Technical Report
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Vehicle-to-Grid Fleet Demonstration Prototype Assessment

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7 June 2018

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LEXINGTON, MASSACHUSETTS

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EXECUTIVE SUMMARY

The DoD Vehicle-to-Grid (V2G) pilot program aimed to explore the challenges, impact, and benefits of selling the services of fleet electric vehicles to the commercial power grid as energy storage assets in the ancillary services market. Ancillary services are used by the system operator to balance the instantaneous frequency on the grid by manipulating the power output (and input, for batteries) of the asset. It is an ideal market for electrochemical batteries, requiring large power capacity but small amounts of energy overall. Batteries can supply large amounts of power quickly, handle bi-directional power flow (sending power to the grid and absorbing from it), and are more harmed by the total amount of energy supplied (depth of discharge of the battery) than instantaneous large swings of power.

Laurence Berkeley National Laboratory developed the hardware and software necessary to allow the fleet of vehicles to interface with the California Independent System Operator's ancillary services dispatch system. MIT Lincoln Laboratory investigated the impact of this additional usage on the lifetime of the batteries and explored the use of "second-life" batteries, batteries removed from electric vehicles and used instead as fixed storage assets. Some inaccuracy in the battery capacity was seen because measurements were made on the batteries using existing sensors, but no statistically significant grid-related degradation in the lifetime of the batteries was observed during the pilot program. An aging model of the batteries was also developed, but collected data was deemed insufficient to tune the model. Although payments for participation in the ancillary services market are currently low and require a large fleet of vehicles to participate, the basic overall concept was proven from hardware to payments received. V2G participation on each vehicle is currently limited by the capacity of the charging and inverter equipment connecting the battery to the grid rather than the battery itself.

Costly equipment, low payments, and an immature market result in thin margins and a possibility of losing money due to inefficiency losses in the battery-inverter system. V2G ancillary services do not appear to reduce battery lifetime, and future laboratory testing could be performed to confirm this, but the ancillary services and vehicle charger markets need to improve to fully use the potential of electric vehicles to buttress the nation's electrical grid.

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1. BACKGROUND

The nation has both a long-term economic opportunity and a growing national interest in reducing its dependence on oil. Replacing a portion of the nation's internal combustion vehicles with plug-in electric vehicles (PEVs) offers one promising way ahead. The technology is proven and multiple PEV models are available for purchase or lease. Upfront battery costs are still high, preventing rapid widespread adoption. However, PEV batteries can provide concurrent or second-life value that would greatly mitigate this challenge. The DoD is well-positioned to play an important leadership role by exploring and demonstrating a cost-effective approach to adopting PEVs within its non-tactical fleet that would include maximizing the use of PEV batteries through secondary applications. This role especially makes sense since PEV batteries can offer added value to the central DoD energy mission of cost-effectively ensuring the security of its critical missions either in the field or in the face of grid outages at fixed installations. The batteries do not necessarily need to support all the load power but can be used to ensure that under- or over-generation can be absorbed so that system voltage and frequency are within normal bounds.

Results from initial DoD PEV analyses indicate that PEVs using vehicle-to-grid (V2G) technologies can achieve significant cost savings for the DoD, compared with conventional vehicles, while providing additional military operational capabilities. The DoD has initiated a V2G pilot project that includes the following activities. Vehicles were selected to cover the range of types typically used in a base motor pool:

- Commercial purchase and lease of 32 PEVs with V2G capability, which consisted of:
  - Passenger vehicles
  - Light duty (LD) pick-up trucks
  - LD cargo/passenger vans
  - Medium/heavy duty (MD/HD) trucks and vans
  - Buses
- Development, procurement, and installation of V2G-capable charging stations (one charging station per PEV)
- Development and procurement of software to manage a V2G-capable PEV fleet
- Training for multiple DoD constituencies
- Sustainment and technical support for PEVs, infrastructure, and software
- Program management and systems integration

V2G activities use the PEV battery as an energy resource when the vehicle is not being driven. As an energy resource, the PEV draws revenue by providing services back to electrical utilities. The value of these services can be significant when management overhead is kept to a minimum. This programs looks to test out the overall validity and assumptions with a real-world demonstration.

Grid support ancillary services provided by the vehicles are regulation up (reg-up) and regulation down (reg-down). These ancillary services are dispatched by the grid operator in the Los Angeles area, California Independent System Operator (CAISO), to regulate the frequency of the grid. Regulation-up services are used to increase the frequency of the grid by adding power to it, and vice versa for regulation down. Day-ahead and real-time bidding is performed by the grid operator to ensure that they have adequate resources to balance the grid. Payouts are made for the $/MW bid into the market at the hourly price in per-hour increments regardless of whether the asset was dispatched, as well as for usage of the asset, called "mileage." CAISO requires a minimum of 0.5 MW of available assets to bid into the market, which necessitated interconnecting a fleet of electric vehicles into a single "virtual battery."

The overall Vehicle-to-Grid program has a long history and has endured several iterations as the overall scope was adjusted to better achieve project goals given changing funding amounts, assumptions, shifting market conditions, and project progress. In many cases, the size of the investment needed to design, test, and integrate a new technology was underestimated by DoD contractors, as well as individual vendors. During this descoping phase of the project, adjustments were made that reduced the data quality, as well as any subsequent resources available for iterating on the data collection methods. The project began five years ago, but full grid interaction at Los Angeles Air Force Base (LA AFB) was only in place on December of 2015. Concurrent Technologies Corporation (CTC) is the prime subcontractor on the project. CTC subcontracted FleetCarma to log on-board data from the vehicles. Kisensum was contracted to develop a server interface to dispatch the vehicle's bidirectional chargers in response to demand signals from the ISO (Independent System Operator), and vehicle availability. The data they collected from their server was then shared with MIT Lincoln Laboratory. Kisensum was also contracted at MIT Lincoln Laboratory's insistence to perform periodic state- of-health tests to track vehicle battery degradation over the duration of this experiment. During these tests, which are performed once per month on a Saturday at full power, the vehicle is fully charged at its maximum rate until full at 90% from its base condition, fully discharged to 20% state of charge (hereafter abbreviated SoC), and recharged back to 90%.

The vehicle fleet contains thirteen 2012 Nissan Leafs and one 2014 Phoenix ZEUS electric shuttle bus. The fleet also contained four EVAOS modified Ford F150 pickups, two 2014 EVI stake bed pickup trucks, two 2014 EVI box trucks, and ten 2014 Via Motors electric vans. The pickup trucks, vans, and box trucks experienced integration issues that caused the suspension of data collection for these vehicles partway through the experiment. This report will focus on the Nissan Leafs and Phoenix bus, as they consistently worked well and provided some usable data.

1.1 BATTERY DEGRADATION

Battery capacity loss is driven by the irreversible sequestration of lithium ions from the electrolyte of the battery [1]. As lithium is depleted over time, less lithium is available to shuttle charge between the anode and cathode and participate in electrochemical reactions, leading to a reduction in the amount of energy that can be stored in the battery and a reduction in its capacity. It is hypothesized [2] that the dominant driver of lithium sequestration is due to formation of lithiated solids at the electrolyte/anode interface (SEI, solid-electrolyte interface). Lithium intercalates into the porous graphite anode during charging, and flows out when discharging. Microscopic cracks can develop in these pores as they are cyclically loaded; expanding as they charge and contracting as they discharge, and it is in these cracks that lithium can permanently bond, leaving less lithium to store and transfer energy.

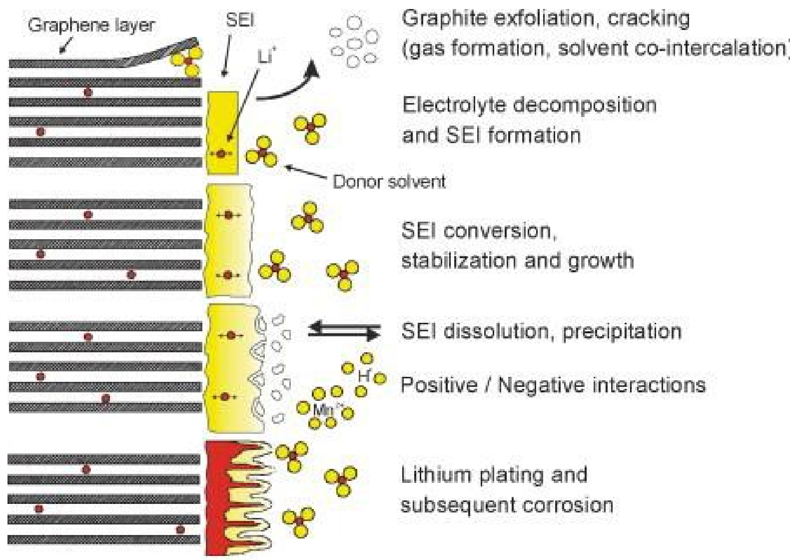

Figure 1. Changes at the anode/electrolyte interface. [1]

This is a process of mechanical fatigue; both the amplitude of the stress in each cycle and the rate that it is applied are important in how the performance of the batteries degrades. Consider the graphite as a pressure vessel loaded with internal pressure: the flow rate of lithium in and out of the battery, determined by the power (kW) in or out of the battery, drives the ramp rate of the stress, analogous to a quick inflation/deflation of the vessel. Deeper charge-discharge cycles (more total energy (kWh) released and absorbed) drive more material into and out of the pores, taking the vessel to higher pressure peaks and deeper valleys. The sequestration of the lithium, however, is an electrochemical process: increasing the temperature and voltage of the battery will increase the speed of this reaction and hasten the degradation of the battery [3]. The actual importance of each of these factors and their effect on battery lifetime depends on the chemistry of the battery in question and requires careful fitting of several parameters to accurate data recorded over the entire life of the battery [4]. Data gathered in this project is useful, but not complete enough nor long enough in duration to extrapolate battery lifetime.

