ARE ELECTRIC VEHICLE TARGETS ENOUGH? THE DECARBONIZATION
BENEFITS OF MANAGED CHARGING AND SECOND-LIFE BATTERY USES

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ABSTRACT
Vehicle electrification delivers fast decarbonization benefits by significantly improving vehicle
efficiency and relying on less carbon-intense feedstocks. As most nations’ power grids lower their
carbon intensity and battery energy density improves, the transportation sector’s greenhouse gas
savings may deliver upwards of a 75% reduction in many nations’ current carbon footprints. Actual
savings depend on many variables, like power grid feedstocks, charging rates and schedules, driver
behavior, and weather. A special synergy between power and transportation sectors comes via
managed charging and second-life battery uses for energy storage systems. This paper reviews the
added carbon and energy savings that can come from these two strategies. If charging stations are
widely available at one’s destination, utility-controlled managed charging could reduce EV-
charging emissions by one-third. And downcycling EV batteries for energy storage can lower
peaker power plant use, avoiding curtailment of renewable feedstocks, and lessen households’
power-based carbon footprints by half — or contribute up to 5% of grid power capacity.

Keywords: managed charging, second-life battery storage, electric vehicles, decarbonization
pathway, charging strategy, emissions analysis

INTRODUCTION
The U.S. transportation sector surpassed electricity as the largest emitter of carbon dioxide (CO₂)
in 2018 (1). The electricity sector reduced emissions largely due to a shift from coal-powered electricity generation to less carbon-intensive power feedstocks (like natural gas, solar, and wind) and a decline in power demand. At the same time, vehicle-miles traveled (VMT) by light-duty and heavy-duty vehicles (LDVs and HDVs) rose, as the U.S. economy emerged from the Great Recession, along with high consumer demand for larger vehicles—like sport utility vehicles (SUVs). Although there have been improvements in fuel economy and fuel content standards, petroleum products still account for about 90% of total transportation sector energy use (1–3). In other developed countries, such as the European Union member states, transportation sector CO2 emissions have fallen to levels seen before the Great Recession, while those from the largest emitter, the electricity sector, has fallen 16.8% (4). Since LDVs contribute to nearly 60% of U.S. transportation’s GHGs (5, 6), electrifying these vehicles will translate into significant reductions in emissions, even if other behaviors persist¹ (e.g., rising VMT and SUV popularity).

Absent further federal and state decarbonization support (e.g., higher vehicle registration fees, fuel economy requirements, gas taxes, and PEV incentives), local governments can look at compact transit-oriented development, building efficiency requirements, parking fees, and behavioral nudges toward shared, electric, and active transportation modes. However, such strategies cannot deliver the deep and relatively rapid decarbonization benefits that come with PEV use and a renewables-reliant power grid (8–10) — which is necessary to stay below 1.5°C warming (11). Moreover, the COVID-19 pandemic’s effects on location and travel choices may inhibit greater transit use, vehicle occupancies, 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 (12). Since tailpipe emissions move upstream with PEVs², the power sector carries increasing responsibility for decarbonizing. Though this sector is under increasing governmental directives (or pledges) to transition to renewable energy (13, 14), future grid emissions are uncertain and depend on more stringent policy directives and technological advances.

As lithium-ion battery (LIB) prices continue to fall (15, 16), projections suggest that new U.S. BEVs may soon reach cost parity in purchase price with internal combustion engine vehicles (ICEVs) (mid-2020s for 150 to 200-mile BEVs and late-2020s for 250 to 300-mile BEVs (17, 18)). 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 (19)), 4.9% in China, and 3.5% in Europe³ (20). 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. (21). While PEVs’ environmental benefits⁴ will depend on driver behavior, charging patterns, and the carbon intensity of local grids, most governments only focus on the number and type of PEV adopted and designing incentives to reach those targets (23, 24).

