ASSESSING THE ENERGY EQUITY BENEFITS OF MOBILE ENERGY STORAGE SOLUTIONS

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Abstract

Rapid market growth and ambitious climate goals to increase adoption of all types of electric vehicles necessitates that decarbonization, resilience, and energy equity and justice strategies are simultaneously employed to keep pace with the evolving social and policy climate. This is even more imperative now that electric vehicles can be considered a grid storage asset with the implementation of vehicle-to-grid bidirectional charging strategies. This study aims to characterize the energy equity and community benefits of mobile energy storage solutions (MESS) via a storage adequacy analysis of energy access for the following three use-cases—utility-scale networks of MESS assets that are operated within the distribution system; community public transit MESS assets; and behind-the-meter personal vehicle MESS assets. These different use-cases correspond to different battery capacities, charging schedules, and distribution within the grid for which the relevant equity co-benefits must be understood. The results of the resource adequacy analysis will inform a discussion of additional energy equity metrics to establish a prioritization framework matching community and system needs to better inform the distribution of electric vehicles and charging infrastructure, utility planning processes, and the wider network of transportation and energy system stakeholders.

1. Introduction

The Long-Term Strategy of the United States aims for half of all new light-duty vehicle sales to be zero-emission vehicles by 2030 by lowering vehicle costs, fuel economy and emission standards, incentives, and investment in charging infrastructure [16]; many countries have similarly ambitious goals. The global increase in electric vehicles (EVs) has the potential to drastically reduce the transportation sector's emissions and improve air quality in cities and other congested areas as fewer combustion engine vehicles remain on the road. However, the increase in electricity demand required to support this clean energy transition will place substantial pressure on the electric grid, as it coincides with other clean energy initiatives such as increased distributed energy resource generation and the transition to electric heating and other appliances [1]. The need for grid infrastructure upgrades is highly dependent on the number of EVs charging within a system, the burden of which can be offset by employing various smart charging strategies such as off-peak charging to shift charging times; managed charging, whereby the power system operator or aggregator controls the charging time, rate, and duration to match the needs of the power system (V1G); and lastly via bidirectional managed charging, requiring bidirectional inverters and control systems [2] to allow EVs to serve as distributed energy storage assets, charging during low demand and discharging to the grid as needed [1].

Bidirectional managed charging of electric vehicles, known as vehicle-to-grid (V2G), vehicle-to-building (V2B), or vehicle-to-home (V2H), transform demand-heavy electric vehicles into mobile energy storage solutions (MESS). As this technology becomes commercially available and evaluated in energy system planning, it is imperative that these planning processes be informed not only by the potential grid benefits that MESS can provide but also by the equity benefits of such assets. Along with infrastructure upgrade deferral, MESS can support the reduction of emissions by providing energy to the grid during peak demand, preventing the highest fossil fuel burning "peaker" plants, often sited in disadvantaged communities and resulting in adverse health effects [3], [4], from being brought online or ramped up during these times. This can also reduce energy poverty and energy burden (% of median income spent on utilities) by eliminating the expensive peak pricing of Time-of-Use rate structures.

MESS have the unique ability to serve an even wider range of functionalities and stakeholders than their stationary storage counterpart. MESS can provide increased system and local resiliency during extreme weather events and outages by being dispatched directly to areas of need, maintaining critical healthcare and emergency services as well as continued operation of vital community shelters [3]. Depending on ownership model, use case, and market and regulatory framework, MESS also have the potential to provide a revenue stream for grid services provided [5]. The goal of this paper is to characterize the grid and equity benefits of V2G electric vehicles at the consumer, community, and utility scale to inform future grid, transportation, and infrastructure planning activities.

This paper is structured as follows: Section 2 provides a background discussion on energy equity and current mobile energy storage solutions; Section 3 offers a storage adequacy analysis of the three use cases; Section 4 offers a discussion of the analysis results and concludes the paper; and section V briefly comments on future work.

