., Shafie-Khah, M., & Catalao, J. P. (2022). Resiliency-driven multi-step critical load restoration strategy integrating on-call electric vehicle fleet management services. *IEEE Transactions on Smart Grid*, *13*(4), 3118–3132. https://doi.org/10.1109/tsg.2022.3155438

Erenoğlu, A. K., & Erdinç, O. (2023). Real-time allocation of multi-mobile resources in Integrated Distribution and Transportation Systems for Resilient Electrical Grid. *IEEE Transactions on Power Delivery*, *38*(2), 1108–1119. https://doi.org/10.1109/tpwrd.2022.3206272

Feng, K., Lin, N., Xian, S., & Chester, M. V. (2020). Can we evacuate from hurricanes with electric vehicles? *Transportation Research Part D: Transport and Environment*, *86*, 102458. https://doi.org/10.1016/j.trd.2020.102458

Ford. (2023, May 29). *2023 Ford F-150® lightning® truck: Intelligent backup power features. 2023 Ford F-150® Lightning® Truck | Intelligent Backup Power Features*. https://www.ford.ca/trucks/f150/f150-lightning/intelligent-backup-power/

Gao, H., Chen, Y., Mei, S., Huang, S., & Xu, Y. (2017). Resilience-oriented pre-hurricane resource allocation in distribution systems considering electric buses. *Proceedings of the IEEE*, *105*(7), 1214–1233. https://doi.org/10.1109/jproc.2017.2666548

Gazijahani, F. S., Salehi, J., & Shafie-khah, M. (2022). Benefiting from energy-hub flexibilities to reinforce distribution system resilience: A pre- and Post-Disaster Management Model. *IEEE Systems Journal*, *16*(2), 3381–3390. https://doi.org/10.1109/jsyst.2022.3147075

Gholami, A., Shekari, T., Aminifar, F., & Shahidehpour, M. (2016). Microgrid scheduling with uncertainty: The quest for resilience. *IEEE Transactions on Smart Grid*, *7*(6), 2849–2858. https://doi.org/10.1109/tsg.2016.2598802

Gouveia, C., Moreira, C. L., & Lopes, J. A. (2013). Microgrids emergency management exploiting EV, demand response and energy storage units. *2013 IEEE Grenoble Conference*. https://doi.org/10.1109/ptc.2013.6652395

Guo, Y., Liao, K., Yang, J., Zheng, S., & He, Z. (2021). Distribution system resilience enhancement with battery swapping stations of Electric Vehicles. *2021 6th International Conference on Power and Renewable Energy (ICPRE)*. https://doi.org/10.1109/icpre52634.2021.9635569

Hasan, A. S., Enriquez-Contreras, L. F., Yusuf, J., Barth, M. J., & Ula, S. (2021). Demonstration of microgrid resiliency with V2G operation. *2021 IEEE Transportation Electrification Conference & Expo (ITEC)*. https://doi.org/10.1109/itec51675.2021.9490165

Hussain, A., & Kim, H.-M. (2021). Evaluation of multi-objective optimization techniques for resilience enhancement of electric vehicles. *Electronics*, *10*(23), 3030. https://doi.org/10.3390/electronics10233030

Hussain, A., & Musilek, P. (2022). Resilience enhancement strategies for and through electric vehicles. *Sustainable Cities and Society*, *80*, 103788. https://doi.org/10.1016/j.scs.2022.103788

Hussain, A., Bui, V.-H., & Kim, H.-M. (2020). Optimal sizing of battery energy storage system in a fast EV charging station considering power outages. *IEEE Transactions on Transportation Electrification*, *6*(2), 453–463. https://doi.org/10.1109/tte.2020.2980744

IEA (2023), *Global EV Outlook 2023*, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2023, License: CC BY 4.0

Johnson, C., Cappellucci, J., Spath Luhring, L., St. Louis-Sanchez, M., Yang, F., Brown, A., Sipiora, A., Kolpakov, A., Li, X., Li, Q., White, S., Gonzales, J., Nobler, E., & Wood, E. (2022). Florida Alternative Transportation Fuel Resilience Plan. Golden, *National*

Renewable Energy Laboratory. NREL/TP-5400-83795. https://www.nrel.gov/docs/fy23osti/83795.pdf.

Ku, A., Kammen, D. M., & Castellanos, S. (2021). A quantitative, Equitable Framework for Urban Transportation Electrification: Oakland, California as a mobility model of climate justice. *Sustainable Cities and Society*, *74*, 103179. https://doi.org/10.1016/j.scs.2021.103179

Lei, S., Chen, C., Zhou, H., & Hou, Y. (2019). Routing and scheduling of mobile power sources for Distribution System Resilience Enhancement. *IEEE Transactions on Smart Grid*, *10*(5), 5650–5662. https://doi.org/10.1109/tsg.2018.2889347

Li, B., Chen, Y., Wei, W., Huang, S., Xiong, Y., Mei, S., & Hou, Y. (2021). Routing and scheduling of electric buses for resilient restoration of distribution system. *IEEE Transactions on Transportation Electrification*, *7*(4), 2414–2428. https://doi.org/10.1109/tte.2021.3061079

