Impact of Vehicle-to-Grid (V2G) Technology in School Bus Fleets on Historically Disadvantaged Communities for Energy Resilience and Sustainability

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Abstract
This study examines the impact of Vehicle-to-Grid (V2G) technology integration in school bus fleets on historically disadvantaged communities, focusing on energy resilience and sustainability. V2G technology enables electric vehicles, such as school buses, to discharge stored energy back into the power grid, providing crucial support during peak demand periods and emergencies. Historically disadvantaged communities often face higher energy costs and inefficiencies, with significant disparities in energy expenditures observed across different ethnic and income groups. Hispanic or Latino and Black households, along with lower-income households, bear a disproportionate energy burden. By utilizing the substantial unused battery capacity of school buses, especially those operating within a common 25 to 75-mile daily range, V2G technology can alleviate these burdens. This study explores how V2G-enabled school buses can act as mobile energy storage units, offering financial benefits through cost savings and revenue generation, environmental benefits by reducing greenhouse gas emissions, and enhanced energy resilience. The findings highlight the importance of targeted V2G deployment in regions and communities with the greatest need, promoting energy equity and a sustainable energy future. Comprehensive impact assessments, community engagement, and supportive policy frameworks are essential for the successful implementation of V2G technology, ensuring that its benefits are equitably distributed.

Keywords Vehicle-to-Grid, Electric School Buses, Energy Resilience, Disadvantaged Communities, Sustainability

1. Introduction

The integration of Vehicle-to-Grid (V2G) technology within school bus fleets represents a significant advancement in the pursuit of energy resilience and sustainability, particularly for historically disadvantaged communities. V2G technology allows electric vehicles, such as school buses, to communicate with the power grid to either draw electricity for charging or discharge stored electricity back into the grid. This bidirectional flow of energy can provide a range of benefits, including grid stabilization, enhanced energy security, and cost savings. As the world increasingly embraces renewable energy sources, V2G technology offers a viable solution to some of the pressing challenges faced by modern power systems.[1]

Historically disadvantaged communities often bear the brunt of energy inefficiencies and higher costs. These communities are typically characterized by lower-income households, a higher proportion of rental properties, and older, less energy-efficient housing stock. These factors contribute to a disproportionate energy burden, where a significant portion of household income is spent on energy bills. For instance, data from the U.S. Energy Information Administration (EIA) reveals that Hispanic or Latino households and Black households have higher energy expenditures per square foot compared to their non-Hispanic or Latino and White counterparts. Similarly, lower-income households, particularly those earning less than $10,000 annually, face the highest energy costs per square foot. Addressing these disparities is crucial for promoting energy equity and ensuring that all communities have access to affordable and reliable energy. The deployment of V2G technology in school bus fleets can play a pivotal role in alleviating these energy burdens. School buses are an ideal candidate for V2G applications due to their predictable operating patterns and substantial battery capacity. Most school buses travel between 25 and 75 miles per day, which means they have significant unused battery capacity that can be utilized during non-operational hours. This capacity can be harnessed to support the local grid during peak demand periods or in times of emergency, providing a stable and reliable source of energy. By integrating V2G technology, school buses can act as mobile energy storage units, helping to stabilize the grid, reduce energy costs, and enhance energy resilience.[2]

The potential benefits of V2G technology extend beyond immediate cost savings and grid support. For disadvantaged communities, V2G-enabled school buses can provide a crucial backup power supply during outages, which is particularly valuable for maintaining power to critical infrastructure such as hospitals, emergency response centers, and community shelters. Additionally, the revenue generated from selling excess stored energy back to the grid can be reinvested into the school system, enhancing educational resources and infrastructure. This creates a positive feedback loop, where the community benefits from improved energy resilience and the school district benefits from additional funding.

Moreover, the environmental benefits of V2G technology are significant. By reducing reliance on fossil fuel power plants during peak demand periods, V2G technology helps lower greenhouse gas emissions and other pollutants. This is especially important for communities located near power plants, which often suffer from higher levels of pollution and associated health issues. The promotion of renewable energy integration through V2G technology further supports environmental sustainability, contributing to a cleaner and healthier environment. Therefore, implementing V2G technology in school bus fleets offers a promising solution to enhance energy resilience and sustainability, particularly in historically disadvantaged communities. By leveraging school buses' existing infrastructure and predictable usage patterns, V2G technology can provide a range of economic, environmental, and social benefits.