Battery manufacturers combat this degradation process by limiting the depth of discharge of the battery, thereby reducing the amplitude of the cyclic stress process. Maximum power flow of the battery is a physical limit, driven by the speed at which the chemical reaction in the battery can proceed. The Nissan Leafs ship with a 24 kWh battery [5], limited to 21.3 kWh [6], and can discharge at a maximum rate of 90 kW or 3.75C [7]. Power in and out of the Leafs during grid participation is limited to 15 kW by the installed CHAdeMO charger, but high power flows in excess of 80 kW can occur when driving. The bus has a 105 kWh battery pack [8] with 25 kWh reserved (observed in data) and is charged and discharged at 40 kW by a DC Level III charger.

1.2 BATTERY MODELING AND PARAMETER ESTIMATION

The simple question of "does V2G affect battery life?" could be investigated by splitting the vehicle population into two categories with and without V2G, but for several reasons that was deemed non-optimal. The relatively small number of operational vehicles in the demonstration were all needed to be on grid to meet minimum energy thresholds required by CAISO. In addition, effects like part-to-part variation, measurement accuracy, and varied usage patterns all contributed to the decision not to proceed with a split A/B type test.

The team instead decided to develop a battery model that included several pieces. Lifetime, electrical, SoC, and thermal sections were developed. Each section had parameters that could be adapted to each individual type of vehicle and battery. Most parameters could be determined using datasheet values, but the lifetime model required fitting to existing data. The subsystems fed into each other, and together they could be used to approximate the impact of a given usage pattern on the lifetime of the battery. The model would also be useful in second life analyses, where usage patterns may differ or thermal cooling systems may differ. It should be noted that during operation it might not be possible to keep all external factors between the two groups the same.

System modeling is very beneficial, but requires truth data to tune and fit the model to. In the case of the lifetime model, this requires laboratory testing of an identical model of battery through its full lifetime with accurate measurement equipment. The model above has been generated and tested, but was not tuned with truth data to predict the lifetime of the batteries. None of the test batteries were taken through their full lifetime, as non-accelerated lifetime testing of the batteries would take years and no laboratory accelerated testing was performed. Collected data was too sparse, with an average of six state-of-health tests performed in 1.5 years on each vehicle, and too inaccurate, with a test-to-test spread of 7% to use as "truth" to tune the model. Therefore, the parameters were never fit to the data collected.

1.3 DATA COLLECTION OVERVIEW

During the first year of the project, MIT Lincoln Laboratory proposed, designed, and deployed a data collection system that consisted of an on-board data collection box (OBDC), shown in Figure 2. This approach was needed because project sponsors dictated that no DoD vehicle data should travel on networks outside the DoD perimeter, vehicle users should not have to interact with the data collection equipment, and the vehicles could not be modified in any substantial way. The box connected to the Controller Area Network (CAN bus) in the vehicle, collected data, and downloaded it over Power Line Communications to a network bridge on the other side of the charger. This system was deployed on one vehicle at LA AFB and collected data for a few months (see Figure 2). After that period, project sponsors decided that while this approach met all the initial requirements it was not affordable given the funds available. In addition, in their view such detailed data was not needed in order to analyze battery degradation.

Figure 2. The on-board data collection box was installed in a vehicle and relayed data to the charger when the vehicle was charging.

A commercial system, from FleetCarma, was identified that collected a reduced set of data and utilized existing commercial cellular networks for offloading the data. A portion of the prototyping work with the OBDC and the Nissan Leaf was fed into the FleetCarma efforts to improve the breadth of data that was collected. This change proved adequate but did entail additional effort to interface to yet another subcontractor before the data was available, transferred, and understood by the Lincoln Laboratory team.

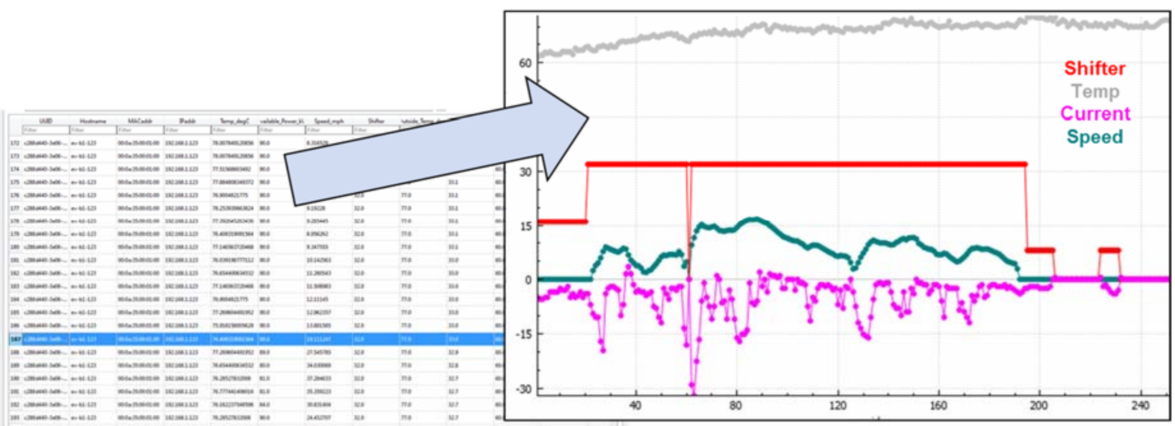

Figure 3. Data from the prototype OBDC box was collected for initial analysis.

There are four primary data sets collected during this experiment:

1. Internal vehicle data collected with loggers

2. External data gathered for each vehicle by its charger
3. Grid participation data, including the ISO's dispatch target and the site's net meter
4. Charger data gathered during specific state-of-health tests.

Generally, the internal vehicle data from FleetCarma shows driving and frequency regulation from the perspective of the battery, while the charger and ISO data capture frequency regulation market participation from the perspective of the system aggregator and ISO. The first data set is gathered and stored by FleetCarma, and the latter three by Kisensum. As previously mentioned, the vans and trucks proved difficult to work with by stubbornly refusing to cooperate with the dispatch controller and producing poor-quality data. They were removed from the site in the spring of 2017, and will be mostly omitted from this report. That leaves 13 Nissan Leafs (21 kWh) and one Phoenix electric shuttle bus (80 kWh).

1.4 DATA OVERVIEW

Vehicle data is logged internally by the on-board loggers; fields collected are dependent on the vehicle in question, but the important fields—battery pack voltage, current flow, battery pack temperature, and vehicle speed—are logged by all vehicles and are essential for any battery lifetime forecasting. Vehicle odometer and speed are logged on all vehicles to assess how far and how hard the vehicles are driven. Figure 4 is an example of FleetCarma vehicle data capturing a 44 mile round-trip commute.

