EVTC

Electric Vehicle Transportation Center

Battery Technologies for Mass Deployment of Electric Vehicles

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EVTC Project 8 – Battery Technologies for Mass Deployment of Electric Vehicles

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The objective of the Battery Technologies for Mass Deployment of Electric Vehicles project was to assess current and emerging battery technologies in electric vehicles and to determine how battery lifetime is impacted by existing and future usage patterns. Focus was placed on identifying potential economic impacts of the battery technologies and their usage for transportation and V2G applications.

Final Research Project Report

Battery Technologies for Mass Deployment of Electric Vehicles

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1. Abstract

Electric vehicle (EV) batteries have significantly improved since their inception. However, lifetime of these batteries is still strongly dependent on the usage profiles. This report describes aspects of EV battery utilization, and their impact on battery lifetime. Additionally, this report will describe potential future uses of EV batteries, particularly in vehicle-to-grid applications.

2. Research Results

Preliminary research was conducted to assemble information about the impact of temperature on battery lifetime, they serve as a foundation for understanding the role of temperature and cell voltage on battery degradation. These results have been compiled into a paper and submitted to Current Opinion in Electrochemistry to be published in mid-2018. Published results from this research include a report and an article that can also be found on the EVTC website:

1. P. Brooker and N. Qin, "Identification of potential locations of electric vehicle supply equipment" Journal of Power Sources 299 (2015) pp 76-84
2. D. Click, "PV and Batteries: From a Past of Remote Power to a Future of Saving the Grid", The Electrochemical Society Interface, vol 24 no. 1, Spring 2015, pp 49-51

A conference presentation was given at the Renewable Energy and Sustainability Conference, held at Florida Polytechnic University July 31-Aug 1, 2017. A summary of the findings from each of these reports and presentation follow.

Calendar Aging of Commercial Li-Ion Cells of Different Chemistries – A Review[1]

Lifetime of batteries is a significant research topic, and has been intensively studies for several decades. The introduction of lithium ion batteries has resulted in new applications for batteries in new and novel technology areas, such as power tools, consumer electronics and even electric vehicles. For each of these applications, the battery lifetime is a critical factor that influences the cost effectiveness and performance of the device. To ascertain battery lifetime, researchers have typically relied on two testing strategies: calendar aging and duty cycling.

In calendar aging tests, cells are kept at open circuit for extended periods of time, with periodic reference performance tests conducted to measure capacity and resistance. These tests are typically conducted at constant temperature and cell state of charge (SOC). The results from these tests reveal how capacity and resistance changes as a function of temperature and initial

[1] M. Dubarry, N. Qin and P. Brooker. Submitted to Current Opinion in Electrochemistry.

SOC. Cycling tests are much more complicated, and are conducted by continuously charging and discharging the cell while holding temperature constant. The charge/discharge rates can vary, as well as the depth of discharge and high voltage cutoff, all of which will have a significant effect on battery degradation rates.

The purpose of this report was to investigate the literature for calendar aging tests for the various Li-ion battery chemistries that are in commercial use. Focus was limited to calendar aging due to the more simplified nature of the test and the larger available dataset in the literature. Cell chemistries investigated were graphitic intercalation compound (GIC) and lithium titanium oxide (LTO) anodes with cathodes consisting of lithium iron phosphate (LFP), nickel cobalt aluminum oxide (NCA), cobalt oxide (NCO), nickel manganese cobalt oxide (NMC), manganese oxide (LMO) and some composite blends. Degradation rates were obtained from 60 reports identified in the literature, and these rates were compiled for each electrode chemistry as a function of temperature and state of charge. Analysis was also conducted to evaluate and compare modeling approaches and post-mortem analysis from these papers.

Identification of potential locations of electric vehicle supply equipment[2]

As EVs become more widely adopted, the need for public charging stations is likely to increase. However, there is a real cost associated with the purchase, installation, and maintenance of these stations, and proper planning for publically-accessible electric vehicle supply equipment (EVSE) requires an understanding of vehicle usage patterns. In order to maximize potential revenue from a public charging station, the owner/operator desires to have as many charging events each day, which will require placing the EVSE at locations that meet two conditions: 1) high frequency of EVs arrive at the site, and 2) a high number of EVs that require charging. Even when those two conditions are met, charging preferences of the EV owner will vary, where some EV owners prefer to have a high state of charge vehicle at all times due to range anxieties, while others are more willing to tolerate low states of charge. This complex interplay between EV charging needs, vehicle location, and driver SOC preferences makes it difficult to identify the optimal location for EVSE.