¹ One study determined that a feasible transportation pathway to stay below 1.5°C is a combined 20% reduction in VMT and the electrification of 70 million passenger cars (PCs) by 2030 (to reduce emissions by at least 45%) (7).
² Both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are types of plug-in electric vehicles (PEVs). PHEVs have an electric motor and an internal combustion engine, whereas BEVs only use a battery system. Most PHEV drivers can complete their daily trips on battery-depletion mode and not use gasoline.
³ There is high variability in Europe by country – in Norway, BEVs are over 55% of new vehicle sales at the time of this report.
⁴ Argonne National Laboratory’s GREET model simulates energy use and emissions from different vehicle and powertrain combinations using a joint fuel-cycle model (i.e., well-to-wheel (WTW) for fuels) and vehicle-cycle model (i.e., raw material mining to disposal for vehicles). A 54-kWh Tesla 3 reaches carbon parity with a Toyota Corolla ICEV within a year on an average U.S. grid where coal supplies 23% of electricity (22).
Moreover, some regulations meant to incentivize PEVs have weakened carbon accounting by using sales-averaged CO₂ emissions that are diluted by PEV policy incentives (e.g., super-credits) and omitting charging emissions (i.e., leakage effect) (25). Carefully designing incentives to prevent the regulatory dilution effect is not only necessary as the number of PEVs increases but including the true emissions for PEVs may incentivize more managed charging programs. Aligning charging with renewable energy has the potential to further reduce transportation emissions, while providing co-benefits for the power sector’s decarbonization. PEVs can be treated as distributed storage devices, especially since vehicles are parked 95% of the time, on average (26). Changing charging profiles from home-dominant charging to grid ‘opportunistic’ charging can reduce renewable curtailment, better balance supply and demand, and lessen the need for stationary energy storage for grid reliability (27–29). Once PEV owners scrap their vehicle or replace the battery at the end of its warranty period (often 10 years), the battery pack can still have upwards of 70–80% of design capacity (30, 31). Repurposing scrapped battery packs for stationary storage is a sustainable downcycling approach that can increase life-cycle emission benefits, afford society time to commercialize LIB recycling, and lessen supply-side constraints of cobalt and other critical minerals (32–34). These two strategies, managed charging and second-life battery use offer further decarbonization benefits that should be pursued in conjunction with EV adoption targets and appropriate policy support.

The existing literature lacks a comprehensive review of environmental benefits (if studies mention them at all) and co-benefits of managed charging and second-life energy storage (B2U-ESS). As a result, policymakers have not considered measuring charging emissions and the benefits of downcycling battery packs in creating policy incentives to decarbonize transportation through vehicle electrification. The purpose of this paper is to assemble individual studies to (1) better understand and quantify environmental benefits and co-benefits and (2) explain how both transportation and power sector professionals can work together to achieve these benefits.

**MANAGED CHARGING**

Managed charging (MC)⁵, is a demand-side management (DSM) strategy that seeks to optimize the added PEV loads on the grid according to some objective strategy (like peak shaving). Peak shaving may indirectly be controlled in the form of demand charges or controlled by a utility toggling power. MC strategies can be categorized from a PEV fleet operator’s perspective into centralized control, transactive control, and price control (Figure 1). 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 or demand charges) to vehicles to nudge charging decisions.

Although these three control strategies (35) are for fleet operators rather than grid operators (36), the two perspectives can be in harmony (37) if the charging infrastructure, incentives, and strategies align. A commercial fleet operator 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 household vehicles are more responsive to convenience-based charging, followed by cost-minimization (38).

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 (37). In contrast, decentralized control such as tiered TOU pricing may unintentionally create an EV peak load at

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⁵ Also known as smart charging, coordinated charging, or V1G.
the start of off-peak pricing if not coordinated across vehicles (38). EV-specific charging incentives may shift loads better than TOU rates (21) and can lower emissions if time-dependent pricing incentives are designed to support RES generation (39, 40).

![Managed charging strategy directional flowchart of information (based on (35)).](insert_image)

In general, this paper defines MC to be when the utility or another third-party controls charge scheduling through communication signals or by offering financial incentives to charge at off-peak periods (35). 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 (41). Interested readers are referred to (42) for detailed information about MC standards, requirements, and nuances in PEV-grid integration. Further, household meters cannot accurately detect or quantify Level 1 or 2 charging events\(^6\) without an added sub-meter (43), nor can chargers know the driver’s mobility needs and departure time requirements, necessitating a separate communication protocol. Thus, most pilots devise an app-based interface system for drivers or random nighttime charge scheduling with a pre-set departure time. Programs are typically designed to manage the added EV load by adopting an off-peak TOU price incentive or a utility-controlled peak shaving demand response event with an incentive. Although off-peak periods may naturally align with high renewable output, like nighttime wind in Austin, Texas, these programs are not designed to lower the charging emissions (44).

The literature finds that prospective and current PEV owners are more sensitive to price incentives than any other savings (even renewable savings) when engaging with MC over an unmanaged approach (45–49). Those with MC experience are more willing to continue, including those in a utility-controlled MC program. Still, the majority of owners prefer having an opt-out/override option for MC to ease charging anxiety of not having enough range when needed (47). During an MC pilot with 700 UK drivers, 67% did not request to opt-out when notified by app of a peak load shaving event. Moreover, only 20% of participants were responsible for 90% of these opt-out requests. Participants with long-range BEVs were more likely to opt-out (48). In a Toronto MC study of 30 PEVs, up to 80% of the evening PEV load could be cut during DR events and still meet owner-set departure times (50).