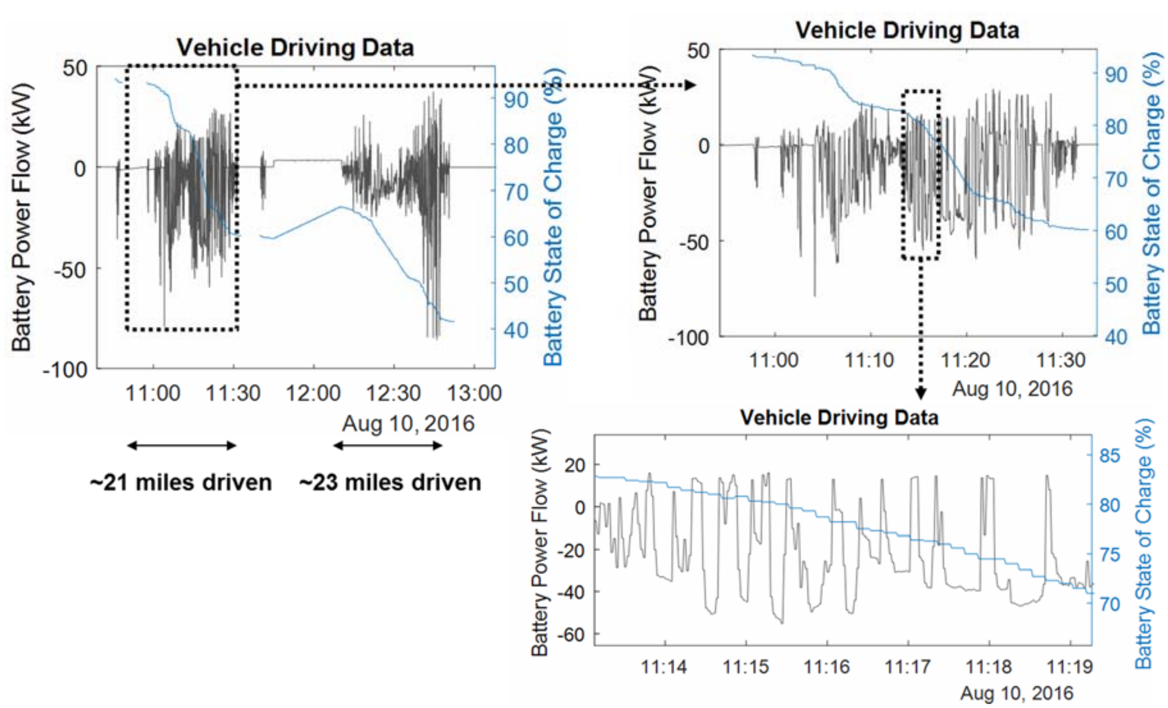

Figure 4. 12B80019 Leaf driving example data. Negative power flow (black) indicates power out of the vehicle's battery pack delivered to the motor. Positive power indicates regenerative braking action returning energy to the vehicle. Data was filtered for driving only; holes or gaps indicate a parked or charging vehicle.

The first 21-mile drive (11:00–11:30) consumed approximately 35% of the vehicle's battery and peaked at 80 kW delivered to the wheels. The vehicle was charged for an hour back to 70%, and driven 23 miles back to its home, consuming another 30% of the battery. 11.7 kWh were consumed to cover 44 miles, a specific consumption of about 4 miles per kWh, which is slightly better than the EPA estimated 3 miles per kWh [9].

The vehicle fleet is overall lightly used with the exception of the bus and a few Via Vans and Leafs. A plot of vehicle drive distance is shown in Figure 5. This would seem to indicate that V2G usage and some increase in battery degradation are compatible with the other system-level requirements for vehicle usability by drivers.

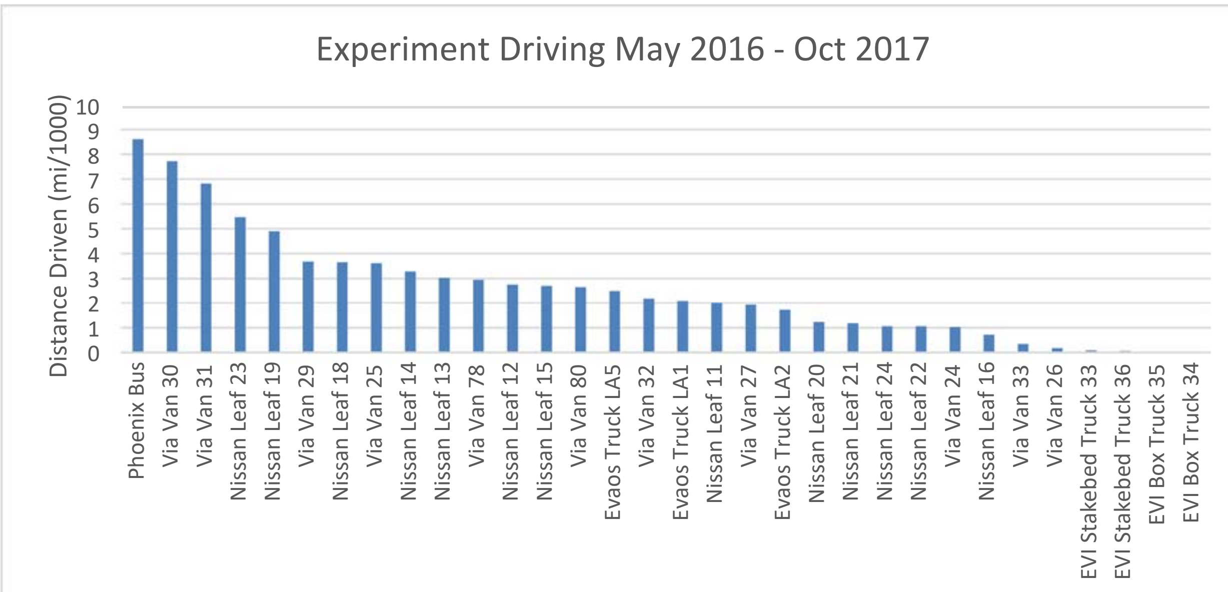

Figure 5. Fleet mileage (miles/1000).

Kisensum's inverter data logged from May 2016 to May 2017 shows how each vehicle is interacting with its charging station while connected. The data is compressed by logging only changes in measured field and timestamping the change. Some values generated externally to the vehicle are logged by Kisensum's dispatch controller and aggregator. These include the dispatch signal sent to the car from the electric vehicle dispatch aggregator, and the external meter power flow in and out of the charger. Other values, such as battery pack voltage, current, and temperature, are pulled from the car for monitoring by the dispatch aggregator. These values are identical to those logged by the FleetCarma loggers, with the addition of the vehicle's estimate of its own maximum battery capacity. State-of-health test data is a subset of this inverter data captured during a vehicle state-of-health test and stored as separate files for convenient access. An example state-of-health test is shown in Figure 6.

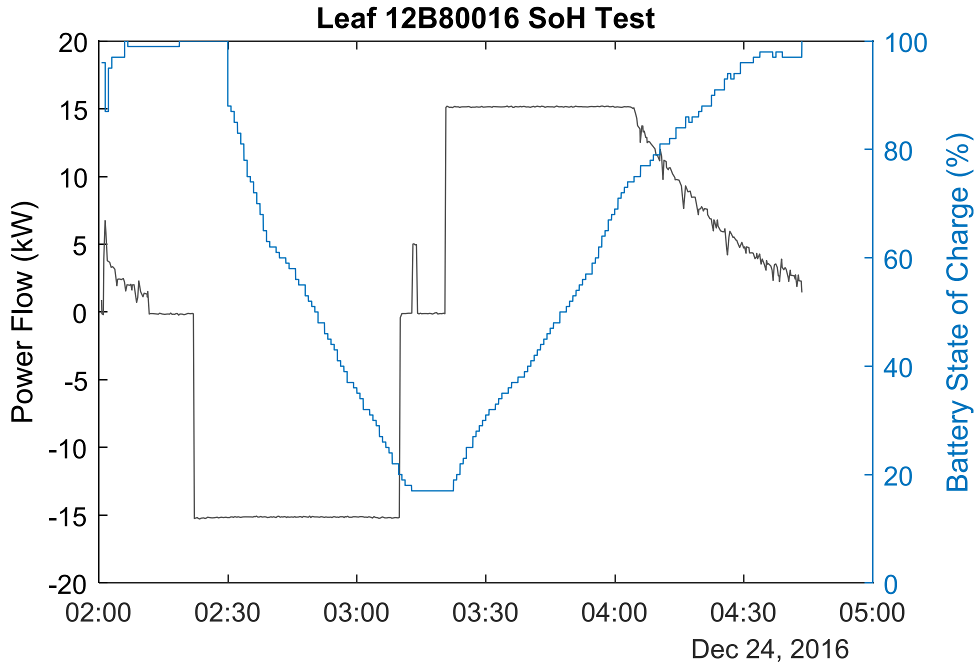

Figure 6. Nissan Leaf 12B80016 successful state-of-health test.

The state-of-health test shown above is typical for a successful test. The vehicle was discharged at 15 kW from full capacity (100%) to empty (20%) in approximately 45 minutes, rested for 15 minutes, and recharged to full. The decrease in power after the vehicle reaches 80% capacity is typical for a lithium ion battery as the battery reaches its upper voltage limit and the current is curtailed. This test showed that the vehicle delivered 12.4 kWh when discharging and absorbed 14.2 kWh to recharge, a round-trip efficiency of 87% (including battery and inverter). This level of efficiency falls within normal bounds for lithium ion batteries and AC/DC inverters [10], [11].

Kisensum's dispatch data was logged daily from May 2016 to May 2017 and captures how the collection of vehicle batteries is aggregated into a single "virtual battery" and dispatched by the ISO's demand signal. Fields are sampled at 0.1 Hz and include current and target power flow, virtual battery total available power, SoC, the number of individual vehicles participating in the virtual battery, and a Boolean indicating if the site is under local control by its internal charge plan or remotely dispatched by the ISO. This data set is primarily used to monitor what the ISO frequency regulation demand signal actually looks like and how accurately the fleet tracks the ISO's requested power. An example evening of grid participation for the fleet is shown in Figure 7.