To address this challenge, travel patterns and charging preferences were analyzed from National Household Travel Survey (NHTS) and EV Project data, respectively. The NHTS data was collected from over 250,000 households between 2009 and 2010, where each household recorded all their travel for one assigned day out of the year, including the mode of transportation, as well as the time and destination. This data could then be used to determine what fraction of the population was at a particular destination as a function of time, as well as the total miles driven throughout a given day. Figure 1 shows how the destination for vehicles changes as a function of time of day for the three most popular destinations. The percentages represent the fraction of all vehicles that would travel throughout the day. For example, at 7AM, roughly 15% of vehicles are traveling to work, another 2% are traveling home, and about 1% are going shopping. At 5PM, 19% of all vehicles are traveling home, 1% are traveling to work and 5% are traveling to shopping destinations. The utility of this approach is that is provides a mechanism to estimate how many vehicles are going to be at a given location for each hour period throughout the day.

[2] R. Paul Brooker and Nan Qin. "Identification of potential locations of electric vehicle supply equipment", Journal of Power Sources vol 299 (2015), pp 76-84

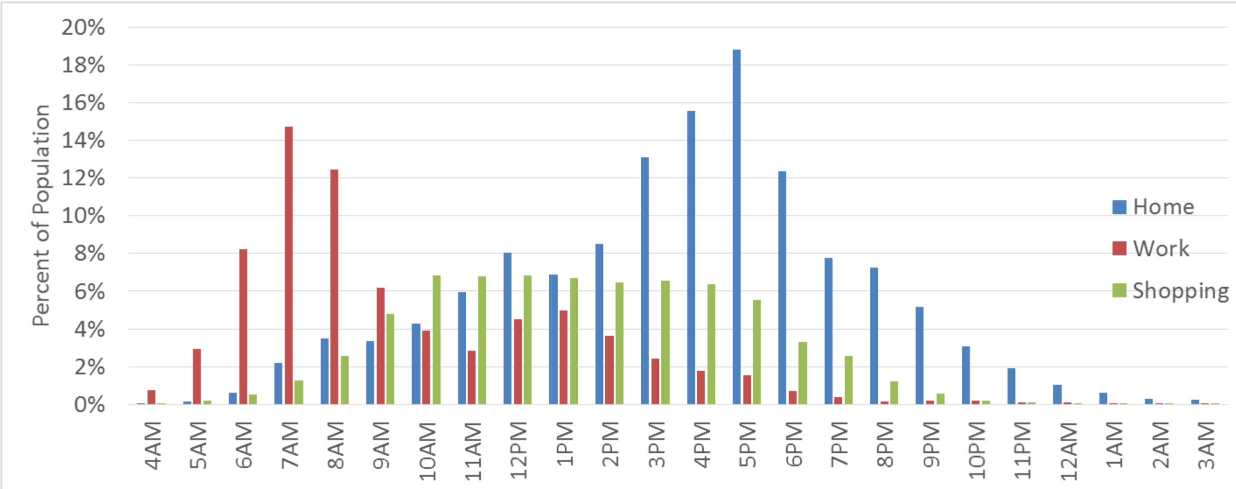


Figure 1. Distribution of arrival times for the three most popular destinations for weekday travel

In addition to destination type, the NHTS allows for estimates of the total miles traveled as a function of time of day and destination. Figure 2 shows how the average daily miles driven changes as a function of time for the three most popular destinations. Generally, as the day progresses, the cumulative miles increases for each destination type. These values represent the average of all vehicles that arrive at these destinations, but some vehicles will have travelled more or less than the average. In the early evening hours, there appears to be a slight decrease in the daily miles traveled for vehicles arriving at work and shopping destinations, which may be representative of a smaller population of vehicles traveling during evening and nighttime hours. The average cumulative miles driven for vehicles arriving at home remains near 40-50 miles and doesn't change much after about 9PM, which is in agreement with other published NHTS analysis of driving patterns.