Li, B., Chen, Y., Wei, W., Mei, S., Hou, Y., & Shi, S. (2022). Preallocation of electric buses for resilient restoration of distribution network: A data-driven robust stochastic optimization method. *IEEE Systems Journal*, *16*(2), 2753–2764. https://doi.org/10.1109/jsyst.2021.3123623

Li, Qi, Huang, Q., Qin, W., Xing, Y., Zhao, H., Song, X., Hu, E., & Shen, Z. (2021). Resilience lifting method of active distribution network considering charging and discharging scheduling of electric vehicles. *2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2)*. https://doi.org/10.1109/ei252483.2021.9713196

Li, Qianwen, Soleimaniamiri, S., & Li, X. (2022). Optimal mass evacuation planning for electric vehicles before natural disasters. *Transportation Research Part D: Transport and Environment*, *107*, 103292. https://doi.org/10.1016/j.trd.2022.103292

Lin, Y., Wang, J., & Yue, M. (2022). Equity-based grid resilience: How do we get there? *The Electricity Journal*, *35*(5), 107135. https://doi.org/10.1016/j.tej.2022.107135

Liu, H., Wang, C., Ju, P., Xu, Z., & Lei, S. (2023). A bi-level coordinated dispatch strategy for enhancing resilience of electricity-gas system considering virtual power plants. *International Journal of Electrical Power & Energy Systems*, *147*, 108787. https://doi.org/10.1016/j.ijepes.2022.108787

Liu, W., Liu, Y., Yang, Y., Xu, Q., & Dong, F. (2023). Power restoration model for distribution networks after extreme rainstorm disasters based on electric vehicle travel characteristics. *Energy Reports*, *9*, 372–380. https://doi.org/10.1016/j.egyr.2022.10.387

MacDonald, C. D., Kattan, L., & Layzell, D. (2021). Modelling Electric Vehicle Charging Network capacity and performance during short-notice evacuations. *International Journal of Disaster Risk Reduction*, *56*, 102093. https://doi.org/10.1016/j.ijdrr.2021.102093

Maharjan, S., Zhang, Y., Gjessing, S., Ulleberg, O., & Eliassen, F. (2015). Providing microgrid resilience during emergencies using distributed energy resources. *2015 IEEE Globecom Workshops (GC Wkshps)*. https://doi.org/10.1109/glocomw.2015.7414031

Marami Dizaji, A., Saniee, M., & Zare, K. (2019). Resilient Operation Scheduling of Microgrid Using Stochastic Programming Considering Demand Response and Electrical Vehicles. Journal of Operation and Automation in Power Engineering, 7(2), 157-167. doi: 10.22098/joape.2019.5350.1396

Momen, H., Abessi, A., & Jadid, S. (2020). Using EVS as distributed energy resources for Critical Load Restoration in Resilient Power Distribution Systems. *IET Generation,* *Transmission & Distribution*, *14*(18), 3750–3761. https://doi.org/10.1049/iet-gtd.2019.1561

Momen, H., Abessi, A., Jadid, S., Shafie-khah, M., & Catalão, J. P. S. (2021). Load restoration and energy management of a microgrid with distributed energy resources and electric vehicles participation under a two-stage stochastic framework. *International Journal of Electrical Power & Energy Systems*, *133*, 107320. https://doi.org/10.1016/j.ijepes.2021.107320

Moore, E. A., Russell, J. D., Babbitt, C. W., Tomaszewski, B., & Clark, S. S. (2020). Spatial modeling of a second-use strategy for electric vehicle batteries to improve disaster resilience and circular economy. *Resources, Conservation and Recycling*, *160*, 104889. https://doi.org/10.1016/j.resconrec.2020.104889

Morris, C. (2015, October 19). *PG&E exportable power truck saves the day in California wildfire evacuation.* Charged EVs. https://chargedevs.com/newswire/pge-exportable-power-truck-saves-the-day-in-california-wildfire-evacuation/

Purba, D. S., Balisi, S., & Kontou, E. (2023). Refueling station location model to support evacuation of alternative fuel vehicles. *Transportation Research Record: Journal of the Transportation Research Board*. https://doi.org/10.1177/03611981231171156

Purba, D. S., Kontou, E., & Vogiatzis, C. (2022). Evacuation route planning for alternative fuel vehicles. *Transportation Research Part C: Emerging Technologies*, *143*, 103837. https://doi.org/10.1016/j.trc.2022.103837

Rahimi, K., & Davoudi, M. (2018). Electric vehicles for improving resilience of distribution systems. *Sustainable Cities and Society*, *36*, 246–256. https://doi.org/10.1016/j.scs.2017.10.006

Razeghi, G., Lee, J., & Samuelsen, S. (2021). Resiliency Impacts of Plug-in Electric Vehicles in a Smart Grid. UC Office of the President: University of California Institute of Transportation Studies. http://dx.doi.org/10.7922/G2CV4G13 Retrieved from https://escholarship.org/uc/item/4j19d5p1