Environmental Benefits & Co-Benefits of Managed Charging

Though many studies examine theoretical peak load reductions, system-optimal MC of EVs, or willingness to participate in MC programs, there is a lack of literature exploring the environmental benefits of MC. Benefits most often come in the form of absorbing RES and reducing peak loads (and thus more expensive peaker fossil-fuel power plants). Co-benefits also come by deferring

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\(^6\) 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.
There are two approaches that most studies take in deriving the environmental benefits of managed PEVs. The first approach uses least-cost electric grid resource dispatch models (e.g., HiGRID or PLEXOS) by adding PEV loads to the net load. Then the model attempts to find the minimum grid resources necessary to meet load requirements and return values like levelized cost of electricity (LCOE) and grid emissions. Table 1 summarizes the study methodology and key inputs used in this first approach. The second approach is to pair historical travel survey data, real-world mobility and charging data, or synthesized travel behavior from an agent-based travel demand model with grid emissions factors to understand emission benefits. The difference here is the priority on the transportation or grid model, though some attempt to integrate the two fields (51).

Priority on Grid Resource Dispatch Modeling

One study explored the energy storage benefits of an optimal MC program for California in 2030 and 2050 (52). The MC strategy, defined as minimizing the net load on the statewide power grid, increased 2050 RES penetration from 56.7% with unmanaged charging to 73% to align charging with solar generation. A scenario with bi-directional vehicle-to-grid (V2G) 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 given the limited scale of this technology and uncertainty about drivers’ willingness to participate in V2G due to range anxiety and shortened battery life (53).

An expansion of (52) compared the economic and emissions benefits of both decentralized and centralized MC of PEVs (37). The strategy here minimized individual charging costs and system-wide electricity costs, respectively. The decentralized MC strategy can result in equivalent CO₂ savings, minimum feedstock capacity requirements, and LCOE as the centralized MC when the grid receives predicted EV loads no more than every two hours. This study assumed that all vehicles are long-range (68kWh), and Level 2 charging (10kW) is available at home and work locations. Vehicle uniformity and universal charging is not realistic for most regions even though BEVs are preferred to PHEVs, and public charging growth remains steady.

Another study considered how MC (50% and 100% of 3M PEVs) benefits a grid with a 56% RPS compared to unmanaged charging using two grid scenarios (i.e., high solar & minimum mandated storage buildout vs diverse RES with 2x the storage capacity) (54). They found a 3–8% savings in production costs ($210–$660M) and a 3–5% reduction in grid CO₂ emissions due to a 13% reduction in curtailment. When all PEVs are managed, 95% of the PEV load is supplied during working hours, necessitating a minimum of 3.8M workplace/public charging stations in California. Since parked PEVs are connected to a charger but not necessarily charging, the lifetime cost for each charge must be less than $1,000 to reach break-even (assuming a grid with high solar & minimal stationary storage and 10-year charger lifespan).
### TABLE 1 Summary of main studies investigating environmental and co-benefits of managed charging with a priority on grid resource dispatch modeling

<table>
<thead>
<tr>
<th>Reference</th>
<th>Methodology</th>
<th>Key Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(52)</td>
<td>HiGRID balancing generation module dispatches generating units for statewide grid load profile based on EV charging load dispatch, renewable generation model, and system load demand. • Post-process calculation of renewable penetration</td>
<td>• CAISO load data • Renewable generation mix • BEV efficiency (NREL FastSim), PEV composition Forecast, EVSE parameters, Charging strategies</td>
</tr>
<tr>
<td>(37)</td>
<td>HiGRID balancing generation module dispatches load-following and peaking power plant units for statewide grid load profile based on EV MC dispatch strategy (centralized versus decentralized), renewable generation model, and system load demand. • Post-process calculation of GHG, NOx, and LCOE</td>
<td>• 2009 NHTS Data • Load data and renewable generation mix (CA E3 PATHWAYS Straight Line Scenario) • BEV efficiency, EVSE Parameters, Charging Algorithm</td>
</tr>
<tr>
<td>(54)</td>
<td>PLEXOS dispatched generating units across the WECC area but focuses on CA dispatch, loads, and constraints. • Post-process calculation of renewable curtailment, CO2, total system costs, and EVSE installation requirements</td>
<td>• 2009 NHTS Data • Renewable generation mix • Annual PEV Load • CEC Load &amp; non-CA Load Forecast • Charging strategies</td>
</tr>
<tr>
<td>(51)</td>
<td>BEAM agent-based travel demand model outputs utility-maximizing PEV charging sessions (max kW and total kWh) based on EVSE availability, costs, and mobility needs. • PLEXOS dispatches generating units across the WECC area but focuses on CA dispatch, loads, and constraints. • Post-process calculation of renewable curtailment, CO2, total system costs</td>
<td>• BEAM travel inputs (NREL SERA model for PEV Composition and Characteristics, ChargePoint EVSE locations, MTC &amp; CARB VMT) • CEC Load &amp; non-CA Load Forecast • Renewable portfolio • Charging strategies</td>
</tr>
<tr>
<td>(29)</td>
<td>V2G-SIM estimates load shifting potential of PEV loads through valley-filling and peak-shaving objectives. • SWITCH model develops statewide feedstock investments based on EV charging load, system load scenarios, and power plant constraints. • GridSim model minimizes grid operations while ensuring RPS goals are met based partially on MC strategies. • Post-process calculation of renewable curtailment and deferred stationary energy storage</td>
<td>• CEC Load • CEC PEV Composition &amp; Characteristics Forecast • 2017 NHTS Data</td>
</tr>
</tbody>
</table>