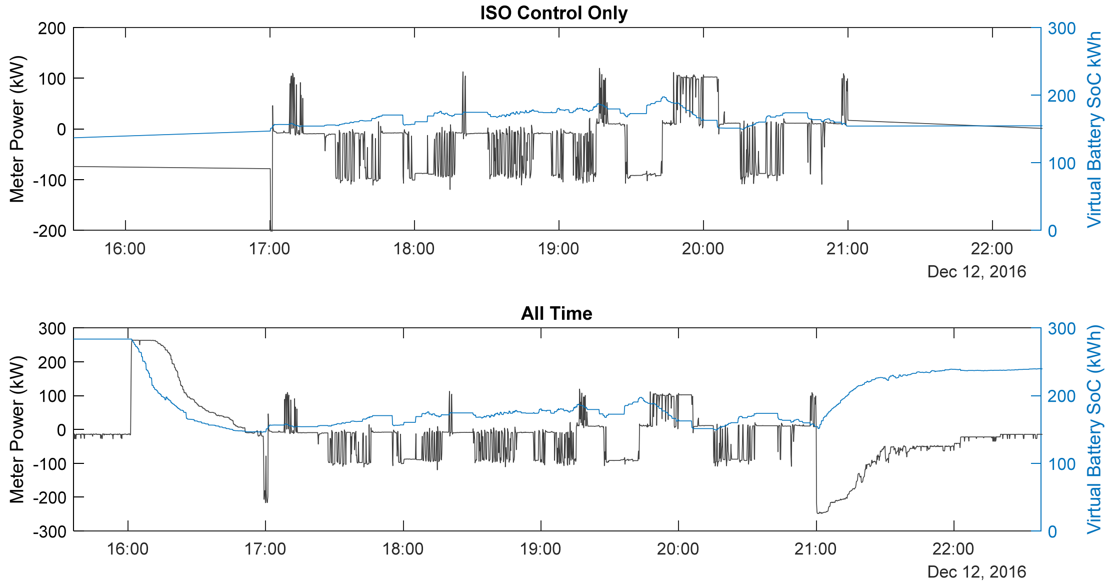

Figure 7. Frequency regulation market participation. Bottom graph: power flow and state of charge of the fleet "virtual battery." Top: power flow and fleet state of charge filtered for ISO control only. Positive power indicates power flowing out of the site from the batteries to the grid.

Figure 7 shows fleet revenue meter power flow in black on the left axis, and the SoC of the fleet "virtual battery" on the right. The bottom graph displays all data for the evening; the top panel shows data only while the site was under ISO control. Market participation started at 17:00 and ended at 21:00. The fleet prepares for market participation an hour before it begins by discharging or recharging vehicles to 60% SoC to make capacity available for reg-up and reg-down dispatch. The fleet then tracks the ISO's dispatch signal, absorbing and supplying power as requested until market participation ends at 21:00. The vehicles are then recharged to back to full capacity in preparation for the coming day. In the virtual battery SoC, one can see that the full capacity is somewhat short of the theoretical total kWh for the site, and this is due to both vehicle availability and charger/vehicle operational status.

CAISO found the site out of compliance and decertified the site from reg-down operation on January 24, 2017. The site's measurement and reporting system was not configured to report to the ISO with the proper accuracy, and had not done so for the entire duration of the project. Limited communication between CAISO and the site prevented this error from being communicated and addressed in due time. The site was never recertified as a floor of 500 kW of assets was set, which would have required doubling the size of the fleet from 240 kW or changing the charging infrastructure. The site continued providing reg-up service after decertification until conclusion of the pilot on September 30, 2017.

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2. DATA FINDINGS

Table 1 shows drive mileage and energy moved through each vehicle's battery, separating driving and grid participation from May 1, 2016 to May 1, 2017. Grid support activity dominated battery usage in all vehicles except the bus. On average, the Nissan Leaf fleet moved 11 times more energy in grid support than driving but had less effect on health due to the shallow depth of discharge and overall power. This finding is expected and follows the small cycling and resulting small degradation theory mentioned in Section 1.2.

TABLE 1

Battery Usage of Leafs and Bus, May 2016–October 2017

Vehicle	Distance Driven (mi)	Total Energy Driving (kWh)	Total Energy Grid (kWh)	Total Usage (kWh)
Leaf 12B80011	996	644	7,374	8,018
Leaf 12B80012	1,401	962	8,183	9,145
Leaf 12B80013	1,574	1,021	8,479	9,500
Leaf 12B80014	1,678	1,006	7,010	8,016
Leaf 12B80015	1,623	935	7,911	8,846
Leaf 12B80016	393	197	8,115	8,312
Leaf 12B80018	814	404	8,700	9,104
Leaf 12B80019	2,819	902	4,892	5,794
Leaf 12B80020	692	398	7,530	7,928
Leaf 12B80021	595	404	7,520	7,924
Leaf 12B80022	520	331.3	9,366	9,697
Leaf 12B80023	2,619	1,783	7,981	9,764
Leaf 12B80024	27	20	6,218	6,238
Phoenix Bus	8500	59,653	7,699	67,352
Totals	**24,251**	**68,660**	**106,978**	**175,638.3**

2.1 GRID PARTICIPATION SUPPORT VS. DRIVING EFFECTS

A plot of an evening's grid support for a single vehicle is shown in Figure 8.

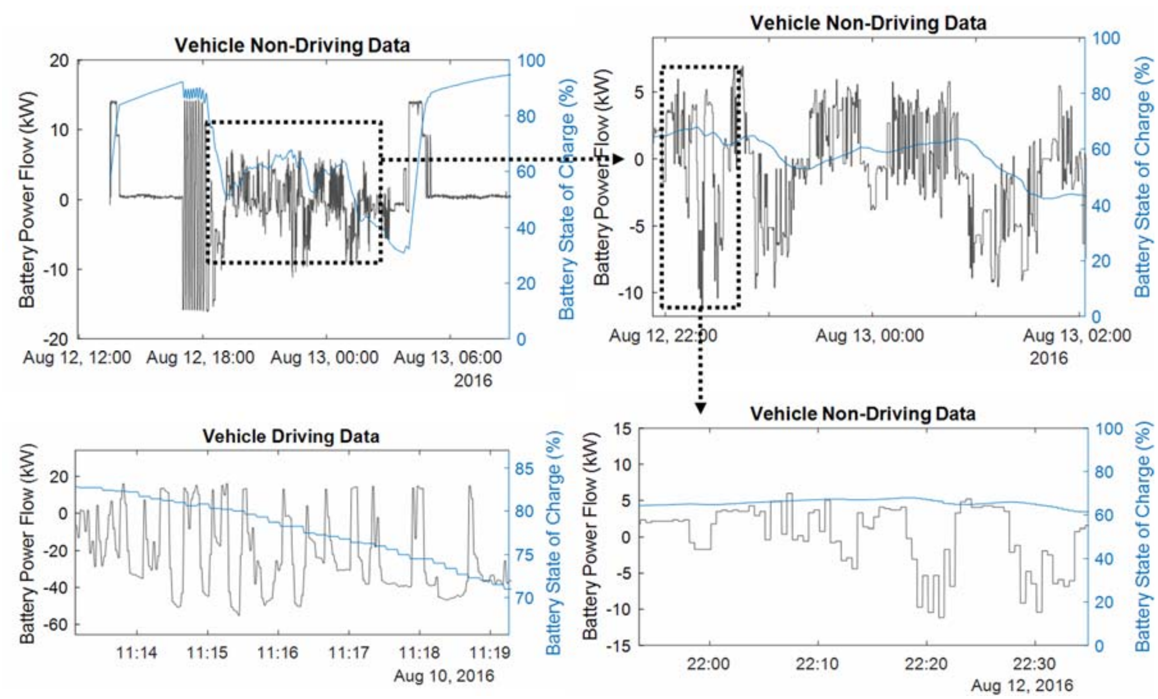

Figure 8. Leaf 12B80019 pre-decertification grid participation and driving data.

The grid participation data shown above is typical for pre-decertification reg-up and reg-down operation, with state of charge mostly floating between reg-up discharging and reg-down charging. In reg-up only operation, the vehicle supplies power until it is discharged to approximately 65% SoC. At 65% SoC, it drops out of market participation, recharges to 90%, and then rejoins the market. This results in more cycling of the batteries though at less net depth of discharge. The histograms in Figure 9 show daily depth of discharge pre (left) and post (right)-decertification operation of the Nissan Leafs. Post-decertification reg-up only operation increases cycling in the 4–6 kWh range.