2. Literature Review

Vehicle-to-grid (V2G) technology has been extensively researched in recent years as a promising solution to integrate electric vehicles (EVs) with the power grid. Early studies explored the technical feasibility and potential benefits of V2G, such as providing ancillary services like frequency regulation and spinning reserves, as well as reducing energy costs and emissions through optimal EV charging/discharging strategies. Subsequent research has focused on addressing challenges like battery degradation from V2G operation, developing efficient scheduling and control algorithms, and investigating business models and policies to facilitate widespread V2G adoption. Additionally, the integration of V2G with renewable energy sources has been studied to improve grid stability and enable higher penetration of intermittent re-

newables.
Research on electric vehicles (EVs) in public transport systems has highlighted significant environmental and performance benefits, as well as positive impacts on community health and well-being. Studies have shown that electric buses, compared to their diesel counterparts, produce zero tailpipe emissions, thereby significantly reducing greenhouse gases and pollutants such as CO2, NOx, and particulate matter, which are linked to respiratory and cardiovascular diseases. Additionally, electric buses offer superior performance in terms of energy efficiency and lower operational costs due to fewer moving parts and reduced maintenance needs. Pilot programs in various cities, including Cape Town and Shenzhen, have demonstrated the feasibility and advantages of electric buses, such as lower noise pollution, improved air quality, and enhanced passenger comfort. Furthermore, the integration of renewable energy sources for charging these buses can amplify their environmental benefits, making them a sustainable option for urban public transport. Overall, the transition to electric buses in public transport systems not only supports environmental sustainability but also promotes healthier and more livable communities.
Renewable energy solutions have profound impacts on communities, offering both significant benefits and challenges. These projects contribute to job creation and economic growth by providing employment opportunities in construction, operation, and maintenance, thereby stimulating local economies. Community engagement and empowerment are also enhanced as renewable energy projects often involve local residents in decision-making processes, fostering a sense of ownership and pride. Additionally, renewable energy projects improve public health by reducing air and water pollution, which leads to a decrease in respiratory illnesses and other health issues. However, the rapid development of renewable energy can sometimes conflict with community interests, particularly when projects require large amounts of land or bring industrial development into rural areas, leading to opposition from local residents. Despite these challenges, the overall benefits of renewable energy, such as enhanced energy access, reduced carbon footprint, and improved quality of life, make it a crucial component of sustainable community development.
Despite the promising findings, several critical gaps remain in the current research on the impact of V2G technology in school bus fleets on historically disadvantaged communities. Most studies focus on the technical and economic aspects of V2G technology, with limited attention to its broader social and environmental impacts. There is a need for comprehensive impact assessments that consider the following

- **Health Benefits** While some research highlights the potential health benefits of reduced emissions from electric school buses, there is limited data on the specific health outcomes for children and communities in disadvantaged areas. Detailed studies are needed to quantify these benefits and understand their long-term implications.
- **Environmental Justice** Research should explore how V2G technology can address environmental justice issues, such as the disproportionate exposure to air pollution in low-income and minority communities. This includes assessing the potential for V2G to reduce localized pollution and improve air quality in these areas.

Effective implementation of V2G technology requires active community engagement and participation. However, current research often overlooks the role of community involvement in the success of V2G projects. Future studies should investigate the following

- **Community Perceptions and Acceptance** Understanding community perceptions and acceptance of V2G technology is crucial for its successful deployment. Research should explore the concerns, expectations, and willingness of communities to participate in V2G programs.

- **Participatory Planning** Studies should examine best practices for involving communities in the planning and decision-making processes of V2G projects. This includes identifying strategies to ensure that community voices are heard and that projects are designed to meet their specific needs and priorities.

The successful deployment of V2G technology in school bus fleets requires supportive policy and regulatory frameworks. However, there is a lack of research on the specific policies and regulations needed to promote equitable V2G adoption. Key areas for future research include

- **Incentives and Funding** Investigating the effectiveness of various incentives and funding mechanisms in promoting V2G adoption in disadvantaged communities. This includes evaluating the impact of federal and state programs, such as the EPA's Clean School Bus Program, on V2G deployment.
- **Regulatory Barriers** Identifying and addressing regulatory barriers that hinder the implementation of V2G technology. This includes examining issues related to grid interconnection, rate structures, and the integration of V2G into existing energy markets.

