

Estimating the Deep Decarbonization Benefits of the Electric Mobility Transition: A Review of Managed Charging Strategies and Second-Life Battery Uses

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ABSTRACT

Emissions-reduction pathways in transportation are often characterized as a “three-legged stool”, where vehicle efficiency, fuel carbon content, and vehicle miles traveled (VMT) contribute to lower emissions. The electric mobility (e-mobility) transition provides fast savings since plug-in electric vehicles (PEVs) are nearly three times more energy efficient than internal combustion engines (ICEs) and most nations’ power grids are lowering their carbon intensity irrespective of any further climate policy. The transportation sector’s greenhouse gas (GHG) savings via electrification are subject to many variables – such as power plant feedstocks, vehicle charging locations and schedules, vehicle size and weight, driver behavior, and annual mileage, which are described in existing literature. Savings will also depend on emerging innovations, such as managed charging (MC) strategies and second-life battery use in energy storage systems (B2U-ESS). This paper’s review of MC strategies and B2U-ESS applications estimates additional GHG savings to be up to 33% if chargers are widely available for MC-enabled passenger cars, and up to 100% if B2U-ESS abates peaker plants over its second-use lifetime. In this way, an e-mobility transition can deliver additional lifetime decarbonization benefits, both on- and off-road, long term.

INTRODUCTION

The U.S. Environmental Protection Agency reported the transportation sector eclipsed the electricity sector in 2018 as the largest emitter of CO₂, due in large part to (1) a shift from coal-powered electricity generation to less carbon-intensive power via natural gas and renewable feedstocks and (2) a decline in electricity demand (2020). At the same time, VMT by light-duty and heavy-duty vehicles (LDVs and HDVs) rose as the U.S. emerged from the Great Recession, along with high consumer demand for larger vehicles, like sport utility vehicles (SUVs). Such shifts offset benefits of better corporate average fuel economy and ethanol content standards required for new vehicle sales (IEA 2019; US EPA 2020). Since the 1990s, the gap in average fuel economy of passenger cars (PCs) and light-duty trucks (LDTs) has grown while the share of highway vehicle-miles traveled has gone in opposite directions (-22% for PCs and +20% for LDTs) (Davis and Boundy, 2019). In 2018, LDVs (including LDTs) accounted for 59% of transportation-related GHG emissions (Sivak and Schoettle, 2017; US EPA, 2019). Electrifying LDVs will translate to significant reductions in transportation GHG emissions, even if demand-side factors hold (e.g., rising VMT and a preference for larger LDTs).

Absent further federal and state initiatives (e.g., higher vehicle registration fees, fuel economy requirements, gas taxes, and PEV incentives), local governments look at long-term policies and practices such as compact development, greater building efficiency requirements, and

behavioral nudges toward shared and active transportation modes. Such soft and long-term strategies cannot deliver the deep decarbonization that an e-mobility transition coupled with a clean grid can provide (MnDOT 2019; Steinberg et al. 2017; Williams et al. 2014). Moreover, the COVID-19 pandemic's effects on mode choices, especially sharing rides with strangers, may inhibit progress in increasing vehicle occupancy and land use densities. Improving the efficiency and fuel source of LDVs is imperative, given Americans' reluctance to shift modes and change other behaviors, like home and lot sizes (Webber, 2020). Since tailpipe emissions move upstream with PEVs¹, the power sector carries increasing responsibility for decarbonizing, which a growing number of U.S. states and utilities are committing to under legislative/executive directives or pledges (Ricketts et al., 2020; SEPA, 2020). Even then, future grid emissions are uncertain and depend on both policy directives and technological advances.

As lithium-ion battery (LIB) prices continue to fall (BNEF, 2020; Henze, 2019), projections suggest that new U.S. battery electric vehicles (BEVs) may reach cost parity (purchase price) with ICE vehicles (ICEVs) between 2024 and 2025 for 150 to 200-mile BEVs and 2026-2028 for 250 to 300-mile BEVs (Lutsey and Nicholas, 2019; Slowik et al., 2019). PEV market share has risen every year in the U.S. (and abroad), and PEVs now constitute 2% of total new U.S. LDV sales – up from 0.7% in the U.S. in 2015 (Hertzke et al., 2019), 4.9% in China, and 3.5% in Europe² (IEA, 2020). A combination of improved battery capacity, lower prices, and popular models (like the Tesla Model 3) has allowed BEVs to outpace sales of plug-in hybrid electric vehicles (PHEVs) in the U.S. (Goody, 2020). Still to come in the commercial fleet transition are electric last-mile delivery vehicles and shared autonomous electric vehicles (SAEVs) (Cruise, 2020; Motavalli, 2020), which may be electrified much faster than PCs due to their duty cycles.