Abbreviations not previously used (aside from modeling acronyms): CAISO = California ISO, CEC = California Energy Commission, CARB = California Air Resources Board, EVSE= Electric Vehicle Supply Equipment (i.e., charger), WECC = Western Electricity Coordinating Council, MTC = San Francisco Bay Area Metropolitan Transportation Commission
An integrated transportation-power sector model obtained the economic and curtailment benefits from PEV MC strategies (51). An agent-based simulation of San Francisco Bay Area PEV drivers provided maximum power and total energy per charging session for an unmanaged base case. PEV loads were added to PLEXOS to study curtailment, carbon emissions, and operating costs for both utility-controlled MC and TOU pricing (assuming a 50% RPS in 2025 and 0.95–5M PEVs adopted). The utility-controlled MC strategy toggled power flow within each charging session (versus over a day) to minimize statewide dispatch costs. Up to $690M could be saved in statewide operating costs by lowering peak loads, the frequency of dispatching expensive generators, and shifting more PEV load to RES. As a result, total curtailment is reduced by 40% (about the annual energy of 39K U.S. homes) — which is sizeable given a 50% RPS and just 5M PEVs. An overnight TOU pricing policy can reduce charging costs but leads to the most curtailment. This is problematic for California with a more dramatic ‘duck curve’ net load profile each year, which leads to more peaking demand. Unlike other studies, this study used a utility-maximizing charging model to increase realism of when and where drivers charge their PEVs.

The latest 60% RPS by 2030 target with both V1G and V2G was used to study the deferred infrastructure investments of stationary storage (29), expanding upon similar studies by (51, 55). They found that MC (V1G only) with 3.3 million PEVs in California is equivalent to a nearly $16 billion investment in storage, offering more GWh of energy than what was produced by solar in 2019 (equivalent to 14.2% of the then in-state generation portfolio) (56).

**Priority on Modeling with Real-World Travel Datasets**

A study across all eight North American Electric Reliability Corporation (NERC) regions estimated how MC might minimize CO₂ emissions (57). Loads were derived from daily driving distances in the 2009 National Household Travel Survey (NHTS), grid carbon intensity was taken from summer and winter monthly marginal emission factors (MEFs), and four charging scenarios were considered: pre-timed (daytime public/workplace charging (12 pm +), evening post-work charging (6 pm +), and overnight charging for grid valley-filling (12 am +)) charging, and MC. Over a vehicle’s lifetime (100K miles), MC could reduce between 8–39% of charging emissions relative to pre-timed charging, depending upon the region and PEV type. The use of V2G could further increase emission reductions by up to 59%.

CO₂ reduction estimates are inherently region-specific. A Toronto metro area case study estimated PEVs could have up to 97% lower life-cycle GHG emissions compared to gasoline-powered ICEVs, but nuclear and hydroelectric plants power over half of the regional grid (58). If MC is not pursued at scale and motorists are not able to charge mid-day in solar-rich regions, 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 (59).

Some initial MC pilot programs examining PEV effectiveness during demand response (DR) events have been examined to include emissions savings. A joint utility-auto manufacturer\(^7\) study estimated the carbon reduction impact of 400 PEVs (60). If all chargers were utility-controlled and were accessible at all destinations, the PEVs in the study 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. The study also reports that if 40% of the load from the expected 5M California PEVs in 2030 were managed, it could eliminate the need for curtailment by absorbing 2,400 GWh of renewables (equal to the annual energy demand of 231K US homes).

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\(^7\) Also called original equipment manufacturer (OEM).
SECOND-LIFE BATTERY USES

Electrification of LDVs alone will not eliminate transport emissions. Increasing renewable
generational capacity with MC can provide synergies for the grid, which has increasing
responsibility in decarbonizing transportation emissions in the future. MC can help to alleviate
distributional grid strains and defer investments in stationary storage. The latter is critical if both
the transportation and power sector sharply increase their demand for batteries under aggressive
decarbonization targets (61). One bottom-up modeling approach has suggested mineral demand
for clean technologies in 2040 could be 4–6 times 2020 demand (34). Moreover, existing and in-
development mines could only meet 50% of the expected 2030 lithium and cobalt demand and
80% of copper demand.