While the technical feasibility of V2G technology has been demonstrated, there are still several operational challenges that need to be addressed. Research should focus on

- **Battery Degradation** Investigating the impact of frequent charging and discharging on battery life and performance. Understanding how V2G operations affect battery degradation is crucial for developing strategies to mitigate these effects and ensure the longevity of electric school buses.
- **Infrastructure Requirements** Assessing the infrastructure requirements for V2G deployment, including the need for bidirectional chargers and grid upgrades. Research should explore cost-effective solutions to address these infrastructure needs, particularly in underserved communities with limited resources.

The economic viability of V2G technology is a critical factor for its widespread adoption. However, there is limited research on the long-term economic sustainability of V2G projects in disadvantaged communities. Future studies should examine:

- **Cost-Benefit Analysis** Conducting comprehensive cost-benefit analyses to evaluate the economic feasibility of V2G projects. This includes assessing the potential savings from reduced fuel and maintenance costs, as well as the revenue generated from providing grid services.
- **Financial Models** Developing innovative financial models to support the deployment of V2G technology in underserved communities. This includes exploring public-private partnerships, community financing, and other mechanisms to reduce the financial burden on school districts and ensure equitable access to V2G benefits.

Addressing these gaps requires a multidisciplinary approach that considers the technical, economic, social, and environmental dimensions of V2G deployment. By focusing on comprehensive impact assessments, community engagement, supportive policy frameworks, technical challenges, and economic viability, future research can help ensure that the benefits of V2G technology are equitably distributed and contribute to the resilience and sustainability of historically disadvantaged communities.

3. Methodology

This study employed a mixed-methods research design to comprehensively assess the impact of Vehicle-to-Grid (V2G) technology in school bus fleets on historically disadvantaged communities, focusing on energy resilience and sustainability. The mixed-methods approach allowed for the integration of both quantitative and qualitative data, providing a holistic understanding of the subject matter. The quantitative component involved the analysis of secondary data sources, while the qualitative component included thematic analysis of existing surveys and interviews with key stakeholders.

This research utilized secondary data from various reputable sources to ensure a robust and comprehensive analysis. The primary data sources included:

- **Community Energy Usage Data** Data on energy consumption patterns, peak demand periods, and energy costs were obtained from local energy providers and public databases. This data was crucial in understanding the baseline energy usage and the potential impact of V2G technology on energy resilience in disadvantaged communities.
- **School Bus Fleet Data** Information on the operational schedules, battery capacities, and energy consumption of electric school buses was sourced from school districts and transportation departments. This data provided insights into the feasibility and efficiency of implementing V2G technology in school bus fleets.
- **Surveys and Interviews with Stakeholders** Existing surveys and interviews conducted by other researchers and organizations were analyzed to gather perspectives from various stakeholders, including school district officials, energy providers, and local government representatives. These qualitative data sources offered valuable insights into the perceived benefits, challenges, and acceptance of V2G technology in the target communities.

The study employed a combination of statistical and thematic analysis techniques to analyze the collected data:

- **Statistical Analysis** Quantitative data from community energy usage and school bus fleet operations were subjected to statistical analysis. Descriptive statistics were used to summarize the data, while inferential statistics, such as regression analysis, were employed to identify correlations and potential causal relationships between V2G technology implementation and improvements in energy resilience and sustainability. This analysis helped quantify the potential energy savings, cost reductions, and emission reductions attributable to V2G technology.
- **Thematic Analysis** Qualitative data from surveys and interviews were analyzed using thematic analysis. This involved coding the data to identify recurring themes and patterns related to the impact of V2G technology on historically disadvantaged communities. Key themes included community engagement, perceived benefits and challenges, policy and regulatory considerations, and the overall acceptance of V2G technology. The thematic analysis provided a nuanced understanding of the social and contextual factors influencing the implementation and success of V2G projects.