While PEVs' environmental benefits will depend on driver behavior, charging patterns, and the carbon intensity of local grids, most government agencies only focus on the number and type of PEVs adopted. To maximize PEVs' decarbonization benefits³, policymakers and planners should work with utility companies, original equipment manufacturers (OEMs), and electric vehicle supply equipment (EVSE) manufacturers to develop practice-ready MC programs and battery repurposing schemes for B2U-ESS. For example, strategically charging PEVs is important since most drivers charge at home in the evening upon returning from work, which increases the evening peak (when renewable generation is low and both business and home energy demands overlap). Added PEV charging loads may impact aging distribution-level transformers⁴ (Alonso et al., 2014; Cheng et al., 2018; Gan et al., 2013; Hilshey et al., 2013; Masoum et al., 2011), but also increase emissions since many regions use fast-response natural gas peaker power plants for the evening peak. MC can minimize GHGs by shift charging to times when the grid has peak renewable energy source (RES) generation (McLaren et al., 2016).

¹ Plug-in electric vehicles (PEVs) are used to describe both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) when appropriate. PHEVs have both an electric motor and internal combustion engine whereas BEVs only use a battery system. With battery-depletion mode engaged first, most PHEV drivers can complete daily trips on all-electric mode.

² There is high variability in Europe by country – BEVs in Norway are around 50% of new vehicle sales, for example.

³ Woo et al. (2017) conducted nation-state, regional, and worldwide well-to-wheel (WTW) analyses using 2014 power grid generational mix data to measure the tradeoff between 2016 BEVs and ICEVs. GHG emissions of compact, full-size luxury, and SUV BEVs were lower than gasoline ICEVs regardless of the range of chosen emissions factors (but not necessarily for diesel ICEVs). The 2020 Transportation Annual Technology Baseline from NREL reports a WTW analysis for midsize PCs using 2020 fuels. Relative to a gasoline ICEV, PHEVs have a WTW reduction factor of 0.645 and 0.580 for all-electric ranges of 20 and 50 miles, respectively. Although lower for BEVs, the manufacturing impact of long-range batteries is noticeable (e.g., 0.389 versus 0.484 for 200- and 400-mile BEVs).

⁴ Other potential problems include voltage instability, frequency variation, and power loss (Hussain et al., 2021).

This paper reviews how aligning PEV charging with low-carbon power generation can lead to enhanced carbon reduction beyond ensuring that PEVs have lower CO₂ emissions than ICEVs (Jochem et al., 2015; Tamayao et al., 2015). It also describes the benefits of battery collection and downcycling schemes to repurpose used/retired EV batteries for battery storage systems (B2U-ESS), displacing fossil-fuel power generation sources, such as natural gas peaker plants. At lower costs per kilowatt-hour (kWh), B2U-ESS can also help modernize grids around the world to accommodate additional EV loads and intermittent RES generation while also freeing up raw battery resources (e.g., nickel, cobalt, magnesium, and lithium) for transportation use.

MANAGED CHARGING

Managed charging, also referred to as smart charging, coordinated charging, or V1G, is a demand-side management (DSM) strategy to optimize the additional PEV loads on the grid. The utility or another third-party directly controls charge scheduling through communication signals (with the vehicle or the charger/EVSE) or by offering financial incentives to charge at off-peak periods (Hu et al., 2016). The former requires both low-cost communication systems and standardized message protocols for both chargers and PEVs, which some utilities report as a barrier in MC pilots (Myers, 2017). Further, household meters cannot accurately detect or quantify Level 1 or 2 charging events⁵ without an added sub-meter (Apostolaki-Iosifidou et al., 2019), nor can chargers know the driver's mobility needs and departure time requirements, necessitating a separate communication protocol between the vehicle, driver, EVSE, and the grid operator. Thus, most pilots devise an app-based interface system for drivers or random nighttime charge scheduling with a pre-set departure time.