2. Background

2.1 Connecting Energy Equity and Mobile Energy Storage

MESS could help address multiple challenges faced by disadvantaged communities, including transportation and energy burden. Taking the United States national average as an example, household vehicle fuel cost (gasoline burden) is about 7% of total household income [6], and energy cost is 6% of total expenditures [7]; these burdens are significantly higher for low-income households—with gasoline burden equal to 13.8%-14.1% [6] and energy

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burden 13% [7]. As low-income communities spend a significant portion of their income on transportation and energy cost, they have limited or no "residual income" [8] to cover other necessary household costs such as food and medicine. In addition, these burdens are exacerbated by socioeconomic and socio-environmental challenges including housing burden, exposure to pollution, utility service disconnections, etc.

The social equity implications of MESS can be examined through the lens of energy justice. Energy justice is a concept that encompasses four key tenets: distributive, recognition, procedural, and restorative, through which energy systems and processes can be assessed to understand how system planning and operation can produce fair and equitable outcomes for everyone. Distributive justice explores the unequal allocations of benefits and burdens of the energy system; recognition justice focuses on identifying the practices of cultural domination, disregard of people and their concerns, and misrecognitions surrounding energy systems; procedural justice evaluates the fairness of the energy decision making process; and restorative justice examines the response to those impacted by the burdens of past energy projects. Although the issue of transportation and energy burdens have been studied from a justice perspective [5], [9], the intersectionality of the challenges have not yet been adequately explored. In this paper, we highlight the drivers of these overlapping inequities and introduce MESS as an asset that addresses the dual burden on vulnerable communities.

The three key drivers of transportation and energy burdens include:

1. Infrastructural — Access to new technology such as EVs, charging stations, distributed energy resources, etc. are limited or non-existent in low-income communities.
2. Socioeconomic — Access to financing to purchase energy efficient vehicles, efficient household appliances, and other advanced technologies are inaccessible to many low-income communities.
3. Policy — Incentive programs designed to provide access to resources (infrastructural and financing) are often underfunded and have misaligned eligibility criteria that make it impossible for low-income communities to access these resources.

As the focus of this paper is to examine the ways MESS could be used as a grid equity asset, we apply distributive justice as our analytical lens. MESS can help address the transportation and energy challenges for disadvantaged communities in relation to access to safe and reliable transportation and energy services. For example, low-income and minority communities in the United States are exposed to 28% more NOx pollution [10] that leads to various health impacts including respiratory and heart diseases. From a cost perspective, owning and operating a gasoline vehicle compared to an EV is found to be more expensive over time [11], [12]. The cost saving implications of EVs would add greater value to low-income populations, increasing their residual income that would have otherwise been spent on gas. However, these transportation related burdens must be considered alongside household energy burdens for a complete picture.

As transportation electrification continues to expand, it is imperative that equity implications are considered to ensure fair allocations of benefits and burdens. For example, the limited availability of renewable generation supporting the grid means that the increase in EVs would necessitate the continued usage of fossil-fuel generation, heightening the pollution burdens on frontline communities. However, the dual target of reducing both transportation and energy burdens means that transportation electrification will be accompanied by increased renewable energy penetration as well as enabling systems including vehicle-to-grid integration technologies. In doing so, reducing the intersectional energy and transportation inequities will be achieved while maximizing their equity co-benefits. Table I provides a summary of some of these energy-equity co-benefits.

2.2 Current Mobile Energy Storage Solutions Use Cases

Charging EVs have the potential to provide many grid services that may help offset the burden of their charging, such as peak shaving, improved load factor and grid reliability, frequency and voltage regulation, and spinning and non-spinning reserves [13]. MESS can be categorized based on their charging location within the grid, ownership model, and capacity. Three use cases offering significant contrast in these categories that are instructive for equity effects were selected for this analysis: (1) utility-scale