At the same time, the global stockpile of used PEV batteries could exceed 3.4M by 2025,
compared to just 55K in 2018 (62). Globally, PEVs may represent 58% of new PC sales in 2040,
most of them BEVs, ensuring a large supply of used batteries in the future (63). In the US, 40% of
new vehicle sales are in states with California’s zero-emission vehicle (ZEV) mandate, and three
states have expressed interest in joining in 2020 (64). As PEV sales continue to increase across the
US, more regions will see an increase in the supply and subsequent market for battery downcycling
in the coming decades. By 2030, worldwide utility-scale LIB-storage demand may reach 183 GWh
annually, with an estimated annual second-life PEV LIB supply of 112–227 GWh (65).

As an alternative to landfiling or recycling, downcycling of used PEV batteries can capture
residual capacity in the batteries for second-life battery use in energy storage system (B2U-ESS)
applications before recycling or other end-of-life disposal practices. Downcycling is a concept
from the circular economy sustainability field wherein a product is re-assembled and repurposed
to a new purpose of lesser value. In this application, B2U-ESS is an intermediate product between
the original PEV battery and products from a battery recycling plant (Figure 2). Although research
is ongoing to develop cost-competitive battery recycling processes (e.g., US ReCell Center and
UK RELiB project), repurposing may buy time until recycling is more efficient and lead to net
economic savings (33, 66). Moreover, the market for repurposing is large, given that recycling
accounts for less than 5% of the LIB waste stream (67).

FIGURE 2 Battery life-cycle stages with new B2U-ESS (blue = current system, green = B2U-ESS component).

8 Other battery types exist beyond Li-ion, such as NiMH, but are less common.
The sustainability advantage of downcycling is three-fold: the embodied carbon of the existing PEV battery pack is extended over several more years, using repurposed battery defers the environmental cost of creating a new battery pack (e.g., mine-to-outlet), and B2U-ESS can minimize emissions at essentially zero carbon cost (since the battery would otherwise be retired\(^9\)). The embodied carbon of batteries ranges from 61–106 kg CO\(_2\) equivalent per kWh (68), with original manufacturing accounting for 40% of embodied carbon (69, 70). In addition to avoiding manufacturing emissions in new BSS, the environmental\(^10\), social, and natural security concerns of raw materials can be reduced. When using repurposed PEV battery packs for energy storage, the only added emissions come from battery testing, reassembly, and transportation. Relative to an ICEV, a BEV battery with second-life energy storage use can reduce GHG emissions by 56% over an expected 18-year lifespan (71).

**Pilot Projects & Power Sector Use Cases for Second-life BSS**

Early studies projected the first uses of B2U-ESS would be 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\(^11\) (72). Several proofs of concept are ongoing to understand system architecture, performance, costs, and effectiveness of battery testing. In addition to these laboratory-focused studies, pilot projects integrated with the grid range from BTM uses for energy arbitrage and resilience up to grid-scale energy storage.

Smaller pilots include powering select streetlights in Japan, elevators in Paris, and a data center in Michigan (73, 74). The Michigan pilot includes five 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 backup power (30). Another pilot not only ties two BSS units with RES, but also with 22 BEVs and V2G-enabled chargers. The complexity of this pilot is achievable due to the scale (an island) and urgency with transitioning from imported natural gas to renewables (75). A minor component to the second joint utility-OEM study in California was the installation of four BTM 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 (60). 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 microgrid\(^12\). 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 (77, 78). Table 2 summarizes several pilot locations with known BSS capacity/power and purpose where information was publicly available.

**TABLE 2** Summary of known second-life BSS pilots and key characteristics

<table>
<thead>
<tr>
<th>Location</th>
<th>Opened</th>
<th># PEV Batteries</th>
<th>Power (MW)</th>
<th>Capacity (MWh)</th>
<th>Purpose</th>
</tr>
</thead>
</table>

\(^9\) This bears some resemblance to carbon credit schemes that pay landowners not to log or develop forests.

\(^{10}\) For example, it can take up to 750 tons of mineral-rich brine to produce 1 ton of lithium, affecting water availability in mining regions (33).

\(^{11}\) Early LIBs had a 7- to 10-year and 100,000-mile warranty, with test results indicating battery degradation to 70–80% of design capacity (30, 31). Recent data from Tesla BEVs suggest improved battery design and heat flow management could limit deterioration to 90% of the original capacity (68).