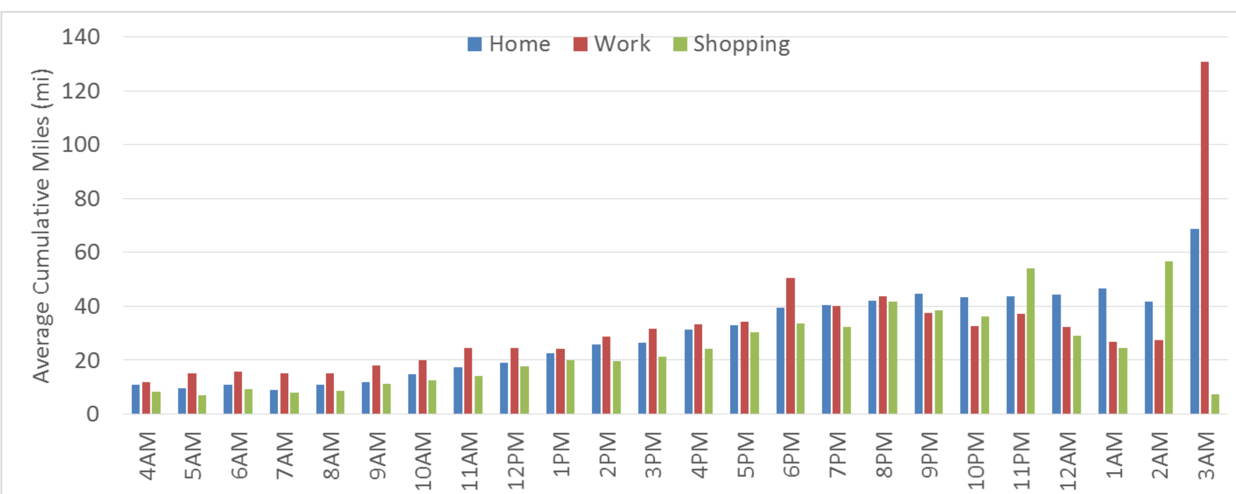


Figure 2. Average cumulative miles driven as a function of arrival time for the three most popular destinations

The purpose of the two foregoing figures was to estimate typical driving patterns for the typical consumer's gasoline vehicles. These patterns were then adopted for EVs by assuming a typical electric driving range to determine when and where the battery state of charge (SOC) may be low enough to warrant the need for recharging. Understanding where vehicles were located and how many miles had been driven at that point enables an estimate of the typical SOC as a function of time and destination. Figure 3 and Figure 4 show how the SOC changes as a function of time and destination for EVs with 80 mile and 40 mile electric ranges, respectively. For the 40-mile EV, it can be seen that the vehicle will require recharging before the end of the day, since the SOC drops to 0.

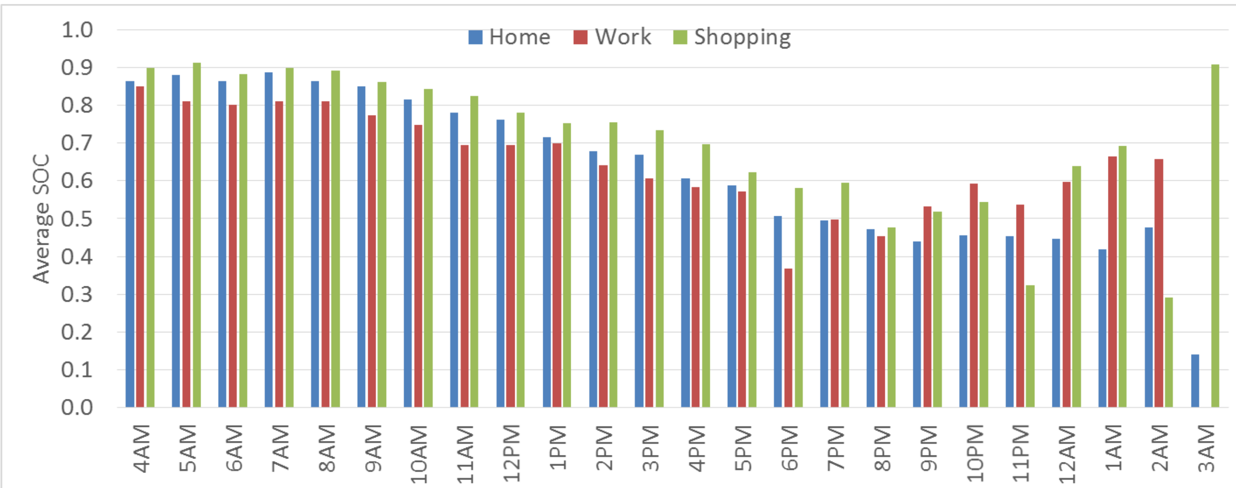


Figure 3. Average state of charge for 80-mile range EVs as a function of time for the three most popular destinations