Hu et al. (2016) categorized MC strategies from a PEV fleet operator's perspective into centralized control, transactive control, and price control. Centralized control describes fleet operators who manage the charging schedules of PEVs to obtain system equilibrium (in price and mobility needs). Transactive control is a market-based method where bidirectional information of price and charge scheduling occurs between vehicles and the fleet operator until pricing results in charging equilibrium. Price control is the unidirectional sharing of pricing (such as time of use (TOU) rate structures) to vehicles to nudge charging decisions. Centralized control may cause a few isolated peak charging events but the aggregate charging schedule is smoothed to lessen the marginal load on the grid (Cheng et al., 2018). In contrast, decentralized control such as tiered TOU pricing may unintentionally create an EV peak load at the start of off-peak pricing if not coordinated across vehicles (FleetCarma, 2019). EV-specific charging incentives may shift loads better than TOU rates (Goody, 2020) and can lower emissions if incentives support RES generation (Jochem et al., 2015; McLaren et al., 2016).

Cheng et al. (2018) compared the economic and emissions benefits of both decentralized and centralized MC for PEVs (from the grid perspective) and their respective grid capacity requirements, assuming that large-scale centralized charging of privately-owned PCs remains infeasible. Using a 2030 California PEV fleet and grid, they found decentralized charging can result in the same CO₂ emissions benefits, grid resource capacity, and electricity costs as centralized charging but only when the grid receives predicted EV loads at least every two hours.

Although these three control strategies from Hu et al. (2016) are for fleet operators rather than grid operators (Hussain et al., 2021), the two perspectives can be in harmony (Cheng et al., 2018) if the charging infrastructure, incentives, and strategies align. A commercial fleet operator

⁵ Level 1 corresponds to a 120-volt AC outlet while Level 2 corresponds to a 240-volt AC outlet. The charge rate is about 5 miles per hour and 20 miles per hour, respectively.

with centralized control must balance revenue-generating opportunities, such as deliveries and ride-hailing services, with cost-minimizing charging opportunities. In contrast, individual travelers, using their own household vehicles, are more responsive to convenience-based charging, followed by cost-minimization (FleetCarma, 2019). If PEVs were able to absorb RES in real time with MC, utilities could also significantly defer energy storage projects, which are necessary to meet state-wide renewable portfolio standards (RPSs) (Forrest et al., 2016). In solar-rich areas like California, utilities could partner with governments to expand workplace and public charging stations to both nudge motorists to adopt PEVs and to realize the benefits of MC (García-Villalobos et al., 2014; Zhang et al., 2019). The following few studies paired historical travel data with recent grid feedstock mixes to predict the environmental benefits of optimal MC in various future years.

Forrest et al. (2016) explored the energy storage benefits of an optimal MC program for the state of California in 2050. Their MC strategy, defined as minimizing the net load on the grid, increased RES penetration from 56.7% to 73%, since more daytime charging events could take place to absorb RES generation and prevent curtailment. A scenario with vehicle-to-grid (V2G) bidirectional flow of energy increased RES up to 84%, surpassing the then-renewable portfolio standard (RPS) target of 80%. However, they assumed each destination had V2G-enabled chargers, which overestimates RES target findings. van Triel and Lipman (2020) used the latest 60% RPS by 2030 target with V1G and V2G to study the deferred infrastructure investments of stationary storage, expanding upon similar studies, by Coignard et al. (2018) and Szinai et al. (2020). They found that MC with 3.3 million PEVs in California is equivalent to a nearly \$16 billion investment in storage, offering more gigawatt-hours of energy than what was produced by solar in 2019 (equivalent to 14.2% of the in-state generation portfolio) (Nyberg, 2020). A similar target study found a 3% to 8% savings in electricity production costs (\$210-\$660 million), and a 3% to 5% reduction in grid CO₂ emissions, helped by the potential to reduce renewable curtailment by up to 13% (Zhang et al., 2019).

Hoehne and Chester (2016) optimized pre-timed plug-in EV (PEV) charging schedules with or without V2G use to reduce CO₂ emissions across all 8 North American Electric Reliability Corporation (NERC) regions in the US. They used average urban daily driving distances from the 2009 National Household Travel Survey (NHTS) dataset alongside monthly marginal emission factors (MEFs) by NERC region by the hour of the day for both temperate and extreme months to optimize three charging schedules. Daytime charging (12 pm +) simulated workplace and public charging, evening charging (6 pm +) simulated post-work residential charging, and nighttime charging (12 am +) simulated valley-filling residential charging. They found emission reductions up to 31% with V1G and up to 59% with V2G⁶.