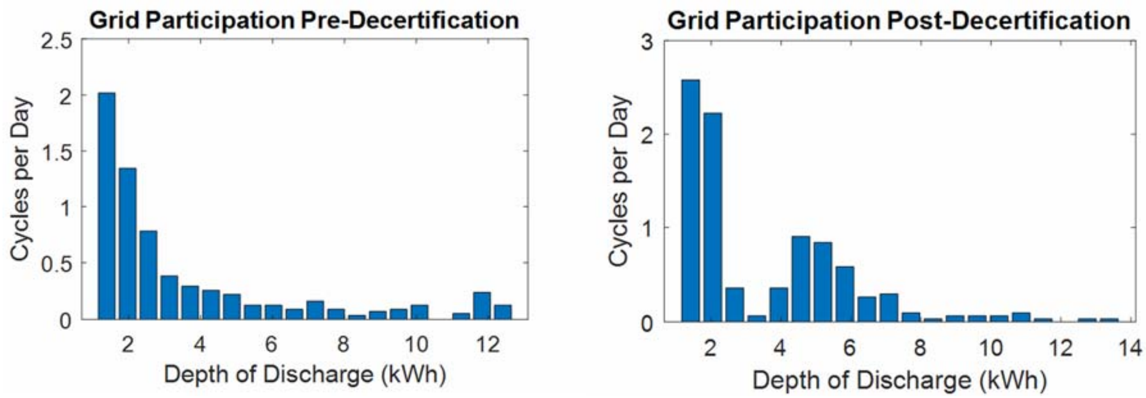

Figure 9. Frequency regulation depth of discharge cycles per day for Leaf 12B80011. The 50 micro cycles of <0.5 kWh are suppressed for visibility. Driving data was not included. Vehicle battery capacity: 18 kWh.

Grid participation is dominated by many small cycles per day (removed for visibility from graph above). Pre-decertification averaged 1 cycle of >7 kWh per day (summing all bars above 7 kWh), while post-decertification operation averaged 4 cycles >4 kWh per day, with the majority between 4 and 6 kWh. While depth of discharge was higher in pre-certification operation, the vast majority of days of grid participation resulted in a single discharge cycle between 7 and 12 kWh; 40–65% depth of discharge. This is roughly equivalent in depth-of-discharge to a daily drive of 30–50 miles but at a much lower power and longer duration than driving. An equivalent full discharge cycle metric could be helpful in rating the total throughput on a given battery.

2.2 BATTERY TEMPERATURE

Vehicle thermal management systems were sufficient to keep the battery pack temperatures within nominal operating range during driving and grid support. A plot of temperature during driving and grid support is shown in Figure 10. Weather was the primary driver of passively cooled pack temperature with diurnal and seasonal trends observed. It should be noted that Los Angeles does have relatively moderate temperatures compared to some DoD sites, so more study of operation during extended ambient temperature ranges may be necessary.

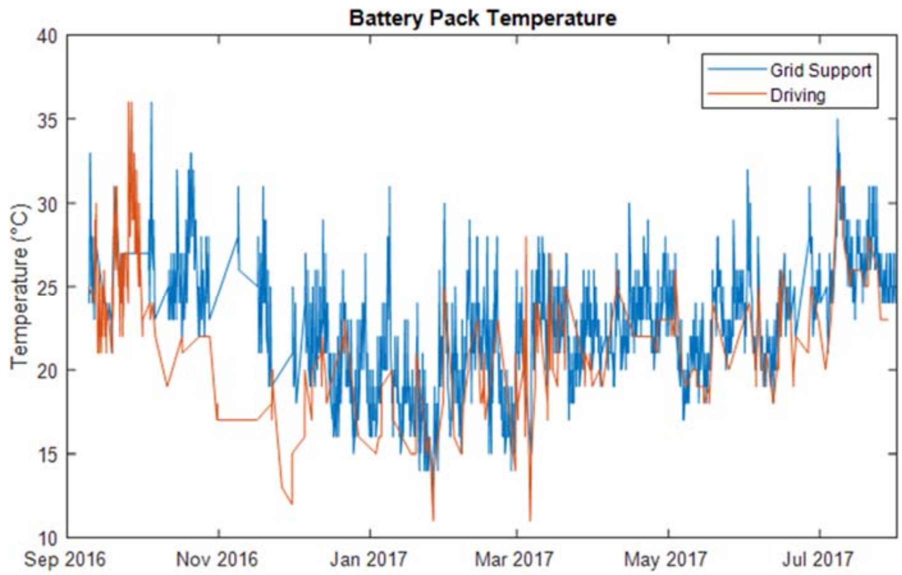

Figure 10. Leaf 12B80012 battery pack temperature.

Cell temperature is one of the most important factors for battery aging, and neither driving nor grid support had a large effect on pack temperature. On a higher average power system (above 1C-rate or heavy driving), this may be more of a concern but wasn't an issue in this study. Cell temperature could also deviate from the pack temperature measurements used during this study, but manufacturers typically locate the pack temperature sensor at a worse-case temperature location. If operating in extreme ambient temperature or higher power levels is desired, some additional study of temperature differences inside the pack may be needed.

Frequency regulation appears less severe than driving on the batteries in three key battery aging factors: depth of discharge, peak power flow, and number of charge-discharge cycles. It should be noted that frequency regulation is less severe in spite of the fact that the time duration is much longer.

2.3 BATTERY DEGRADATION

There was no observable battery degradation captured by the state-of-health tests. The graph in Figure 11 below shows the results of these periodic tests for Nissan Leaf 16. Initial efforts to coordinate and debug the state-of-health testing, as well as charger issues, caused some of the earlier testing opportunities to not yield usable data. The Leafs produced the most complete set of successfully completed state-of-health tests, with 5–7 per vehicle completed in the 1.5-year project period. Other vehicles were much less amenable to completing tests: the EVI trucks never successfully completed a state-of-health test before their removal from the program. It should also be noted that the efficiency is not even consistent and likely due to inaccurate measurements, roughly 7% from test to test.

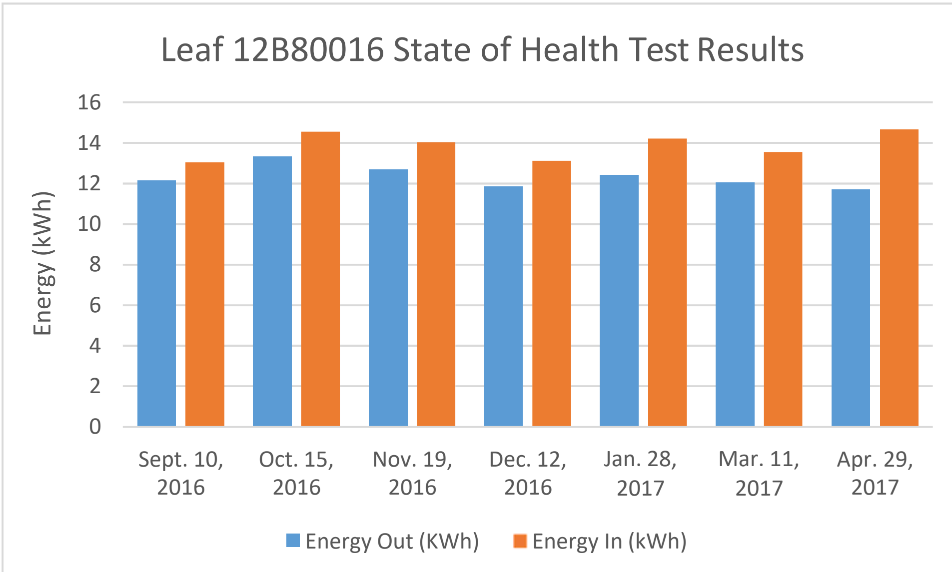

Figure 11. State-of-health tests results, Nissan Leaf 16.

The expected trend of slowly degrading capacity is, however, observable in the vehicle inverter data sets. One of the values tracked in the inverter data sets was the maximum capacity of the vehicle battery as reported to the inverter by the vehicle. Slight capacity degradation is evident when plotting maximum capacity vs. time, shown in Figure 12 for Leaf 19, which participated the least in grid participation. Leaf 16, which was the lightest-driven vehicle in the fleet at 400 miles driven in the 12 months monitored, also showed slight degradation. Leaf 23, the second-heaviest driven vehicle in the fleet at 2619 miles in 12 months, showed almost identical change in capacity.