Table I: Energy Equity Benefits of Mobile Energy Storage Applications

Energy Equity Area	**Mobile Energy Storage-Equity Linkage**	**Example Applications**
Access	MESS, when connected via bidirectional charging to a home, building, or grid, can provide access	Self-consumption of renewables, unelectrified areas, limited resource availability, system capacity for small-scale renewables, EV ownership, eligibility for demand response programs
Affordability	MESS can reduce energy costs for consumers and enhance energy affordability by providing consumers more control of their energy use and a potential revenue stream	Grid upgrade cost avoidance, revenue stream for grid services offered, energy cost burden, demand charges, shut-off notices for non-payment
Decarbonization	MESS can be integrated with renewable energy to provide clean energy in place of traditional fossil fuel systems to mitigate greenhouse gas effects	Generator rate spike aversion, climate/renewable energy targets (solar, wind, etc.), fossil fuel power plant decommissioning, peaker power plant replacement
Environmental Impact	MESS can reduce reliance on fossil fuel-based peaker plants and replace diesel backup generators to mitigate local pollution effects	Health improvement, air quality improvement, emissions reduction
Resilience	MESS can be easily deployed to critical locations on the electric grid to provide energy that is accessible to vulnerable communities during extreme weather events	Avoided energy outages, avoided disruption costs (financial and otherwise), enhanced reliability, sustained critical loads during extreme events (particularly for infrastructure supporting multiple stakeholders, such as a community center, cooling center, library, school, etc.)
Social Impact	MESS can serve as a community asset, providing a variety of both energy and non-energy community benefits	Energy independence, wealth creation, community ownership, community building, personal or community satisfaction, rider/operator comfort

networks of MESS assets that are operated within the distribution system; (2) community public transit MESS assets that are co-owned to serve both the utility and the community; and (3) behind-the-meter personal vehicle MESS assets that are customer-owned to serve the household. This section briefly describes each use case and provides a selection of example projects within the United States.

2.2.1 Customer-Owned: The Biden administration announced in June 2022 its goal to develop a nationwide charging network of 500,000 new fast chargers along major highways and in communities along with adopting new standards for reliable and accessible charging infrastructure to include all charger types [14]. This announcement was made days before the passing of the Inflation Reduction Act, which renewed existing tax credits of up to $7,500 for the purchase of a plug-in electric vehicles [15]. Many states also offer rebates and incentives for electric vehicle purchases, many with tiered benefits based on income level. These incentives in conjunction with market trends supporting electric vehicle adoption for personal vehicles poise mobile BTM storage to become a substantial grid asset upon the full commercialization of bidirectional charging infrastructure. However, affordability has another factor, as the purchase price of an electric vehicle can either be substantially offset by trading in an existing vehicle, or negligibly impacted, depending on the age and condition of the trade-in, typically favoring high-income car owners with newer vehicles. At present, only the state of California maintains a combustion-vehicle buyback program to address this inequity: providing $5,500-9,500, depending on income level, for the trade-in of a model 2005 or earlier combustion engine vehicle to offset an EV purchase [16].

Unfortunately, while many vehicle manufacturers are developing bidirectional charging capable vehicles, the technology is not yet commercially available in the United States. However, Nissan's Energy Share program debuted the Nissan Leaf's bidirectional charging capabilities to support V2H charging in Japan in 2012 [17]. Since that pilot, the program has produced additional demonstration programs supporting vehicle to home, building, and grid. These projects have supported lowering peak electricity demand, frequency regulation, virtual power plants, generation/load stabilization, and load flattening [17]. Additionally, before V2H commercialization is achieved, vehicle warranties must extend to batteries performing grid services, as the consensus on battery degradation from such operation schemes has not yet been achieved.

Personal V2H-capable vehicles can be used for load balancing, peak shaving, increased self-consumption of renewables, or as emergency backup for the household to which it is connected. Providing backup power in the case of an outage offers a pathway for increased resiliency as climate-related disasters, outages, and public safety power shutoff (PSPS) become more frequent. PSPS events tend to disproportionally affect low-income and disadvantaged communities, making V2H vehicles particularly impactful. Load balancing and peak shaving services can reduce consumer's utility bills, especially in areas with expensive time-of-use rates. The commercialization of V2H strategies may also lead to increased electric vehicle adoption, reducing emissions and improving air quality [18].

2.2.2 Community-Owned: Public transportation provides a unique opportunity for community or dual ownership strategies for MESS, such as a fleet of electric buses that are city-owned but the charging infrastructure is utility-owned/operated. While electric public transit buses have numerous benefits, the most promising use-case is that of V2G (or in this case, B2G) electric school buses, due to their predictable and grid-convenient operating schedules. The scale of the U.S. school bus fleet presents an incredibly impactful opportunity—converting all combustion engine school buses in operation across the U.S. to electric would result in more than 60 GWh of mobile energy storage capacity and reduce greenhouse gas emissions by approximately 8 million metric tons per year, drastically improving air quality in communities as well as for its passengers, children with developing lungs more susceptible to air pollutants [18].