The findings of these studies are inherently local. Shifting charging to RES and other low-carbon periods depends on local conditions (e.g., solar and wind) and the feedstock mix of the grid. Tu et al. (2020) conducted a case study of the Toronto metro and estimated PEVs could have up to 97% lower life cycle GHG emissions compared to gasoline-powered ICEVs, but nuclear and hydroelectric powers over half of Ontario's grid. Thus, MC would not have as much of a sizeable impact compared to a grid powered by coal and natural gas. Additionally, some regions would benefit from shifting nighttime residential charging to daytime charging to align with solar generation, but investment in public and workplace chargers is needed to support daytime MC. If the region has significant nighttime wind, sufficient residential charging is necessary, particularly

⁶ Emissions could increase with V2G if stored energy from carbon-intense power generation is discharged during periods of relatively low carbon electricity.

at renter-occupied multi-unit buildings. A foreseeable long-term challenge in California is the ability to shift to daytime charging to absorb solar, as it requires additional public and workplace chargers (BMW, 2020). CAISO curtailed roughly 961 GWh of solar and wind energy in 2019, which was more than double the amount in 2018 and triple the amount in 2016, revealing the urgency for MC in the state (Micek, 2020). If MC is not pursued at scale and motorists are not able to charge mid-day, long-range BEVs could pollute more than PHEVs if they charge at home in the evening and are drawing electricity from natural-gas peaker power plants (Tarroja et al., 2015).

Pilot projects are demonstrating the feasibility of DSM of real vehicles. A 2015-2016 pilot in the Bay Area, with the utility PG&E, and OEM BMW, explored the effectiveness of BEVs under demand response (DR) events (PG&E, 2017). During the 18-month pilot, there were 209 events where BMW had to provide 100 kilowatts (kW) of capacity for the grid, either through deferred BEV charging or stored backup power. Only 20% of the DR power savings was attributed to the 96 i3 BEVs with the remaining 80% coming from a B2U-ESS. Since vehicle owners could opt out of the DR event and vehicle telematics relayed whether interrupting charging would interfere with the motorists' typical travel behavior, the vehicle pool of participating vehicles was small at times. Additionally, the number of vehicles participating in nighttime DR events was highly correlated with households on TOU rates, indicating synergy between rate structures and MC potential. During nighttime events, the vehicle pool contributed up to 50% of the 100kW capacity required. In a separate study in Toronto, the ChargeTO pilot of 30 PEVs showed up to 80% of the peak evening charging load could be curtailed under DR events to reduce grid strain and still meet owner-set departure times (Bauman et al., 2016).

A second joint PG&E-BMW study looked at the driving patterns of nearly 400 PEVs and quantified the carbon reduction impact of MC (BMW, 2020). If all chargers were managed and chargers were accessible at all destinations, drivers could reduce their GHG emissions up to an additional 32% in Northern CA. Under this 'abundant charger' scenario, PHEVs could increase their average renewable energy usage by 108% by using battery-depletion mode for the start of every trip. As a result, a PHEV could obtain 50% more GHG savings per unit of battery capacity than a BEV. Additionally, MC could allow a motorist to travel an additional 3,500 to 5,000 miles with zero-carbon emissions (roughly one-third of a driver's annual VMT). The study also reports that if 40% of the load from the expected 5 million California PEVs in 2030 were managed, it could eliminate the need for RES curtailment by absorbing 2,400 GWh of renewables (equal to the annual output of roughly 5 million rooftop solar panels).

BATTERY STORAGE SYSTEMS (BSS)

Electrification of LDVs alone will not tackle climate change and could pose logistical challenges for the nation's grid and OEM supply chain under aggressive adoption targets (Milovanoff et al., 2020). A second resource for deep decarbonization in the e-mobility transition is found with the anticipated stockpile of used PEV batteries. As a result of increased PEV sales, the global stockpile of used PEV batteries could exceed 3.4 million by 2025, compared to just 55,000 in 2018 (IER, 2019). Globally, PEVs may represent 58% of new passenger vehicle sales in 2040, most of them BEVs, ensuring a large supply of used batteries in the future (McKerracher and Albanese, 2020). In the US, 40% of new vehicle sales are in states with California's zero-emission vehicle (ZEV) mandate, with three more states expressing interest in 2020 (Shepardson, 2020). As PEV sales continue to increase across the US, more regions will see an increase in the supply and subsequent market for battery repurposing in the coming decades. As an alternative to landfilling or recycling, downcycling of used PEV batteries (also called second-life use or repurposing) can capture

residual capacity in the batteries for use in B2U-ESS. Although research is ongoing to try to cost-competitively recover battery byproducts at an acceptable condition (e.g., US ReCell Center and UK RELiB project), the economic conditions are currently in favor of repurposing and may defer recycling until better practices are commercially viable (Fan et al., 2020; Harper et al., 2019). Moreover, the market for repurposing is large given that recycling accounts for less than 5% of the LIB⁷ waste stream (Jacoby, 2019).