\(^{12}\) Microgrids are interconnected with the larger grid but can operate independently. They are used to integrate small RES, lower electricity costs, and provide backup power (76). B2U-ESS is a type of distributed energy source (DER), alongside rooftop solar, microturbines, and V2G-enabled PEVs.
<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Capacity</th>
<th>Efficiency</th>
<th>Utilization</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Francisco, USA</td>
<td>2012</td>
<td>5</td>
<td>0.025</td>
<td>0.05</td>
<td>RES integration</td>
</tr>
<tr>
<td>Osaka, Japan</td>
<td>2014</td>
<td>16</td>
<td>0.6</td>
<td>0.4</td>
<td>RES integration</td>
</tr>
<tr>
<td>Yellowstone, USA</td>
<td>2014</td>
<td>208</td>
<td>-</td>
<td>0.085</td>
<td>-</td>
</tr>
<tr>
<td>Milford, USA</td>
<td>2015</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>RES integration</td>
</tr>
<tr>
<td>San Francisco, USA</td>
<td>2015</td>
<td>8</td>
<td>0.1</td>
<td>0.225</td>
<td>DR</td>
</tr>
<tr>
<td>Davis, USA</td>
<td>2016</td>
<td>864</td>
<td>0.06</td>
<td>0.26</td>
<td>MG</td>
</tr>
<tr>
<td>Elverlingsen, Germany</td>
<td>2016</td>
<td>1,878</td>
<td>20</td>
<td>21</td>
<td>GF</td>
</tr>
<tr>
<td>Hamburg, Germany</td>
<td>2016</td>
<td>2,600</td>
<td>2</td>
<td>2.8</td>
<td>GF</td>
</tr>
<tr>
<td>Indianapolis, USA</td>
<td>2016</td>
<td>-</td>
<td>0.05</td>
<td>0.015</td>
<td>-</td>
</tr>
<tr>
<td>Lünen, Germany</td>
<td>2016</td>
<td>1,000</td>
<td>12</td>
<td>12.8</td>
<td>GF</td>
</tr>
<tr>
<td>Malaga, Spain</td>
<td>2016</td>
<td>4</td>
<td>-</td>
<td>0.0372</td>
<td>RES integration</td>
</tr>
<tr>
<td>Aachen, Germany</td>
<td>2017</td>
<td>6</td>
<td>-</td>
<td>0.096</td>
<td>-</td>
</tr>
<tr>
<td>Paris, France</td>
<td>2017</td>
<td>12</td>
<td>0.144</td>
<td>0.192</td>
<td>EA</td>
</tr>
<tr>
<td>Paris, France</td>
<td>2017</td>
<td>-</td>
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Abbreviations not previously used: GF = Grid Frequency, PS = Peak Shaving, BP = Backup Power, EA = Energy Arbitrage, and MG = Microgrid use

Environmental Benefits & Co-Benefits of Second-Life BSS
While initial studies examined the economic justifications, environmental benefits, and logistical barriers of B2U-ESS (31, 71, 79–81), more recent work has proposed life-cycle assessment (LCA) methods to study the emissions of PEV batteries with B2U-ESS. In addition to this LCA approach, others have estimated the emission reduction potential of BSS pilots or maximum savings under optimization-based scenarios. Similar to the MC benefits, B2U-ESS benefits come in the form of supporting RES, smoothening loads, providing grid storage to offset peaker power plants, and load shifting as a means to lower the environmental footprint of electric batteries (82, 83).

LCA Approach to Benefits of BSS
Using an LCA approach can help to understand how second-life applications can provide environmental benefits, but they can yield differences in estimates due to methodological differences. These include LCA system boundaries (e.g., geographical differences in embodied carbon and life-cycle stages), the scope of the downcycling system (e.g., BTM purpose versus grid-scale storage), and ranges of assumptions that influenced previous studies (83). They found...
few carry out energy modeling of the second-life BSS phase, partially due to limited collected data on this stage. One study found a possible 25% reduction in GHGs from second-life BSS applications (32). However, they did not consider repurposing energy costs (e.g., collection, testing, assembly), which would have a negative impact (83). Others focused on the electricity mix’s impact on the two use stages of PEV battery packs (82, 84). The latter found environmental benefits accrue only when the BSS is paired with RES, given efficiency loss and the potential for the battery to store electricity during carbon-intense periods and discharge during low-carbon times. A similar methodology compared a repurposed LIB to a new lead-acid (PbA) BSS, which could be applied to a hypothetical new stationary storage project (85). Downcycling the LIB reduced the global warming potential (GWP) by 15–70%, depending on the repurposing energy requirements and condition of the packs. 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 (69). When the repurposed BSS is grid-connected to a house with a rooftop photovoltaic (PV) array, up to 57% reduction in GWP is possible compared to using a new BSS (83).