4. Discussion

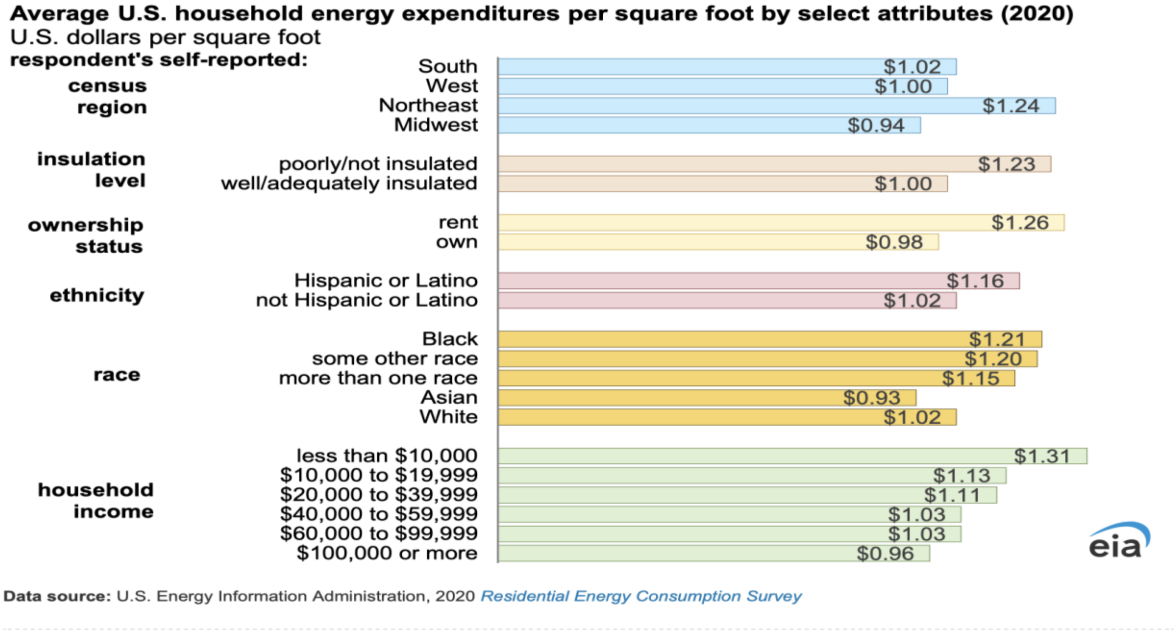

Fig. 1

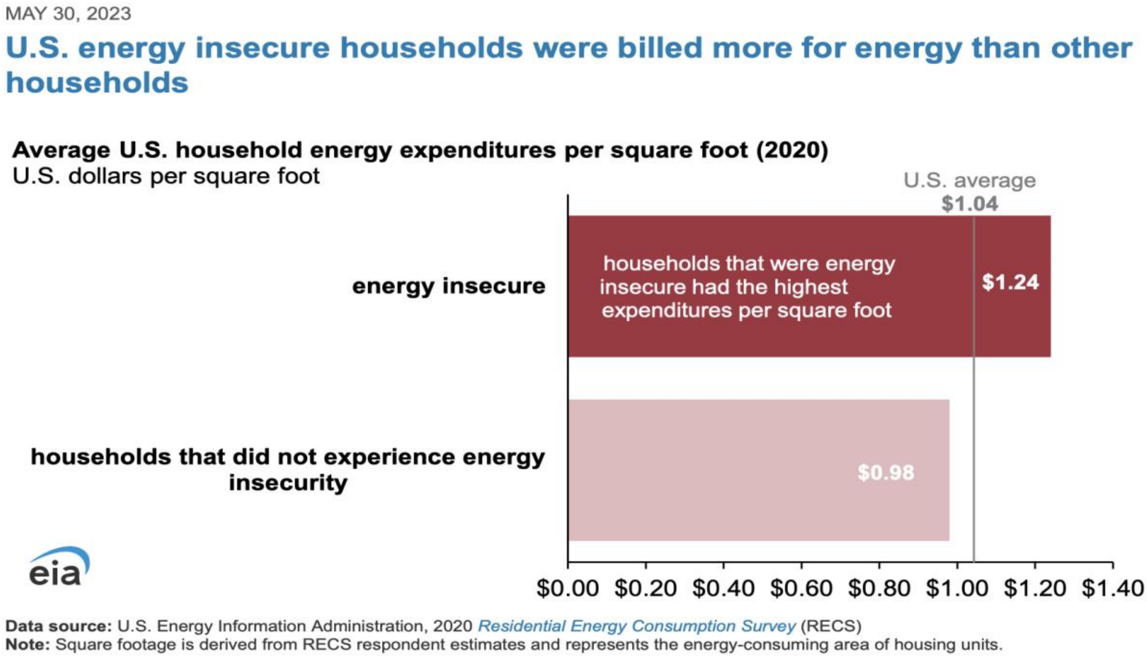

Fig 2.