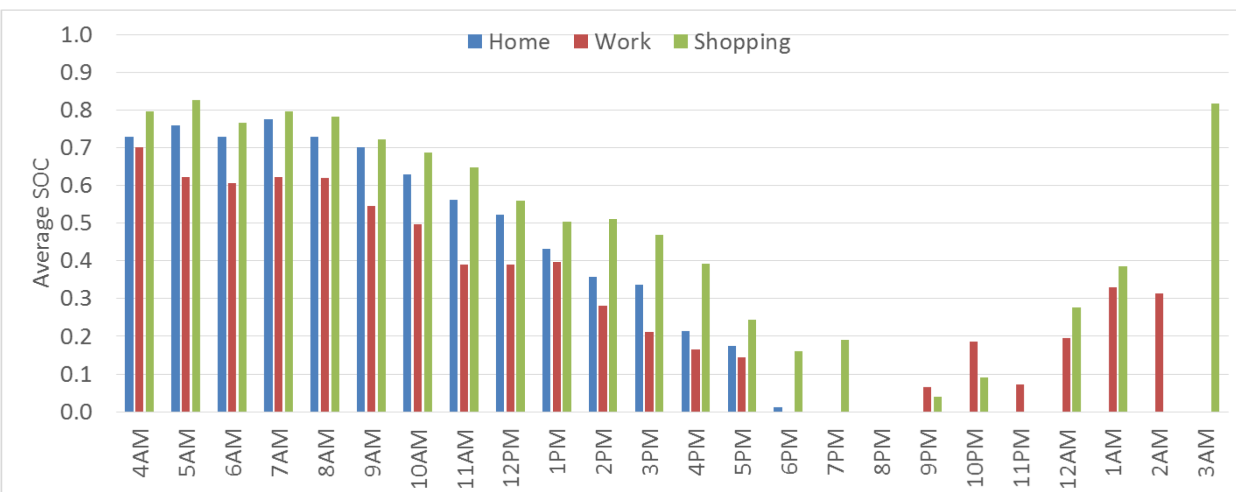


Figure 4. Average state of charge for 40-mile range EVs as a function of time for the three most popular destinations

The last aspect that was considered in this report was the driver's preference for charging. Some drivers will prefer to keep their EV fully charged, while others may be willing to go to lower SOCs. To estimate driver charging preferences, data was used from The EV Project, which tracked several thousand EV owners' charging behavior for several years. Reports from the EV Project illustrated how EV drivers plugged in their cars, which provided a distribution of charging behavior. Using this distribution, estimates were made for the frequency of charging as a function of time of day and destination (see Figure 5 and Figure 6). As can be seen, the majority of charging will occur at home for EVs, but lower range EVs will require more public and workplace charging. This analysis can also be used to determine approximate impacts on electric loads at EVSE locations.

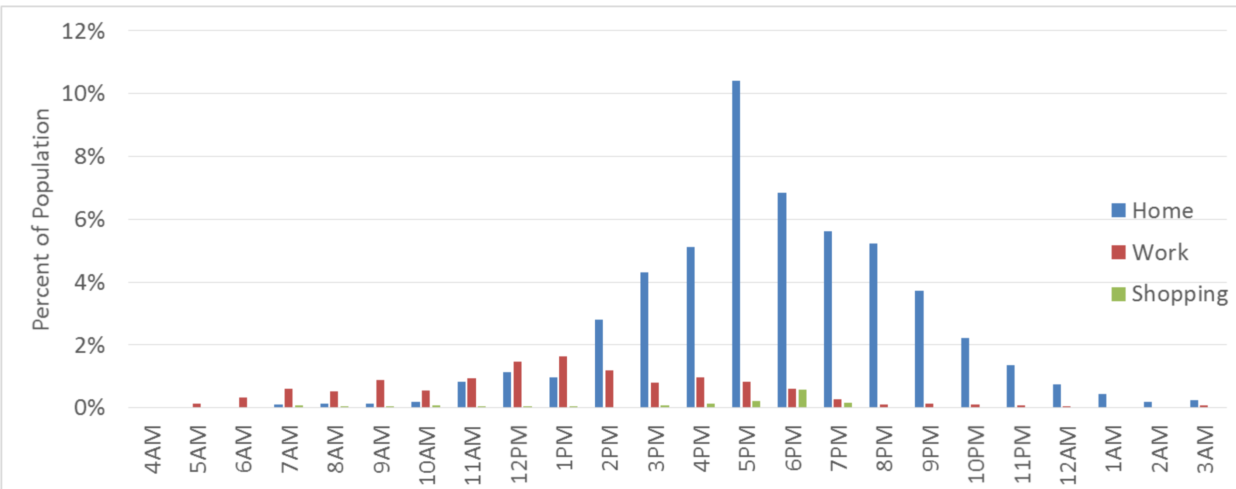


Figure 5. Percent of 80-mile range EV population charging as a function of time at the three most popular destinations