Saitoh, H., Abe, M., & Yashima, W. (2013). A proposal of emergency microgrid operation of distribution systems after large scale disasters. *2013 IEEE Region 10 Humanitarian Technology Conference*. https://doi.org/10.1109/r10-htc.2013.6669030

Sayed, K., & Gabbar, H. (2016). Electric vehicle to power grid integration using three-phase three-level AC/DC converter and PI-Fuzzy Controller. *Energies*, *9*(7), 532. https://doi.org/10.3390/en9070532

Simental, O. Q., Mandal, P., Galvan, E., & Wang, Z. (2022). Leveraging distributed evs and PVS to assess networked microgrids resilience against Extreme Weather Event. *2022 IEEE Power & Energy Society General Meeting (PESGM)*. https://doi.org/10.1109/pesgm48719.2022.9917224

Tessler, M. E., & Traut, E. J. (2022). Hurricane resiliency methods for the new york city electric bus fleet. *Transportation Research Part D: Transport and Environment*, *105*, 103255. https://doi.org/10.1016/j.trd.2022.103255

Tian, M.-W., & Talebizadehsardari, P. (2021). Energy cost and efficiency analysis of building resilience against power outage by shared parking station for Electric Vehicles and Demand Response Program. *Energy*, *215*, 119058. https://doi.org/10.1016/j.energy.2020.119058

Wong, S. D., Broader, J. C., & Shaheen, S. A. (2022). Power trips: early understanding of preparedness and travel behavior during California public safety power shutoff events. Transportation research record, 2676(7), 395-410.

Wong, S. D., Shaheen, S. A., Martin, E., & Uyeki, R. (2023). Do incentives make a difference? Understanding smart charging program adoption for electric vehicles. Transportation Research Part C: Emerging Technologies, 151, 104123.

Wu, Y., Yang, Q., Su, J., Xiang, Y., Zhang, G., Li, Y., & Ji, C. (2022). A rapid recovery strategy for post-earthquake power grids with the auxiliary support of V2G. *2022 IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia)*. https://doi.org/10.1109/icpsasia55496.2022.9949967

Yadav, M., Pal, N., & Saini, D. K. (2021). Resilient electrical distribution grid planning against seismic waves using distributed energy resources and sectionalizers: An Indian's urban grid case study. *Renewable Energy*, *178*, 241–259. https://doi.org/10.1016/j.renene.2021.06.071

Yadav, M., Pal, N., & Saini, D. K. (2023). Low voltage ride through capability for Resilient Electrical Distribution System integrated with Renewable Energy Resources. *Energy Reports*, *9*, 833–858. https://doi.org/10.1016/j.egyr.2022.12.023

Yamagata, Y., & Seya, H. (2013). Community-based resilient electricity sharing: Optimal Spatial Clustering. *2013 43rd Annual IEEE/IFIP Conference on Dependable Systems and Networks Workshop (DSN-W)*. https://doi.org/10.1109/dsnw.2013.6615539

Yamamura, T., & Miwa, H. (2014). Store-carry-forward energy distribution method and routing control method for use in a disaster. *2014 International Conference on Intelligent Networking and Collaborative Systems*. https://doi.org/10.1109/incos.2014.81

Yamane, K., Iioka, D., & Saitoh, H. (2019). Three-Phase Voltage Control Method by single-phase distributed generators connected to Islanded Distribution Network. *Electrical Engineering in Japan*, *207*(3), 14–22. https://doi.org/10.1002/eej.23203

Yang, L.-J., Zhao, Y., Wang, C., Gao, P., & Hao, J.-H. (2019). Resilience-oriented hierarchical service restoration in distribution system considering microgrids. *IEEE Access*, *7*, 152729–152743. https://doi.org/10.1109/access.2019.2948372

Yang, Z., Dehghanian, P., & Nazemi, M. (2019). Enhancing seismic resilience of electric power distribution systems with mobile power sources. *2019 IEEE Industry Applications Society Annual Meeting*. https://doi.org/10.1109/ias.2019.8912010

Yang, Z., Dehghanian, P., & Nazemi, M. (2020). Seismic-Resilient Electric Power Distribution Systems: Harnessing the mobility of power sources. *IEEE Transactions on Industry Applications*, *56*(3), 2304–2313. https://doi.org/10.1109/tia.2020.2972854

Yang, Z., Nazemi, M., Dehghanian, P., & Barati, M. (2020). Toward resilient solar-integrated distribution grids: Harnessing the mobility of power sources. *2020 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*. https://doi.org/10.1109/td39804.2020.9299986

Zhang, J., Zhang, X. (2022). A multi-trip electric bus routing model considering equity during short-notice evacuations. *Transportation Research Part D: Transport and Environment*, *110*, 103397. https://doi.org/10.1016/j.trd.2022.103397

Zhang, Q., Yu, H., Zhang, G., & Ma, T. (2022). Optimal Planning of Flood-Resilient Electric Vehicle Charging stations. *Computer-Aided Civil and Infrastructure Engineering*, *38*(4), 489–507. https://doi.org/10.1111/mice.12853