Analysis of data on US Household Energy Expenditure shows significant insights into energy resilience and sustainability, particularly in historically disadvantaged communities. The data from the U.S. Energy Information Administration (EIA) on average U.S. household energy expenditures per square foot, broken down by various demographic and housing characteristics for the year 2020. This data can be instrumental in understanding the baseline energy usage and the potential impact of Vehicle-to-Grid (V2G) technology on energy resilience and sustainability, particularly in historically disadvantaged communities. Some key insights are as follows

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- **Ethnicity and Energy Cost** Hispanic or Latino households have higher energy expenditures per square foot ($1.16) compared to non-Hispanic or Latino households ($1.02). This indicates that ethnic minorities may face higher energy costs, which can be alleviated through the implementation of V2G technology. By providing additional energy during peak demand periods, V2G technology can help reduce energy costs and improve energy equity for these communities.
- **Racial Disparities in Energy Expenditures** The data shows that Black households ($1.21) and households of some other race ($1.20) have higher energy expenditures per square foot compared to White households ($1.02) and Asian households ($0.93). This suggests that racial disparities exist in energy costs, which can be addressed through targeted V2G initiatives. Implementing V2G technology in school bus fleets can provide a reliable energy source, reduce energy costs, and promote energy equity for racially disadvantaged communities.
- **Income and Energy Expenditures** Households with lower incomes (less than $10,000) have the highest energy expenditures per square foot ($1.31), while those with higher incomes ($100,000 or more) have the lowest ($0.96). This indicates that low-income households face a disproportionate energy burden. V2G technology can play a crucial role in reducing energy costs for low-income households by providing additional energy during peak demand periods and enhancing energy resilience.