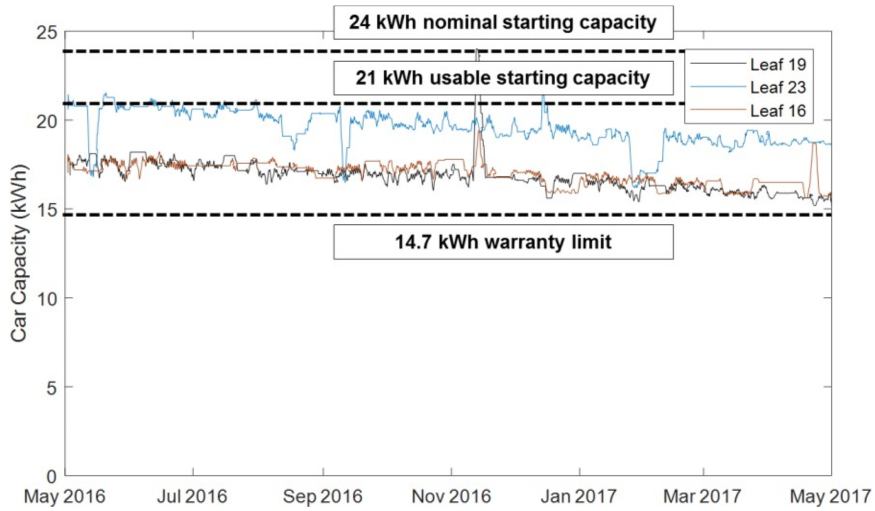

Figure 12. Nissan Leaf 16, 19, and 23 reported maximum capacity. These vehicles are the least grid-participation, heaviest-driven, and lightest-driven Leafs, respectively. Vehicle number in key matches the last two digits of the vehicle identification number (VIN).

Slow capacity degradation was observed for all vehicles, with the exception of the bus and Leaf 24. The latter vehicle is newer than the rest of the fleet and was added to replace Leaf 17, which was damaged in a traffic accident. The Phoenix bus showed no significant degradation in this metric or any other.

This vehicle battery capacity is a calculated value generated by the internal computer on the vehicle and sent to the inverter where it is picked up by Kisensum. The exact algorithm used to generate this is unknown, and it is highly likely to be implemented differently in the Phoenix Bus than the Leafs. A better test, which could not be implemented, is mentioned in Section 3.5, but given that this was the only data available, it was the only choice. Maximum capacity measured by the Leafs appears to vary instantaneously with pack voltage and current (a one-day moving average filter was used to generate the plots), and other unknown factors. Two vehicles, Leafs 22 and 20, appear to have a reported capacity below the warranty limit of 70% usable capacity [12]. The beginning-measured capacity (as reported by the vehicle in May 2016) did report low for many vehicles, so some offset error, such as manufacturer piece-to-piece capacity variability, or sensor error may be present. Nissan's stated warranty is six years or 60,000 miles, so it would seem the low reported capacity would cause several vehicles to drop below that warranty limit in less than six years.

Vehicles with observed capacity degradation in this metric all generally degraded at a similar rate, around 0.125 kWh/month despite starting with different capacities and usage patterns. Figure 12 shows Leaf 19 degrading at roughly the same rate as Leaf 16 despite 30% less usage overall. This suggests, but does not prove, that time is the dominant aging factor on the batteries and that neither grid participation nor light driving is accelerating the aging process a great deal. This assessment agrees with the observation made earlier that grid support activity is lower (peak power, depth of discharge) or equivalent (temperature) in battery stressing factors than daily driving of the vehicles. As the vehicles were designed for a long life of daily driving and are warrantied for 60 months or 60,000 miles, the low-level intensity of grid participation is unlikely to cause more wear. Proper life-cycle testing would allow a degradation model to be developed that could prove exactly how much degradation is caused by grid participation.

2.4 FINANCIALS

Prices for ancillary services are low in CAISO territory but were somewhat higher when the initial analysis was conducted. The average price for reg-up service from December 2015 to May 2016 was $13/MW, $10.5/MW for reg-down; an average price of $11.8, which were a whopping 28% less than PJM's price for the same time period [13]. Typical bids for the vehicle fleet were 0.1 MW due to uncertainty in availability of assets (especially the non-dependable EVI trucks and vans) and the limited size of the fleet. The entire fleet averaged about $300/month income, which was unfortunately more than offset by a $1000/month fee to manually enter bids into the market. At a larger scale, the DoD could automate the interface to the ISO and have it done once for all sites. Decertification from regulation-down service cut the margins deeper still. More money could be made by bidding all of the dependable and available vehicles in the fleet at their full capacity, thirteen Nissan Leafs at 15 kW each and one bus at 40 kW for a total of 235 kW, into the market instead of the typical 100 kW bid. Lawrence Berkeley National Lab's (LBNL) dispatch controller did just this when fully operational between August and December 2016, though awarded regulation did not appear to increase. In addition, project developers could look at bidding the batteries into multiple concurrent ancillary services such as regulation, demand response, and peak shaving. This stacking of services would have additional benefit but would incur additional costs and complication for the controller. This was not attempted due to limited project resources and the possibility of dimensioning marginal returns.

Round-trip battery losses can reduce the small profit posted by a storage system. Round-trip efficiency of the Nissan Leaf batteries is about 85% (Figure 6), typical for battery energy-storage systems. Assuming a balanced 1 MWh grid participation was awarded with 500 kWh up and 500 kWh down, approximately equal to the daily award to the fleet, and the full capacity of the bid was used, the battery and charger system will need to purchase an additional 88 kWh of electricity to cover losses. This power is purchased at the site's electrical rate, approximately $0.06/kWh for a total cost of $5.28. The site is paid $11.80 for the service, leaving a profit of $6.52 for the evening. Decertification from reg-down exacerbates the problem further by removing this subsidy on purchasing power.

This is a very conservative estimate and assumes that the full usage of the bid was exercised by the ISO; lower usage will result in moving less power through the batteries and result in fewer losses for the same payment. The above calculation does not take into account the imbalance payments made by the utility that generally occurred: instructed imbalance paid by the ISO for energy produced or consumed as a result of responding to dispatch instructions (effectively a subsidy for the purchase of power and payout for its sale) [14], which averaged $288/month from the ISO; and uninstructed imbalance energy consumption, energy produced or consumed above or below schedule without dispatch instructions from the ISO, which can be a penalty or payout (averaged $56 *penalty* paid by the site to the ISO). The above calculation also does not take mileage payments into account, which are paid out by the ISO based on how much the frequency regulation signal moves, "feathering the throttle," which were fairly small (<$2.50/month).

Careful consideration should be given to the site's electrical rate (including demand charges) and efficiency of the batteries to intelligently schedule bids and avoid making money-losing bids. LBNL's dispatch controller did just this when fully operational.

CAISO grid-participation rules limit the capacity of the asset to the maximum power than the asset can supply/absorb for a 15-minute period [14]. All vehicles in the fleet are limited by the charger rather than the capacity of the battery, 15 kW for the 21 kWh-capacity Leafs and 40 kW with the DC LVL III charger on the 105 kWh-capacity bus. CAISO limits for these units would be the power required to drain the battery to empty in 15 minutes, 80 kW for the Leaf and 420 kW for the bus. More powerful chargers would allow bidding more power into the market, and therefore more money to be made, though higher power rates may start to age the batteries.

Net revenue generated by the vehicle fleet will need to offset the expenses for hardware and software beyond what is required to charge a simple vehicle fleet overnight. An 8.3 kW EVSE charger can be purchased for $635 [15], while a 19 kW unit like those used in this experiment costs about $2,000. Utility service upgrades like transformers, breakers, and wiring to the charging pad or connected building may be necessary for a larger charger, and the additional equipment and labor could cost several times the value of the charger itself. Vehicle internal (AC to DC) chargers may need to be upgraded at a few $1,000 per unit. Further costs are incurred when installing communication capability between the chargers and dispatcher, and recurring costs may be incurred for aggregation and dispatch.

Acceptance of V2G operation by vehicle manufacturers is another area for improvement. Most vehicle manufactures do not warranty their batteries for anything other than driving and normal charging. In this project, Nissan did not warranty the batteries for any damage incurred while doing V2G. One Leaf battery failed due to a communication glitch in the charging system during this pilot and was replaced for $6k, but this type of failure is not thought to be something that would occur in a fully vetted non-prototype system. The findings from this project and others could be evidence for the original equipment manufacturers (OEMs) to adjust that position to a friendlier one. V2G compatibility could even be a feature that the customer could consider when assessing overall value. Cooperation from OEMs can be a game changer in terms of getting systems that are trouble-free, reliable, and cost-effective. In second-life operation, where the battery is pulled from the vehicle, OEM cooperation can be very useful to assess overall health, any bad battery cells, and get the pack into operation with as few labor-intensive operations as possible.

2.5 DATA ISSUES

There are several historic and outstanding issues with these data sets. The vans and trucks worked inconsistently. For example, the graphs in Figure 13 show power flow during frequency regulation market participation. The top vehicle, a 2-ton stake bed truck from EVI (Electric Vehicles International) operated nominally, while the bottom vehicle, a box truck from the same manufacturer based on the same chassis, was completely unresponsive to the dispatch signal and did not participate.