Early LIBs had a 7- to 10-year and 100,000-mile warranty, with test results indicating battery degradation to 70% to 80% of design capacity (Malcho and Kelly, 2015; Neubauer et al., 2015). Recent data from Tesla BEVs suggest improved battery design and heat flow management could limit deterioration to 90% of the original capacity (Lambert, 2018). If capacity loss is kept low, the longevity and cost-competitiveness of a B2U-ESS could allow for this market to develop more quickly. By re-using PEV batteries for stationary energy storage, the life cycle footprint of the e-mobility transition is further stretched from per-mile to per-kWh used. This would spread out the manufacturing impact of LIBs, which remains very energy intensive (Ahmadi et al., 2017; Pellow et al., 2020). Cicconi et al. (2012) used a life cycle assessment approach to come up with a possible 25% reduction in GHGs from second-life BSS applications. However, they did not consider repurposing energy costs (e.g., collection, testing, assembly) which would have a negative impact. Another study found that the GHG savings from vehicle electrification could double if batteries are repurposed for storage and abate natural-gas peaker power plants, especially at peak periods (Ahmadi et al., 2017). Additionally, the U.S. could lessen its reliance on imported batteries and raw materials for energy storage since the system cost of repurposed B2U-ESS could be as low as 1/6 of a new BSS (Green Technology Laboratory, 2019). While some studies focus on the techno-economic feasibility of a B2U-ESS (Ahmadi et al., 2014; Neubauer et al., 2015; Neubauer and Pesaran, 2011), this section summarizes the findings of the environmental benefits.

Burke (2009) projected the first uses of B2U-ESS in behind-the-meter (BTM) residential and light commercial settings or as backup power for telecommunication equipment, primarily due to start-up barriers of sourcing large quantities of used PEV batteries. Currently, several proofs-of-concept are being deployed in the field to understand the system architecture, performance, costs, and efficacy of battery health tests. The pilots vary from bulk energy storage at the generational level down to behind-the-meter uses for energy arbitrage and resilience.

Smaller pilots include powering select streetlights in Japan, elevators in Paris, and a data center in Michigan, among others (Martinez-Laserna et al., 2018; Schmidt, 2018). The Michigan pilot includes 5 repurposed battery packs capable of storing energy from an on-site 74kW solar array and 2kW wind turbines to lower electricity costs and provide four hours of back-up power (Malcho and Kelly, 2015). Another pilot also pairs 2 B2U-ESS units and RES, but with a third component, 22 BEVs with V2G chargers. This pilot on a Portuguese island is part of a larger goal of transitioning from imported natural gas to renewables (The Mobility House, 2019). A minor component to the second joint PG&E-BMW study was the installation of 4 BMT BSS units to investigate the synergy between residential MC and rooftop solar. As most of the charging occurred overnight due to TOU rates, stored excess solar energy was able to partially charge the four participating BEVs (BMW, 2020). The common element between these three pilot projects is the integration with on-site RES or other power sources (e.g., V2G-enabled PEVs) as a microgrid⁸.

⁷ Other battery types exist beyond Li-ion, such as NiMH, but are less common.

⁸ Microgrids are interconnected with the larger grid but can operate independently. They are mostly used to integrate small RES, lower electricity costs, and provide backup power (Lantero, 2014). B2U-ESS is a type of distributed energy source (DER), alongside rooftop solar, microturbines, and V2G-enabled PEVs.