Daily Operating Patterns of School Buses and V2G Potential

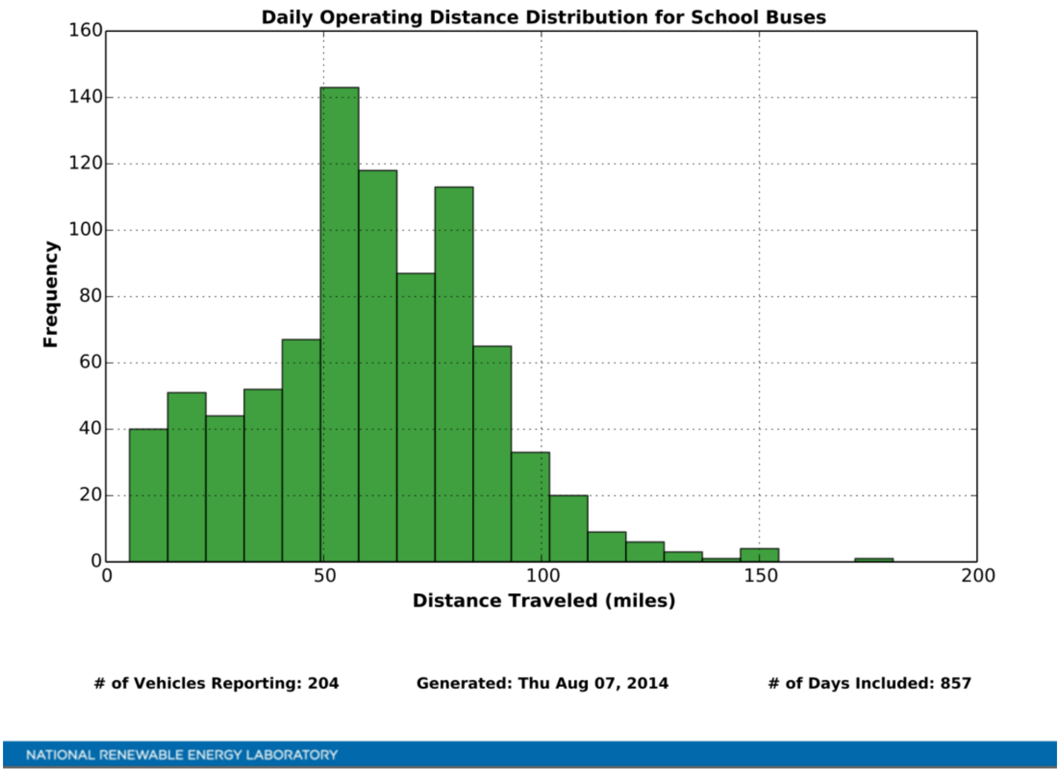

Fig 3.

The majority of school buses travel between 25 and 75 miles per day. The peak frequency of buses operating in this range suggests that it is the typical daily distance for most school bus routes. There is a noticeable drop in the number of buses traveling beyond 100 miles per day, indicating that longer routes are less common. Very few buses travel more than 150 miles in a day, suggesting that the upper limit of daily travel for school buses is typically well below this distance. Given that most school buses operate within a relatively short distance range, there is significant potential for V2G technology to be utilized during non-operational hours. Buses can be charged overnight and during school hours when not in use, providing a stable source of energy to the grid during peak demand times. The relatively short daily operating distances mean that the batteries in these buses are likely to have substantial charge remaining at the end of the day, making them ideal candidates for V2G applications.

4. Analysis and Impact

By integrating Vehicle-to-Grid (V2G) technology into school buses, especially those operating within the common 25 to 75-mile range, communities can significantly enhance their energy resilience. This range indicates that school buses typically have a substantial amount of unused battery capacity at the end of their daily routes, which can be harnessed to support the local electrical grid. Here's how this integration can impact communities, particularly disadvantaged ones:

Mobile Energy Storage Units

- **Stabilizing the Grid** School buses equipped with V2G technology can act as mobile energy storage units. During periods when the buses are not in operation, typically overnight or during school hours, they can be plugged into the grid to supply stored energy. This capability can help stabilize the grid during peak demand times, reducing the likelihood of blackouts and brownouts.
- **Emergency Power Supply** In the event of power outages, these buses can provide a crucial backup power supply. This is particularly valuable in emergency situations, where maintaining power to critical infrastructure like hospitals, emergency response centers, and community shelters is essential.

Financial Benefits

- **Cost Savings** For school districts, the ability to sell excess stored energy back to the grid during high-demand periods can generate additional revenue. These funds can be reinvested into the school system, enhancing educational resources and infrastructure.
- **Reduced Energy Costs** Disadvantaged communities, which often face higher energy costs due to inefficient housing and higher usage rates, can benefit from the price stabilization that V2G technology offers. By reducing peak demand on the grid, V2G can help lower overall energy costs, making electricity more affordable for low-income households.

Environmental Impact

- **Promotion of Renewable Energy** V2G technology supports the integration of renewable energy sources like solar and wind power. School buses can store excess energy generated during the day and release it when needed, smoothing out the variability in renewable energy production. This contributes to a more sustainable and environmentally friendly energy system.
- **Reduction of Carbon Footprint** By reducing reliance on traditional fossil fuel power plants during peak demand, V2G technology helps lower greenhouse gas emissions. This is particularly important for communities located near power plants, which often suffer from higher levels of pollution and associated health issues.

Enhancing Community Resilience

- **Energy Independence** Communities with V2G-enabled school buses can achieve a greater degree of energy independence. This reduces their vulnerability to grid failures and external energy market fluctuations, providing a more reliable and consistent energy supply.

- **Empowering Local Economies** By investing in V2G technology, communities can stimulate local economies through job creation in the installation, maintenance, and operation of these systems. This investment can also spur further innovation and development in clean energy technologies.

Equitable Access to Energy

- **Targeted Implementation** Prioritizing the deployment of V2G technology in disadvantaged communities ensures that the benefits of modern energy solutions are distributed equitably. These communities often face systemic barriers to accessing affordable and reliable energy, and V2G technology can help bridge this gap.
- **Community Engagement** Involving local communities in the planning and implementation of V2G projects fosters a sense of ownership and participation. This engagement can lead to more effective and sustainable outcomes, as community members are more likely to support and maintain systems that directly benefit them.