**Simulation Modeling of Different BSS Use Cases**

A joint BSS-grid operational model was proposed to capture thermal effects and degradation of the BSS while the grid models the displacement of fossil-fuel generation due to BSS (86). Starting at a base year of 2015, the model projected the supply of spent PEV packs based on different adoption curves and PEV disposal assumptions. The second life uses cases include storing decentralized solar and wind, respectively, and a joint centralized solar and wind scenario. Due to the scope of this study, it is the first study known to the authors to include transportation costs in a model with realistic geographies13. They estimated that repurposed batteries could provide 5% of California’s projected electricity demand in 2050, offsetting 7 metric tons of CO2 equivalent (MtCO2e) per year (about 1.5% of the state’s current total emissions per (73)).

Another study compared the economic and environmental differences in using second-life LIBs to new LIBs under three use cases: utility-level PV integration, utility-level peak shaving, and residential BTM storage (87). To account for regional variations in carbon intensity, the study measured effects in five US cities. A net present cost energy system model (Homer Pro) found the optimal power system (including capacity, energy charged/discharged). The GWP of the batteries was calculated using grid fuel feedstocks and power decision variables from the energy model. Since the optimal system for each scenario was based on the lowest annualized net cost, homeowners adopted second-life LIBs to better use rooftop PV, which could decrease emissions by 22–51% compared to no BSS. Compared to using new LIBs, the carbon emission savings ranged from 7–31% across all scenarios when on-site storage was economically justified.

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 one possible reason for increased GHGs with B2U-ESS (88, 89). The carbon benefits are greatest when the system is integrated with RES and lessens the need for peaker plants. The theoretical annual GHG savings of residential BTM BSS for homes with and without rooftop solar from a dataset of 45 metered

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13 The study sited repurposing facilities through a facilitation location problem (i.e., maximum coverage location problem) across California weighted by the number of spent PEV batteries per county, assuming they are collected only at car dealerships. Batteries were sent to decentralized RES sites according to the share of generation.
Austin, Texas homes was estimated in (90). Homes with solar lessened their carbon footprint by over 2.67 tons, which was a nearly twenty-two-fold carbon saving compared to homes solely using the BSS with stored low-carbon grid electricity. To reach break-even with an expected 10-year lifespan of repurposed LIBs, there would need to be low upfront costs to the system and an economic incentive to install the system (e.g., carbon pricing, peak shaving, rebate).

**DISCUSSION**

The urgency in reaching carbon neutrality to limit global warming to 1.5 °C above pre-industrial levels and transportation's dependence on petroleum motivated a review of decarbonization benefits afforded by PEVs. Government targets and policy interventions have sought to increase PEV adoption, especially to nudge early adopters through various demand and supply-side approaches (23, 24, 91). However, with growing PEV adoption in countries like Norway, there is an urgency to examine how to further decrease CO₂ emissions, both in the transportation and electricity sectors. This study reports the benefits of both MC (focusing on V1G) and second-life applications of PEV batteries in stationary storage. There are clear environmental and co-benefits for both sectors when these two strategies are pursued.

MC can provide several ancillary grid services such as demand response, peak shaving, and valley filling. Environmental benefits come from aligning charging load with low-carbon periods, such as midday in California or nighttime in Texas. CAISO reported a curtailment of 961 GWh 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 (92). Shifting unmanaged PEV load from peak periods can decrease the need/use of natural gas peaker-power plants. A study using real-world mobility and charging data from San Francisco Bay Area drivers estimated that MC could reduce charging emissions by a third if chargers are available at all destinations (60). When PEV loads are added to a wholesale power dispatch model such that vehicles serve as a flexible grid resource when parked, California’s grid emissions could fall by 3–5% in 2030 (with an existing 56% RPS), but this relies on 3.8M additional public chargers (54).

Studies also indicate that MC of PEVs can defer multi-billion-dollar investments in stationary storage (29, 51, 55). Communities and policymakers would be wise to subsidize the installation of V1G-enabled chargers through savings in deferring stationary storage investments. Due to RES portfolios and weather patterns, shifting PEV loads may require different EVSE infrastructure outcomes. If the region has significant nighttime wind (e.g., Texas), expanding residential charging is necessary. EV-ready policy in building codes or monetary incentives like rebates and tax credits for charger installation by property type can align charging with RES (93, 94). On the other hand, 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 (60).

Since the purchase-price parity of PEVs with ICEVs in the U.S. is expected within the decade, vehicle and EVSE incentives could transition into MC incentives to alter charging habits (15, 17). Additional research is necessary in understanding best practices of utility-controlled MC since the alternative, TOU pricing, can lead to significant curtailment. Pursuing MC will require OEMs and EVSE suppliers to develop interoperable and open-source charging protocols across a range of vehicle types and charging equipment. For more information on communication protocols, interested readers are referred to (42).