B2U-ESS research primarily centers on its usefulness in supporting RES, smoothing loads, providing storage, and load shifting as a means to lower the environmental footprint of electric batteries (Bobba et al., 2018; Casals et al., 2017). In the future, regions with a larger supply of B2U-ESS may use them in regulating intermittent RES at both the generational- and distributional-level by managing peak loads. One utility in Germany has retrofitted retired coal power plants to store B2U-ESS and has installed about 40MWh of capacity, demonstrating the potential for large-scale applications (POWER, 2018; Schmid, 2018). One estimate found that Germany could have 25 GWh per year of second-life batteries by 2025 for energy storage (Reid and Julve, 2016). Under favorable conditions, the second life of a PEV battery may even exceed 10 years (Neubauer et al., 2015). By 2030, worldwide utility-scale LIB-storage demand will reach 183 GWh annually with an estimated annual second-life PEV LIB supply of 112-227 GWh (Engel et al., 2019). In the US, Sathre et al. (2015) estimated that repurposed batteries could provide 5% of California's projected electricity demand in 2050, offsetting 7 MtCO_{2e} per year (about 1.5% of the state's current total emissions per Martinez-Laserna et al. (2018)), mostly by abating other fast-response natural gas peaker power plants. California will likely become a leader in this field because of the high penetration of PEVs and stringent RPSs that will require innovative DSM and BSS solutions.

However, the potential to reduce GHG emissions requires minimal storage loss of the BSS (i.e., inefficiency), which some studies note as a technological hurdle and a possible reason for increased GHGs with B2U-ESS (Fares and Webber, 2017; Fisher and Apt, 2017). A study focusing on the economic and environmental feasibility of B2U-ESS at fast-charging sites again showed that battery efficiency losses can increase electricity consumption, but that repurposed packs offer more savings (7% to 31%) than new BSS when on-site storage is required (Kamath et al., 2020). The environmental benefits are greatest when the system provides peak shaving services to lessen the need for peaker plants; however, the provision of on-site RES and the carbon-intensity of the grid influence the best use cases for environmental benefits. Khowaja et al. (2021) estimated theoretical annual GHG savings of residential BSS for homes with and without rooftop solar from a dataset of 45 metered Austin, Texas homes. Homes with solar lessened their carbon footprint by over 2.67 tons, which was a nearly twenty-two-fold carbon savings compared to homes solely using the BSS with stored low-carbon grid electricity. Without on-site solar, households could end up paying \$25 annually to operate the BSS (a net loss, assuming moderate to no carbon pricing).

CONCLUSION

The world's interest in quickly decarbonizing to slow the planet's climate emergency motivated this review of two emerging PEV-centered strategies: MC and B2U-ESS. Managed charging (V1G) and discharging (V2G) can provide several ancillary grid services such as demand response, peak shaving, and valley filling. Environmental benefits from MC come from aligning charging sessions with less-carbon-intense periods, such as mid-day in California or early morning in Texas, to take advantage of solar and wind, respectively. A second benefit comes in the reduction of the added PEV load during peak periods, decreasing the need for additional natural gas peaker power plants. Studies vary widely based on regional grid feedstock mix, electricity rate structures, and assumptions on the availability of charging equipment. Two California studies (BMW, 2020; Hoehne and Chester, 2016) estimated that MC could reduce charging emissions by 31% to 32% if chargers are available at all destinations and all charging sessions are optimized. Total grid emissions could fall by 3% to 5%, but this relies on 3.8 million additional public chargers.

Studies also indicate that MC of PEVs can defer multi-billion-dollar investments in stationary storage (Coignard et al., 2018; Szinai et al., 2020; van Triel and Lipman, 2020).

Communities and policymakers would be wise to further incentivize the installation of V2G-enabled charging station networks and work with OEMs to equip all new vehicles with telematics to prepare for MC schemes. Since purchase-price parity of PEVs with ICEVs in the U.S. is expected within the decade, vehicle and charger equipment incentives could be rolled into energy charging incentives to alter charging habits, specifically with early adopters. Greater coordination with electric power companies to create incentives also requires auto manufacturers and charger equipment suppliers to develop interoperable and open-source scheduled charging protocols.

Repurposing PEV batteries for second-life energy storage applications is in its infancy with pilot projects ranging from a few kWh to 40 MWh. Applications are centered primarily in BTM storage due to sourcing issues, but generational-level projects in Europe are advancing, primarily in countries with high electricity costs. B2U-ESS achieve GHG savings by discharging energy during peak periods to lessen the need for natural gas peaker plants (potentially doubling GHG savings of vehicle electrification). Downcycling also spreads out the manufacturing impact of LIBs, lowering life cycle impacts of the e-mobility transition. Direct storage of excess renewables is expected to prevent unintended GHG increases due to battery inefficiencies. Still, there is a need to better understand the impacts of this technology in a holistic life cycle assessment (Nealer and Hendrickson, 2015), since few studies examine the environmental benefits exclusively.

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