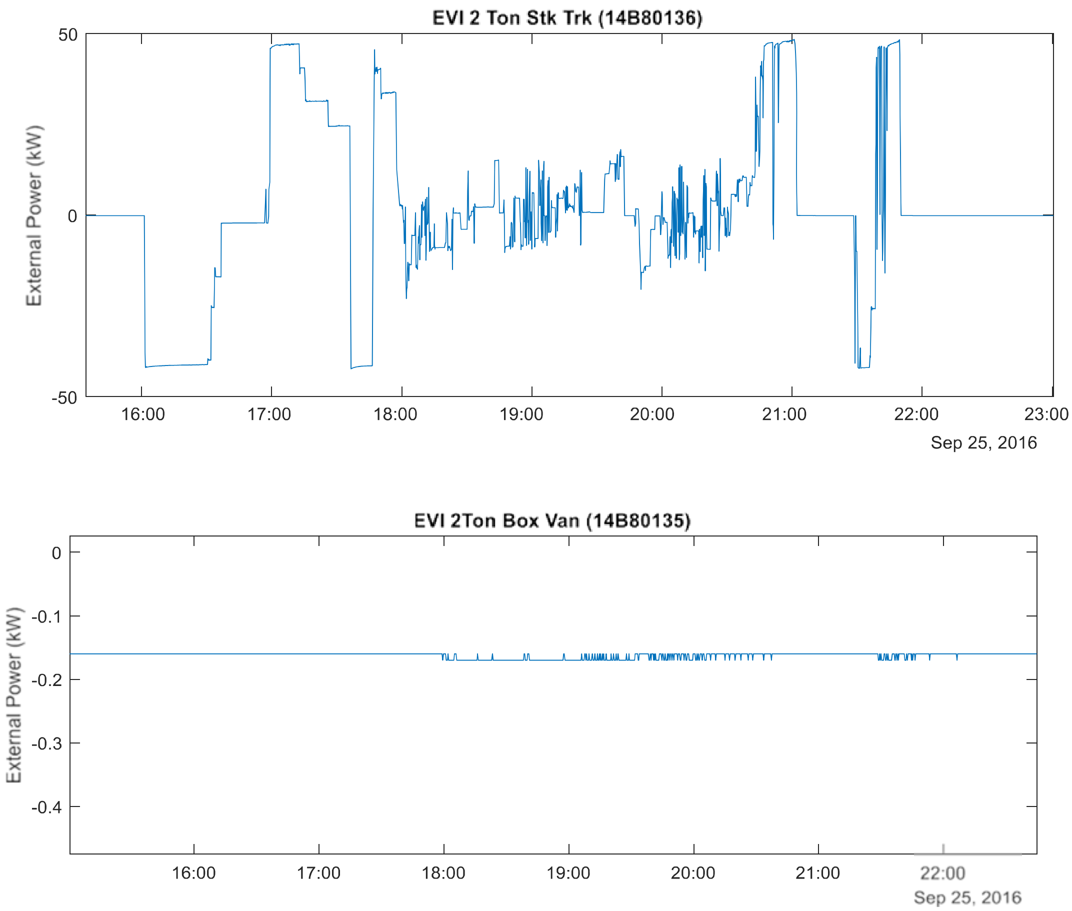

Figure 13. EVI truck and van grid participation. Top vehicle (stake bed truck) operating nominally. Bottom vehicle (box van) unresponsive.

There was no pattern; less than two weeks later, van 14B80135 was participating and responding as expected and truck 14B80136 was unresponsive. Similar communication lapses interrupted state-of- health tests, which require continuous communication and control between the vehicle and inverter. The vans and trucks supplied 40 kW of capacity each, totaling 600 kW across 15 vehicles, representing 2/3 of the total fleet capacity. The fleet became difficult to dispatch with such a large proportion of capacity intermittently inoperative until the offending vehicles were removed from the experiment, leaving the Leafs and bus in the experiment.

Kisensum's state-of-health tests do not provide an accurate assessment of the battery state of health. As explained earlier, these tests involve charging the battery until the vehicle claims that it is 100% full, and discharging until the vehicle says that it is at 20% capacity. Unfortunately, that vehicle capacity value is calculated by a black-box algorithm within the car and appears to vary with many uncontrolled factors such as time, pack voltage, and instantaneous pack current flow. State-of-health tests nominally use 80% of the vehicle's battery capacity; the state-of-health tests for Leaf 16 on Nov 19 (Figure 12) measured

12.68 kWh discharged from the battery, implying that full capacity (if the test used 80% of the capacity) of the battery is 15.85 kWh. Figure 12 shows that the vehicle's estimate of its own capacity at the time was 17.09 kWh, 7.8% higher and roughly equivalent with the observed error in maximum capacity measurements during a state-of-health test. Vehicle capacity degraded in total about 12% over the year according to the vehicle, low enough to let the spread in several state-of-health tests hide the real value, but large enough to be observed when plotted over a long time. The spread in the vehicle's reported capacity is hardly unexpected; 8% accuracy is sufficient to roughly estimate how far the vehicle can go with the remaining charge in the battery pack, and it is doubtful that it was ever intended for scientific experimentation.

Given that it is unclear what analysis methods have gone into this capacity calculation, a better choice would be to extract all the battery data for a "true" capacity test. This would involve starting the battery test at a consistent temperature adjusted voltage that would represent the same amount of energy. The battery would then be discharged and the test stopped when the battery reaches 5–10% charge. As can be seen in Figure 14, at 10% charge the voltage is sharply sloping downward. This large change in voltage vs. energy allows the system to stop the test at a precise level of remaining energy. If the test were stopped at 20%, then the relatively flat voltage curve and small voltage measurement inaccuracy could cause a large error in remaining energy. This would give inconsistent total capacity measurements and make prediction difficult, given the noisy data.

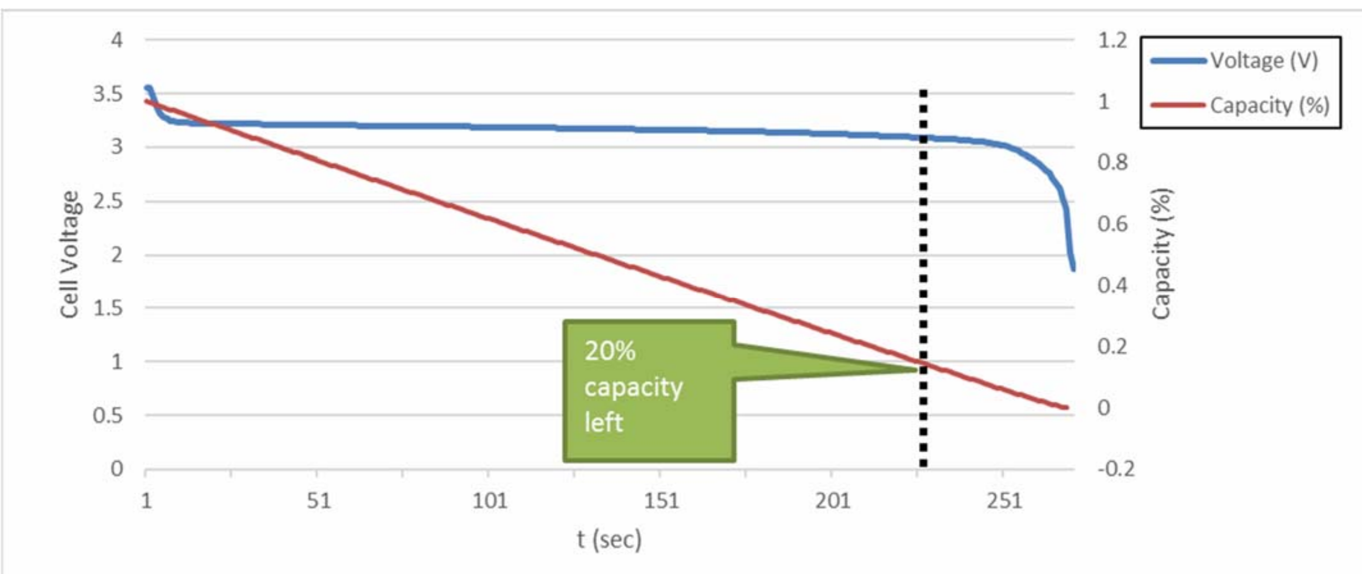

Figure 14. A typical lithium ion cell discharge curve. Discharge current is held constant.

3. HARDWARE WORK AT MIT LINCOLN LABORATORY

At the start of the project, MIT Lincoln Laboratory was tasked with purchasing the batteries that would go into the EVAOS pickup trucks. EVAOS experienced significant challenges getting their vehicles fully tested and working. These delays prompted the Executive Agent to eventually remove them from the demonstration because there would have been less than a year to collect data. EVAOS's halt in production meant that there were several sets of batteries that were not installed on vehicles. Lincoln Laboratory identified the best use for these already purchased batteries would be to investigate second-life usage since additional value left on the batteries after vehicle use may be an important part of the overall value equation.