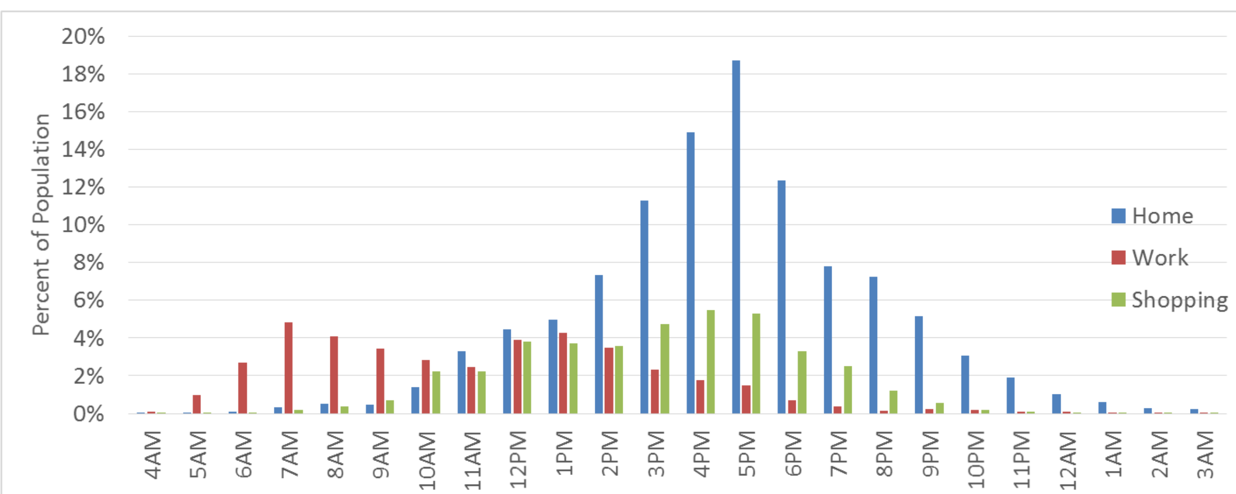


Figure 6. Percent of 40-mile range EV population charging as a function of time at the three most popular destinations

The full report[2] contains complete details on the methodology, analysis of all destinations considered by the NHTS, and consideration of EVSE power requirements as a function of destination.

PV and Batteries: From a Past of Remote Power to a Future of Saving the Grid[3]

This report focused on solar photovoltaic (PV) technology adoption, with particular attention paid to grid interconnection effects. Historically, PV systems have been adopted in remote, off-grid regions and paired with energy storage to meet the local demand. Until the early 2000's, majority of PV installations were not grid-connected, and those systems that were connected were required to disconnect whenever the grid experienced outages. As PV system deployments have increased in size and number, they have started representing a larger portion of the grid's energy supply. Furthermore, the adoption of EVs introduces new loads to the grid with a different load profile than has typically been considered by utility companies. The additional load from EVs may not require more generation capacity from utilities, but it could introduce rapid rises in load in the evening hours that could overload circuits or lower grid power quality. As PV penetration and EV adoption rates increase, the variable effects of PV generation and EV loads begin to have a greater impact on grid operations.

One approach that could mitigate these impacts is to deploy energy storage systems into the grid, either in conjunction with PV systems, or distributed at stationary sites within the grid network. The challenge with storage systems is the cost and lifetime of such a system. The role of the EV market in addressing these challenges is two-fold: first, the manufacturing of EVs requires a rapid increase in battery production scales causing a decrease in manufacturing costs; second, batteries may be employed for stationary systems once they are retired from vehicular applications.

As it relates to manufacturing scale, Figure 7 illustrates how the increased market for Li-ion batteries has contributed to the decrease in prices. As manufacturing scale increases to meet demand, economies of scale help drive per-unit costs lower. Future EV market demand for Li-ion batteries is expected to continue driving growth for battery manufacturers, which in turn will cause the prices to decline further. As of 2016, the pack-level price for Li-ion batteries was reported around $270/kWh[5].