Such a fleet of B2G-capable electric school buses can provide timely and substantial benefits to the grid. School busses are typically operated for a brief period during the morning and early afternoon—and only during the school year, leaving these MESS to serve the grid not only every evening when they charge during the school year, but for the duration of the summer peaking months where they may provide the most benefit.

The ownership structure for fleets of B2G electric school buses varies, but typically a school district will purchase the vehicles using their transportation budget, offset by state and federal funding programs and utility incentives when available, and the charging infrastructure will be partially or fully purchased, operated, and maintained by the utility serving that school district [19]. This ownership-operation structure allows the school districts to overcome the increased upfront cost of purchasing electric over combustion engine as well as provides a revenue stream from grid services performed for the lifetime of the school buses. Additionally, the growing trend of repowering existing combustion engine buses presents a unique opportunity to lower upfront procurement costs and turnaround times as well as reduce waste by repurposing existing frames [20].

Many pilot B2G programs across the U.S. are initiated by utilities and not subject to the U.S. Department of Energy Justice40 initiative mandating that at least 40 percent of the overall benefits from federal clean energy investments go towards disadvantaged communities [21]; utility initiatives therefore may not to lead to equitable outcomes. Utility programs target their service area, rather than the region with the most need. They may also prioritize awardees based on a 'first-come, first-serve' policy, which can exclude school districts with less resources available for applications. While utility programs provide numerous benefits to their service areas, the federal Energy Improvements at Public School Facilities Grant program is beholden to Justice40 to deploy electric school bus projects nationwide which will directly target disadvantaged communities [21].

The present state of the electric school bus market spans 38 states, 415 school districts, and 12,275 currently operated or committed vehicles [20]. The growing rate of adoption is the result of a combination of increased community support, policy commitments, grants and incentives, and the current market status; the Volkswagen settlement has funded nearly a third of all state-level public funding for electric school bus programs, and the maturation of the market and supply chain are steadily reducing prices and turnaround times for both procurement and maintenance [20].

2.2.3 Utility-Owned: Large-scale electric vehicles such as trucks and trains that can connect their on-board battery or their cargo of batteries to the grid can be utilized for a number of grid services. When operated as a mobile network of energy storage assets, such a fleet can provide increased utilization of energy storage compared to its stationary counterpart [22]. The electric grid system is comprised of multiple nodes, or interconnection points, each with unique locational marginal price (LMP) and local transmission congestion, both of which vary with time of day. This allows a MESS to travel to a node and charge at a low price point, then move to a congested node to discharge at high price—making a profit while providing transmission relief; this process is repeated multiple times throughout the day, as the trucks travel between nodes to deliver widespread system benefits and optimal utilization of their storage capacity [22].

Utility-scale MESS can provide increased renewables integration, deferral of grid infrastructure upgrades, and other ancillary services [22]. A spatiotemporal analysis of a network of electric freight trucks carrying 2.7 MWh capacity operating in California concluded that given the necessary market and regulatory structures, utility-scale MESS can provide substantial revenue for ancillary services such as frequency regulation, congestion relief, and deferral of transmission capacity expansion investments system-wide [22]. The speed and scope with which MESS can be deployed can be used to complement the rapidly increasing penetration of DER and electrification efforts. As this solution is mobile and therefore non-permanent, this model also benefits from ease of deployment, free from lengthy permitting and interconnection agreements [22]. It is also inherently flexible, allowing for even greater system benefits. The deployment schedule, service location, and grid system goals can be easily adapted to meet changing generation and load demand or be quickly dispatched to respond to grid interruptions or provide disaster relief.

3. Storage Adequacy Analysis

3.1 Modelling Assumptions

A representative distribution feeder representing a small semi-urban area of the West Coast, United States [23] was used to compare the equity impacts of the three MESS use-cases, (1) personal electric vehicles, (2) electric school buses, and (3) utility-scale freight trucks. The use cases differ in storage capacity, inverter rating, operational schedules, and location on the feeder, detailed in Table II. The capacity and inverter rating for the personal vehicles are set to match the Nissan Leaf-to-Home demonstration project [24]; the school buses are set to match the NV Energy Electric School Bus V2G trial [25]; and the inverters installed at each node to connect the freight trucks are scaled to the capacity of the utility-scale example described in the previous section [22]. The total load that the MESS can support is limited by the power rating of the inverter.