5. Conclusion

The findings highlight the necessity for targeted implementation of V2G technology in school bus fleets, particularly in regions and communities with higher energy expenditures. By focusing on areas with the highest energy costs, V2G technology can provide the most significant benefits in terms of cost savings and energy resilience. This targeted approach ensures that the deployment of V2G technology addresses the areas with the greatest need, maximizing its impact on energy efficiency and sustainability.

Equity and Inclusion The disparities in energy expenditures based on ethnicity, race, and income underscore the importance of equity and inclusion in V2G initiatives. Ensuring that historically disadvantaged communities, such as Hispanic or Latino, Black, and low-income households, have access to V2G technology can help address these disparities and promote energy equity. By prioritizing these communities, V2G technology can contribute to reducing energy costs and improving energy resilience, thereby fostering a more equitable energy landscape.

Policy and Support Policymakers should consider the demographic and housing characteristics that influence energy expenditures, such as insulation level and ownership status when designing V2G programs. Providing financial incentives and support for V2G technology in school bus fleets can help reduce energy costs and improve energy resilience for vulnerable communities. Policies that encourage the adoption of V2G technology in regions with poorly insulated homes and high rental rates can significantly enhance the overall effectiveness of these programs.

Community Engagement Engaging with diverse communities to understand their specific energy needs and challenges is crucial for the successful implementation of V2G technology. By involving community members in the planning and decision-making process, V2G initiatives can be tailored to meet the unique needs of each community, ensuring maximum impact and acceptance. Effective community engagement strategies will help build trust and support for V2G projects, leading to more sustainable and resilient energy systems.

6. Future scope of work

While this study has explored the potential of Vehicle-to-Grid (V2G) technology in school bus fleets to enhance energy resilience and sustainability in historically disadvantaged communities, there remain several areas that warrant further investigation

Detailed Health Impact Assessments
Future research should focus on conducting comprehensive health impact assessments to quantify the specific health benefits associated with reduced emissions from V2G-enabled school buses. This includes examining the long-term health outcomes for children and communities in disadvantaged areas, particularly in relation to respiratory and cardiovascular diseases.

Longitudinal Studies on Environmental Justice Longitudinal studies are needed to explore how V2G technology can address environmental justice issues over time. Research should investigate the extent to which V2G can reduce localized pollution and improve air quality in low-income and minority communities, contributing to broader environmental equity.

Community Engagement and Acceptance Future studies should delve deeper into community perceptions and acceptance of V2G technology. This includes exploring effective participatory planning processes that ensure community voices are heard and that V2G projects are designed to meet their specific needs and priorities. Strategies for building trust and fostering long-term community support for V2G initiatives should also be examined.

Policy and Regulatory Frameworks Research should continue to identify and address policy and regulatory barriers to the implementation of V2G technology. This includes evaluating the effectiveness of various incentives and funding mechanisms, such as federal and state programs, in promoting equitable V2G adoption. Additionally, studies should explore the integration of V2G into existing energy markets and rate structures to facilitate its widespread deployment.

Technological and Operational Challenges There is a need for further research on the technical and operational challenges associated with V2G technology. This includes investigating the impact of frequent charging and discharging on battery life and performance, as well as developing strategies to mitigate battery degradation. Additionally, research should assess the infrastructure requirements for V2G deployment, including the need for bidirectional chargers and grid upgrades, particularly in underserved communities with limited resources.

Economic Viability and Financial Models Future studies should conduct comprehensive cost-benefit analyses to evaluate the long-term economic sustainability of V2G projects in disadvantaged communities. This includes assessing potential savings from reduced fuel and maintenance costs, as well as revenue generated from providing grid services. Innovative financial models, such as public-private partnerships and community financing mechanisms, should be explored to reduce the financial burden on school districts and ensure equitable access to V2G benefits.

Pilot Programs and Case Studies Implementing pilot programs in various regions and documenting their outcomes through detailed case studies can provide practical insights into the real-world benefits and challenges of V2G technology. These case studies can serve as valuable resources for policymakers, school districts, and other stakeholders considering the adoption of V2G technology.

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