[3] David K. Click. "PV and Batteries: From a Past of Remote Power to a Future of Saving the Grid". The Electrochemical Society Interface Vol. 24, No.1 (2015) pp. 49-51

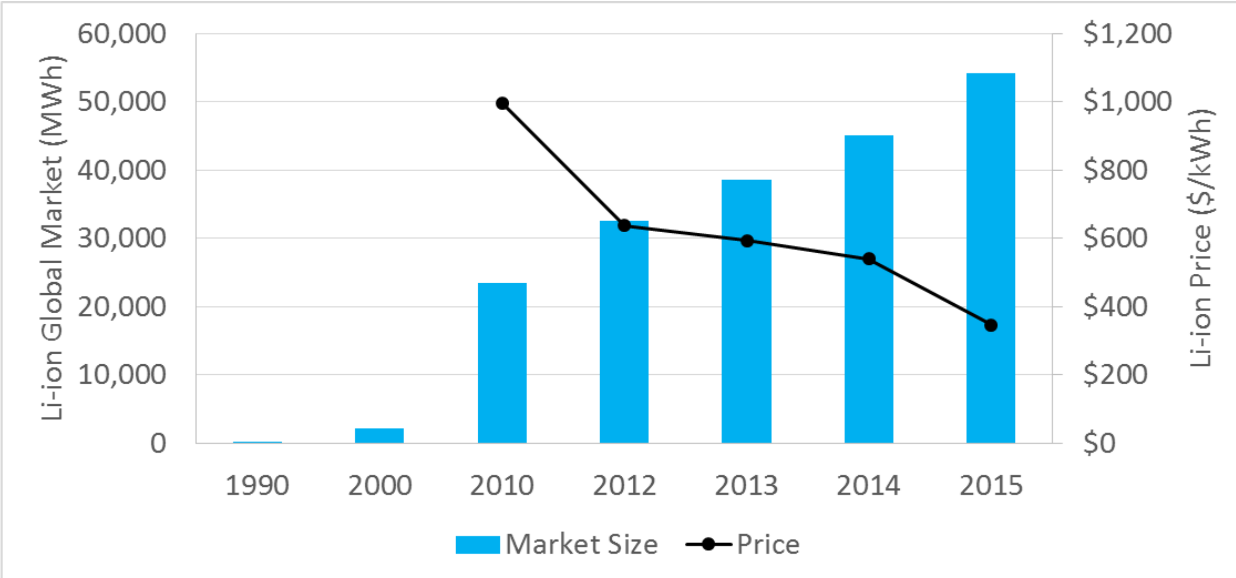


Figure 7. Global Li-ion battery market[4] and battery pack price[5] for 2010-2015

Used EV batteries are also expected to begin entering the market soon, and finding applications for stationary storage. Nissan has already unveiled an energy storage solution that utilizes used battery packs that have been refurbished[6]. This is possible since batteries for EVs often have 70% or more capacity remaining at the end of their useful lifetime in EV. This is no longer sufficient to meet an EV's travel needs, but it is possible to deploy these batteries in other applications, such as stationary storage. This represents a potential market where the price of the battery can be significantly reduced while still providing sufficient energy storage to meet the demands. However, there are safety concerns that need to be addressed before mass deployment could be envisioned and testing algorithms are being developed to ensure safety of second-life cells.

While the connection between PV and EVs is not direct, it is possible to conclude that as EV adoption increases, energy storage prices will decrease, and PV installations can take advantage of lower-cost storage options. Thus, while the presence of EVs on the electric grid has the potential for introducing detrimental effects, the secondary effect of reduced storage costs may prove to be more impactful in increasing renewable energy installations.

Peak Shaving Applications Using Solar and EVs[7]

As the previous discussion highlighted, a connection currently exists between solar PV deployment and EV adoption, through the decreased cost of energy storage technology. The purpose of this presentation was to illustrate a second, more direct connection between solar PV and EVs, through mitigating a building's energy demand. In this approach, we present a scenario

[4] Christophe Pillot, "The worldwide battery market 2011-2025" Batteries 2012, October 24-26, 2012, Nice, France.
[5] Clair Curry, "Lithium-ion Battery costs and Market" Bloomberg New Energy Finance, July 5, 2017.
[6] http://electricalsector.eaton.com/energystorage. Accessed March 15, 2018.
[7] Paul Brooker, "Peak Shaving Applications Using Solar and EVs", Renewable Energy and Sustainability Conference 2017, Florida Polytechnic University, Lakeland Florida, July 31-Aug 1 2018.

where EVs may make solar PV more economical for a commercial building through a reduction in its demand charges.