Table II: Modelling Assumptions by Use Case

	Battery Capacity	Inverter Rating	Grid Location	V2G Schedule	No.
Personal Vehicle	60 kWh	6 kW	BTM	5:30PM - 6:00AM	400
School Bus	220 kWh	60 kW	Bus Depot	Summer Months	5
Freight Truck	2.7 MWh	500 kW	Trunk Node	8:00AM - 8:00PM	3

The complementary schedules of the personal vehicles and the freight trucks are such that one or the other is available at all hours except for a 2-hour gap in the morning. The availability of the school buses is based on the school year, with the buses available for grid services during the summer peaking months. The personal vehicles are connected at the individual household level, the school buses at the bus depot, and the freight trucks can connect at the head of any lateral as the feeder requires.

A storage adequacy analysis was performed using a PNNL taxonomy feeder of 400 households with a large commercial load at its center (trunk node C) representing a school and bus depot, shown in figure 1, to determine the percentage of the load able to be supported by each use case. In all use-cases, the duration of load served is reported for both the average load of the laterals and for the critical load, or 30% of the average load in order to extend access. The feeder contains 38 triplex transformers supplying roughly 10-12 homes per transformer [26]. To represent neighborhoods with households of varying size, as seen in the variation of residential load between the nodes in Table III, the house icons in figure 1 are scaled to match.

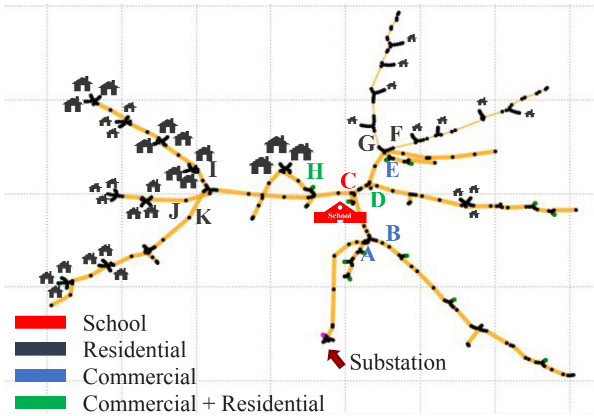

Fig. 1 Representative feeder with 11 laterals, supplying residential-only loads (black), with each house symbol representing 10-12 homes, scaled according to relative load size, mixed commercial/residential (green), commercial (blue), and school and bus depot (red) [26]

3.2 Analysis and Results

3.2.1 Customer-Owned: For this analysis, an idealized case in which every household owns a V2H capable personal electric vehicle is used for modelling purposes. As personal MESS are dual functioning as both a storage and transportation asset, half of the battery capacity is reserved in case of evacuation, especially as the West Coast area being modeled is vulnerable to wildfires. With a usable capacity of 30 kWh, personal electric vehicles are unable to serve the full load of the larger residential homes that exceed the inverter rating of 6 kW (nodes H and I). However, personal MESS are able to support the critical load for between roughly ten hours and nearly four days, depending on household load. Nodes that do not have residential loads