While policymakers pursue MC, continued investment in end-of-life disposal is necessary. Less than 5% of LIBs are recycled compared to more than 95% of PbA batteries. In addition to significant investment in developing commercial LIB recycling methods to capture critical...
minerals (95), further research into battery state of health testing, standardization of battery sizes and identification barcodes, and collection schemes can prepare the nascent reuse and recycling industry (33). The number of exploratory pilot programs repurposing PEV batteries BTM (a few kWh) or at utility-scale (up to 40 MWh) is increasing. Partnerships between OEMs, utilities, and third-party researchers have been the driver behind these schemes, and one may expect that OEMs play a role in battery collection schemes by coordinating with dealerships and scrapage yards.

Applications have historically centered primarily in BTM storage due to sourcing issues, but utility-scale projects in Europe are advancing, primarily in countries with high electricity costs, strong climate targets, and auto agglomerations. B2U-ESS achieves 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 the 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 (83, 96) since few studies examine the environmental benefits exclusively and those that do vary in the LCA scope. Obtaining real-world second-life energy use data can be paired with grid emissions factors to improve current LCA methodologies.

In addition to carbon emission benefits, downcycling batteries may help to reduce supply-side constraints in the push to decarbonize both transportation and electricity sectors together. One estimate found that only half of lithium and cobalt required in 2030 decarbonization plans can be supplied with existing and planned mines (34). Utility-scale LIB storage demand may reach 183 GWh in 2030 and match an estimated supply of second-life PEV LIBs (112-227 GWh) (65). Though some faulty battery packs would be discarded in the assembly phase of the B2U-ESS system, repurposing spent batteries may lessen the demand for raw minerals that goes to stationary energy storage and preserve minerals for PEVs.

In summary, the studies cited used different methods to obtain environmental and co-benefits associated with MC and B2U-ESS technologies. Scientists should be aware of limitations and strengths associated with each approach when making generalizable assumptions about the pathways to net zero. In the MC field, there are integrated transport-power dispatch models, while others prioritize their respective sectors. Regardless of the model used, assumptions on charging behavior and vehicle characteristics are not trivial. There is evidence that motorists prefer to charge at home, and models that assume charging where EVSE is available or that workplace/public charging will be available all the time will obtain environmental estimates that are practically infeasible. However, the studies suggest maximum attainable benefits under certain investments in EVSE and charging incentives. In the B2U-ESS section, different LCA approaches, and assumptions had a similar effect on GHG and GWP reduction estimates.

CONCLUSION
This study highlighted U.S. case studies and characterized transportation-related emissions in the U.S. Wherever possible, perspectives from other developed countries were used, though lessons learned from the U.S. are often transferrable to other states. For perspective, the transportation sector accounts for 23% of globally energy-related CO₂ emissions and is often in the top two largest emitting sectors in developed countries (11). As a sector, petroleum products provide 92% of the final energy demand for the wide range of modes, suggesting challenges for decarbonization targets (97). PEVs offer decarbonization benefits from enhanced energy efficiency (3x that of ICEVs) and less carbon-intense fuel, which will improve as the electricity sector decarbonizes.
Although there are numerous policy incentives designed to encourage the adoption of PEVs, there is little emphasis on measuring the decarbonization benefits of these vehicles once purchased. Policymakers should look closely at charging emissions, not only to obtain more accurate carbon budgets but also to use PEVs to restructure the interaction between the transportation and electricity sectors. MC of PEVs can reduce the curtailment of renewables, shift the additional load to avoid the use of peaker power plants, and possibly make tailpipe emissions truly carbon-free. Investments in charging equipment in locations where parked vehicles can absorb time-dependent renewable energy can offset investments in stationary energy storage systems and preserve critical raw materials for the transition to PEVs. At the same time, investing in downcycling of PEV batteries, first in repurposing and later in recycling, will sustainably manage this new waste stream. The anticipated supply of used PEV batteries for transportation is expected to align closely with the demand for utility-scale LIBs, offering a pathway for second-life batteries to decarbonize the electricity grid.

It is wise to move beyond PEV adoption targets and traditional policy levers to achieve deep decarbonization benefits. Aligning subsidies in charging infrastructure with MC incentives is both economically and environmentally justified. Developing a sustainable end-of-life management ecosystem for PEV batteries can capture the remaining capacity of batteries after their transportation use and provide years of benefits for the grid. In pursuing these two strategies, perhaps the world can have plentiful, carbon neutral travel.

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AUTHOR CONTRIBUTION STATEMENT
The authors confirm contribution to the paper as follows: Matthew Dean: conceptualization, methodology, investigation, writing – original draft, review & editing. Kara Kockelman: supervision. All authors reviewed the results and approved the final version of the manuscript.
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