Most commercial buildings in the United States are subject to “demand charges”, which is directly proportional to the maximum power that the building drew from the grid during a billing cycle. Figure 8 illustrates an example of a monthly load profile of a commercial building. The peak power of 286kW was set on Feb 24, and resulted in a cost of $2860, in addition to the cost for energy. Often, these demand charges can represent up to 50% of a commercial building’s monthly electricity bill. Reducing demand charges has the potential for significant energy cost savings.

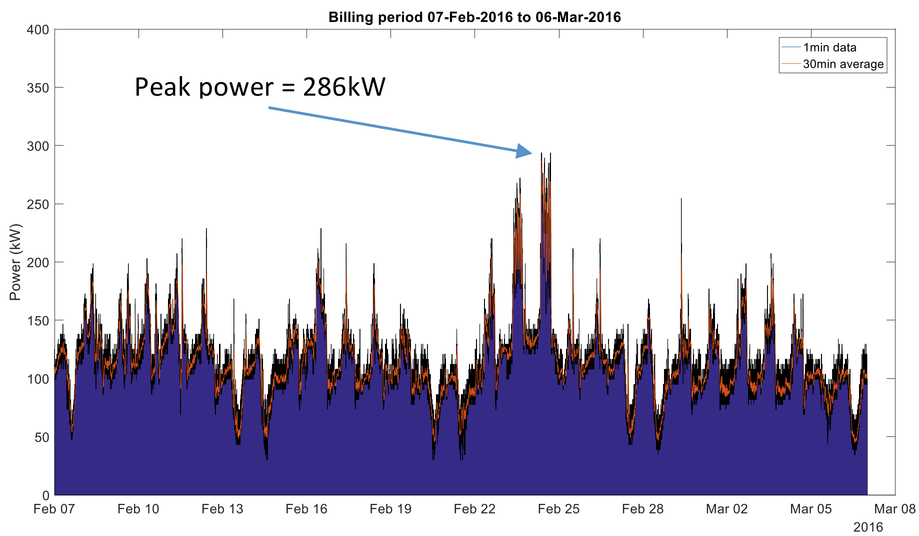
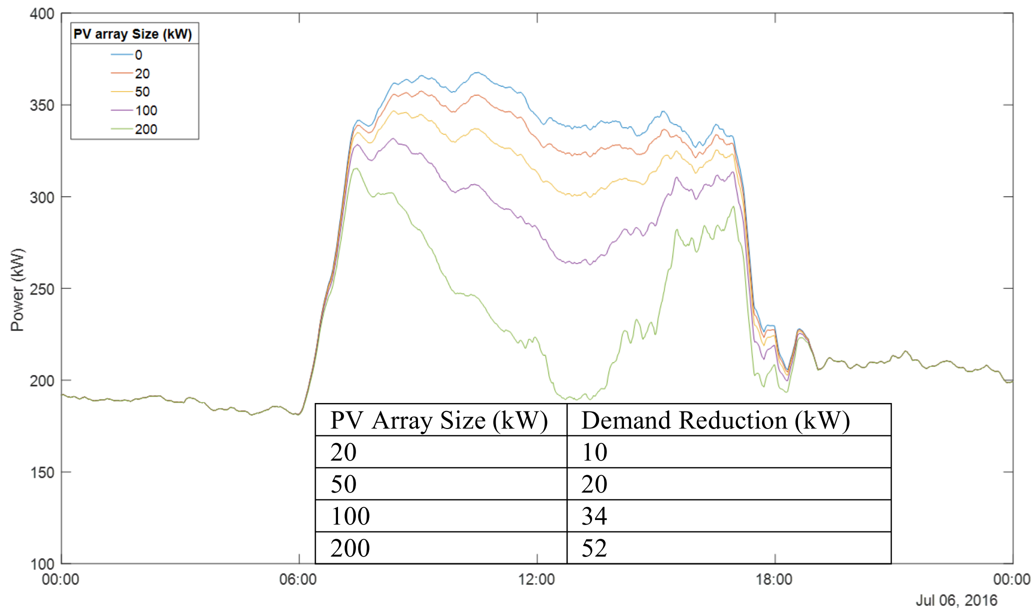


Figure 8. Building load profile for Feb 7 to Mar 7, 2016.