TABLE III: LOAD DISTRIBUTION ON FEEDER AND LOAD SERVED BY USE CASE

Summary of Load Distribution on the Feeder						Personal Vehicles			School Buses			Freight Trucks		
Trunk Node for Lateral	***Number of Homes***	***Residential Load***		***Total Load***		***Inverter Limited Load***		***Critical Load***	***Inverter Limited Load***		***Critical Load***	***Inverter Limited Load***		***Critical Load***
		P_{Resi} ***[kW]***	Q_{Resi} ***[kVAr]***	P_{Total} ***[kW]***	Q_{Total} ***[kVAr]***	***% of Home***	***Time [h]***	***Time [h]***	***% of Lateral***	***Time [h]***	***Time [h]***	***% of Lateral***	***Time [h]***	***Time [h]***
A	0	0.0	0.0	462.2	299.0				64.9	3.7	7.9	100	5.8	19.5
B	0	0.0	0.0	318.8	206.2				94.1	3.7	11.5	100	8.5	28.2
C	School	0.0	0.0	163.0	105.4							100	16.6	55.2
D	30	32.1	20.7	316.1	204.5	100	28.1	93.61	94.9	3.7	11.6	100	8.5	28.5
E	0	0.0	0.0	293.2	189.7				100	3.8	12.5	100	9.2	30.7
F	40	81.8	52.9	81.8	52.9	100	14.7	48.91	100	13.5	44.8	100	33.0	110.1
G	40	75.3	48.6	75.3	48.6	100	15.9	53.10	100	14.6	48.7	100	35.8	119.5
H	45	454.1	293.8	568.3	367.6	59.5	5	9.91	52.8	3.7	6.5	88.0	5.4	15.8
I	125	948.6	613.6	948.6	613.6	79.1	5	13.18	31.6	3.7	3.9	52.7	5.4	9.5
J	60	273.2	176.7	273.2	176.7	100	6.6	21.96	100	4.0	13.4	100	9.9	32.9
K	60	325.5	210.6	325.5	210.6	100	5.5	18.43	92.2	3.7	11.3	100	8.3	27.7
Total	**400**	**2190.6**	**1416.9**	**3825.9**	**2474.8**									

Blue signifying commercial load, red for school, loads unserved [see fig 1]

are omitted in Table III, colored either blue to represent commercial loads or red for the school.

3.2.2 Community-Owned: The five school buses serving this feeder operate on a predictable schedule and are parked at the bus depot in the evening hours until early morning during the school year, and all day every day during the summer holiday. This analysis focused on the summer holiday schedule, as this coincides with summer peaking months due to increased air conditioning demand. During the summer, the bus depot acts as a large stationary storage asset with total capacity of 1.1 MWh. The most effective use of this asset, considering its capacity and availability, is for peak load reduction, resulting in avoided emissions by reducing reliance on peaker plants.

The bus depot can serve to offset 7.8% of the entire load of the feeder or 13.7% of exclusively the residential loadsfor approximately 3.7 hours. Additionally, the bus depot could serve individual laterals as in the other use-cases, the results of which are detailed in Table III. Note that in the summer the school is considered to have no load, as such node C is omitted, filled in red in Table II.

3.2.3 Utility-Owned: The three freight trucks are dispatched to nodes along the feeder according to the needs of the grid such that at any given time, any three of the eleven nodes are served. Each interconnection point has an installed inverter rating of 500 kW, and each lateral served by a freight truck operates independently, akin to a microgrid. Table III details the percent and duration of load served for a given node connected to one of the three freight trucks. The freight trucks can support the critical load of a lateral for between nearly 10 hours and 10 days, depending on the load at the node.

Similar to the bus depot, another scenario to utilize the freight trucks would be to connect all three to the substation to serve the entire feeder. In this scenario, the freight trucks could support 30% of the feeder load for approximately seven hours. To meet the entire load, eight freight trucks would be required, and could serve the load for a total of five hours, though this requires substantially oversizing the fleet size and would be akin to holding a large portion of the capacity of a stationary energy storage asset in reserve in case of an outage, underutilizing the asset in most instances.

4. Discussion and Conclusions

The above resource adequacy analysis provides insight on the impact different MESS use-cases have on energy access within a representative feeder. For all use-cases, the MESS assets are able to provide at least three hours of critical load service, oftentimes longer. For service areas with reliability issues that suffer frequent hours long disruptions and brownouts, MESS can bolster reliability, particularly in the customer and utility-owned cases. The community-owned school bus case would not typically be utilized to support a single lateral as in Table III but would instead provide substantial peak demand reduction in the summer, reducing emissions, improving air quality, and reducing energy burden. During extreme weather events, MESS are not only able to provide increased resiliency by providing backup power, but personal vehicles and school buses can be used for evacuation, and freight trucks can be dispatched beyond their normal service area to provide onsite relief where it is most needed.