To that end, we have begun preparations for testing the batteries at a simulated DoD site. The hypothetical site would likely be one that is remote and faced with poor power quality from the grid. A site which might go islanded in times of crises or when grid power is unreliable could be a particularly good use case for the batteries. The 8 batteries represent 215 kWh of energy and 120 kW of power. At this site photovoltaic (PV) solar modules could be used to minimize operational cost and the batteries could potentially firm up this variable PV resource so that less inefficient generators are needed. Ancillary grid services could still be provided at this site and would essentially provide an income stream when other uses weren't needed.

Initial testing is already underway, and several charge and discharge tests have been run to prove out that a set amount of power can be reliably produced using our control software and an electrical interface that replicates those signals originally seen on the vehicle. In addition, thermal tests were run in cold temperatures to prove out that the battery cell temperature can be elevated by using the liquid coolant lines and a heater. This is important because during testing cell temperature may need to be carefully controlled in order to accelerate the aging process. Given that the hypothesis predicts a long life for the batteries, the length of testing needed to see significant degradation may become a cost issue. If this happens, some time acceleration could be a useful mitigation strategy.

The EVAOS batteries are packaged into Energy Storage Modules (ESMs) and have a 15 kW inverter built in. This fact allows for simple integration into a site without additional external inverters, but two issues have complicated the integration. First, the inverters were never UL tested, so connecting them to the lab electrical network is a concern. Equipment without UL testing is only really useful at a prototype level where extra safety mitigations would already be in place. Second, the inverters are only grid-following, so on an isolated system they can't regulate frequency and voltage without another grid-forming device present. Both of these concerns could be fixed (by the ESM designer EVAOS) in the long term, but for now they do require extra devices in the test plan.

The testing would consist of a combination of usage patterns in order to simulate all the types of services that may be useful for the site. During these tests, we can assess how well the batteries meet the need. The vendor-provided monitoring software is capable of looking at individual cell data so the overall quality of test data will be vastly improved. In addition, the cell-level data may also allow us to understand how battery management systems (BMS) affect the aging of the pack. This setup will allow us to project battery degradation in a more lab-like environment. The variety of usage patterns will allow us to assess which usage is most valuable and best suited for the batteries' capability. In reality, a combination of usage will probably give the best total value for the DoD in second life. This testing will allow us to put a number on that overall second-life-value question, which could be a significant portion of the overall value.

4. FUTURE WORK

A proper state-of-health test in which the vehicle battery is charged and discharged between set voltage points while power is measured would be essential to accurately measure battery health. There are no publically available pre-tuned battery capacity models for the batteries in the Nissan Leafs. Models do exist that can accurately predict battery lifetime, but they require multiple parameters to be fit to be on a data set from a battery that has gone through its full lifetime already. These parameters are specific to the chemistry and manufacturing process of the battery itself; test data must be gathered on the specific battery from a specific manufacturer in question.

The integration and testing of vehicles in this project presented numerous issues, which had to be addressed. Because most of the equipment in this project was still in a prototype phase, there were ongoing failures and unreliable operations. The type of dependability customers associate with mature automotive manufacturers doesn't come without millions of test miles, operation in all climates, and thousands of vehicles on the road. With the exception of the Leaf EV, none of the vehicles in this fleet met those type of standards. This kind of reliability is important in a system that is expected to operate with minimal operator intervention during dispatch.

Additional work to assess the overall value of second-life batteries is also needed. A holistic test to determine how the batteries perform, which grid services they are best suited for, how they might age, and any ongoing operational cost would be very beneficial. This portion of the overall value proposition is largely unknown but could have significant weight.

Future work could also include testing at higher power levels. Overall, V2G batteries are not run at a very high power level relative to what the battery can provide. Driving generally uses up to 10× the output power as V2G. New chargers do seem to be continually pushing to a higher and higher power level. These increases do come with an increased capital investment, but if the market and users demand shorter charging times and increased power, it would seem V2G should take advantage of this capability. It is unclear if pushing the batteries harder would still give only minimal degradation, but if results to date look promising, this additional potential benefit should be explored.

Lastly, testing during islanded operation of the base might show even more benefit. If the electrical network is stressed, such as in an emergency, loads that are flexible can be very useful to shift loading and meet short-term energy needs of higher-priority loads. In the case of these systems, the bidirectional nature makes them twice as valuable because they can swing the power consumed on a feeder by twice their rated load.

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5. CONCLUSION

Frequency regulation market participation appears to have a minimal impact on vehicle battery lifetime. Frequency regulation is less severe or equivalent in key battery aging factors than driving the vehicle, and the vehicles are designed for years of driving operation. Full battery life testing with laboratory instrumentation would generate the better quality data to confirm this point. The financials of frequency regulation market participation are complicated, but margins are only thinly positive in most of the USA, so attention should be given to minimizing operational costs and up-front capital costs. Fees to participate in the market eliminated the revenue from market participation, which would need to be addressed if future adoption is contemplated. Careful consideration should be given to the efficiency losses in the storage asset and price of power necessary to overcome those losses to avoid making money-losing bids. Increasing the bid to also cover energy efficiency losses and the current energy price would ensure that bids are always money-making. Capital expenditures to upgrade the chargers and vehicles to support frequency regulation and recurring expenses of bid aggregation and dispatch should be tallied against predicted revenue in a discounted cash-flow analysis before proceeding with market participation of an electric vehicle fleet. If the industry can agree to a consistent set of V2G standards, the costs for the equipment used for the prototype demonstration would be reduced.

The goal of this project was to show the barriers, effects on electric vehicles batteries, costs, and potential revenue for participating in ancillary services markets. To that end, this project was a success and had many benefits. The Nissan LEAFs and Phoenix Bus were 100% battery electric vehicles and did not consume any liquid fuel to meet the transportation needs, which helped to offset some of the additional EV cost over conventional vehicles. LA AFB’s load is very controllable and could be minimized to reduce operational energy costs to the base. When operating in an islanded configuration, this would be even more valuable. In addition, local greenhouse gas (GHG) emissions associated with liquid-fuel vehicles were reduced. Many states and towns are considering their own legislation for GHG, and workable strategies for the DoD to use could be useful. Past executive orders have also directed reductions in GHG.

The project also presented the users with many learning opportunities. Service members and base operations staff were given an opportunity to become more familiar with EVs and their capabilities. The project integrators as a whole learned about working with an ISO, what information they need, and how to improve that interface. As a whole, this project has collected the data and fielded the systems needed for V2G, so familiarity with those systems has been advanced. Overall understanding of the economics pertaining to these types of systems is now vastly improved, but second life is still under exploration. The battery aging measurements showed that the degradation is so small that it is very difficult to measure. Overall, it does seem that V2G use is compatible with the way LA AFB uses its vehicle fleet. With this information, the DoD can assess whether any future projects have merit and any quickly highlight any potentially future issues based on past experience.

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14. ABSTRACT
The DoD Vehicle-to-Grid (V2G) pilot program aimed to explore the challenges, impact, and benefits of selling the services of fleet electric vehicles to the commercial power grid as energy storage assets in the ancillary services market. Ancillary services are used by the system operator to balance the instantaneous frequency on the grid by manipulating the power output (and input, for batteries) of the asset. It is an ideal market for electrochemical batteries, requiring large power capacity but small amounts of energy overall. Batteries can supply large amounts of power quickly, handle bi-directional power flow (sending power to the grid and absorbing from it), and are more harmed by the total amount of energy supplied (depth of discharge of the battery) than instantaneous large swings of power. Laurence Berkeley National Laboratory developed the hardware and software necessary to allow the fleet of vehicles to interface with the California Independent System Operator's ancillary services dispatch system. MIT Lincoln Laboratory investigated the impact of this additional usage on the lifetime of the batteries and explored the use of "second-life" batteries, batteries removed from electric vehicles and used instead as fixed storage assets. Some inaccuracy in the battery capacity was seen because measurements were made on the batteries using existing sensors, but no statistically significant grid-related degradation in the lifetime of the batteries was observed during the pilot program. An aging model of the batteries was also developed. Although payments for participation in the ancillary services market are currently low and require a large fleet of vehicles to participate, the basic overall concept was proven from hardware to payments received. V2G participation on each vehicle is currently limited by the capacity of the charging and inverter equipment connecting the battery to the grid rather than the battery itself. Costly equipment, low payments, and an immature market result in thin margins and a possibility of losing money due to inefficiency losses in the battery-inverter system. V2G ancillary services do not appear to reduce battery lifetime, and future laboratory testing could be performed to confirm this, but the ancillary services and vehicle charger markets need to improve to fully use the potential of electric vehicles to buttress the nation's electrical grid.

15. SUBJECT TERMS

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