The V2G availability schedules of the three use-cases provide complementary grid benefits; either the personal vehicles or freight trucks are nearly always available to prevent load loss and increased reliability. The school buses were modeled to provide grid services during the summer peaking months with the greatest need, but their school year schedule can also complement the other use-cases. During the school year, school buses finish transporting schoolchildren home and return to the depot for charging an hour or two before most personal vehicles return from the workday, offering increased resiliency in the afternoon.

Most MESS can provide positive environmental impact from both their use as storage assets and by reducing the number of combustion engine vehicles on the road. However, utility freight trucks are not designed to displace existing vehicles, rather to provide substantial grid relief, reducing the reliance on polluting ‘peaker plants’ and even leading to the retirement of some peaker plants altogether. Widespread personal electric vehicle and school bus adoption, on the other hand, can drastically reduce transportation emissions and improve air quality in high congestion areas and for school children and bus drivers alike before even providing grid benefits as storage assets. Potential emissions reductions must again come with the caveat that the increased electricity demand from EV charging must be offset with increased penetration of distributed energy resources and smart charging strategies (both V1G and V2G), or increased EV adoption will exacerbate fossil fuel pollution rather than offset it.

Affordability is still a substantial hurdle for MESS, as bidirectional charging is an emerging technology that will likely be commercialized at high cost until larger market adoption and economics of scale result in cost reductions. The upfront purchase price of electric vehicles is still higher than combustion-engine vehicles, but the overall cost of vehicle ownership [11], [12] is less, and V2G services offer a potential revenue stream. Unfortunately, the cycle of poverty is such that upfront cost is still the most prohibitive factor, leading those unable to afford the initial higher cost to achieve higher overall savings will eventually spend more money over time. Federal and state tax credits and incentives remain the best tool to increase affordability as the EV market grows to become cost competitive. Justice40 grants and programs both for EV purchase and charging infrastructure are likely to drastically change the EV landscape of the U.S. in the coming years in favor of affordability.

MESS have the potential to further decarbonization efforts when integrated with renewable energy generation technologies. Personal electric vehicle and school bus charging infrastructure is often paired with solar generation to this end. However, residential solar installations can be cost prohibitive and are most accessible to higher income households, though the declining cost of solar and similar federal tax credits and incentives exists to subsidize these costs. The greatest potential for decarbonization through MESS exists when affordability and access is maximized, resulting in widespread adoption and integration with renewable technologies; this scenario also best offsets the impact of the increased demand from EV charging when the greatest number of EVs are paired with renewables, utilize smart-charging strategies, and provide V2G services.

While personal EVs have the potential to provide modest revenue from grid services using V1G and V2G charging strategies, and utility-owned freight trucks can provide substantial revenue for local utilities and co-ops, community-owned MESS offer the greatest social impact. A fleet of electric B2G capable school buses, once purchased with the assistance of grants and tax incentives, has the potential to drastically improve the financial well-being of a school district. In operation costs alone, electric school buses save $4,000 - $11,000 per school bus in fuel and maintenance costs per school bus every year depending on local electricity rates, fuel, and labor costs [20]. On top of these cost savings is the revenue stream for grid services provided during the summer, which again vary based on local electricity rates and market structure. Repowering combustion engine buses with electric powertrains is an increasingly popular option, which is likely to result in substantial job creation as B2G programs become more common.

Each of these three use cases has the potential to provide numerous grid and energy equity benefits, the extent of which depends on the market and regulations to which they are subject. As MESS via bidirectional charging strategies is an emerging technology, it is not yet clear beyond pilot projects how owners will be compensated for grid services, nor whether compensation structures will be equitable across the three use cases. As with all renewable technologies and climate strategies, no one solution is the answer—deployment of all MESS use-cases working in tandem can provide the most robust benefits to grid and energy reliability, resiliency, access, affordability, decarbonization, and environmental and social impact.

5. Future Work

Before widespread commercialization of V2G technologies, the market and regulatory framework must evolve to capture the grid services offered by MESS to both adequately compensate vehicle owners as well as incentivize EV sales and V2G participation. As these frameworks progress, further energy equity analysis capturing additional metrics such as air quality, self-consumption of renewables, grid upgrade cost avoidance, revenue stream from grid services, driver/owner satisfaction, outage frequency and duration, and generator rate spike aversion connecting the transportation and energy sectors is necessary to ensure fair and just distribution of these benefits to all stakeholders.

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