Solar PV installed at the site may have an ability to reduce peak demand, but only if the peak demand coincides with PV output. This was simulated by examining a building’s load profile in July and simulating different amounts of PV installed at the site (see Figure 9). As can be seen, increasing the size of the PV array will cause a decrease in peak demand. However, the PV’s impact on reducing demand decreases as the PV array size increases, due to the non-linear output of PV systems. While the larger systems are able to significantly reduce the building load in the middle of the day (during high PV output), the load earlier in the day does not see as large a reduction, since PV output is low at this time. The economics of PV on commercial buildings is further complicated by the fact that the levelized cost of energy (LCOE) of PV (in terms of $/kWh) are often higher than the energy charges from the grid. Thus, while PV may cause a decrease in the demand charges, the energy costs may increase when the energy costs of the PV are included.



PV Array Size (kW)	Demand Reduction (kW)
20	10
50	20
100	34
200	52

Figure 9. Simulated impact of PV on building load profile

Through vehicle-to-building (V2B) technology, EVs may help further reduce a building's demand profile by supplementing PV during periods when solar output is low during morning hours or periods of cloudy skies. This research investigated the impact of V2B for peak shaving on battery cycling, as well as on cost savings for the building owner.

To accomplish this task, simulations were developed that determined the maximum amount of peak shaving that could occur for PV array sizes between 0 and 200kW, using a single V2B-enabled Nissan Leaf as energy storage. For each simulation, the annual savings were calculated for the PV-only and the PV+V2B cases (see Figure 10). As can be seen, increasing the PV array size causes an increase in savings, until about 40kW, at which point the savings decrease. This is due to competing effects where the PV decreases demand charges, but it increases energy costs (i.e., PV LCOE greater than utility energy cost). When the PV array size increases beyond 40kW, the savings from the demand charges begin to be offset by the increased energy costs. At a certain point, the PV array becomes so large that the PV-related energy costs completely overwhelm the savings from demand charges, and the annual costs actually increase (i.e. negative savings).

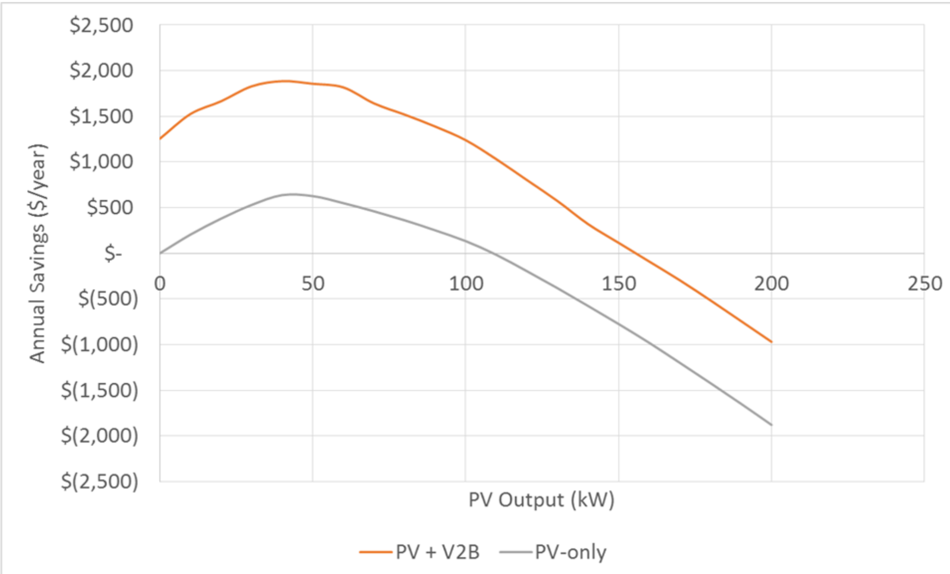


Figure 10. Annual savings in electricity costs for PV-only and PV+V2B applications

Through V2B applications, it can be seen that the annual savings increase significantly and the maximum size of the PV array increases. This is due to the increased demand charge reduction enabled by the use of energy storage that is dispatched during periods of low PV output. By optimizing both the PV and V2B applications simultaneously, it is possible to maximize annual savings and PV array size. Without V2B, the amount of PV that can be installed at a site will be limited due to a reduced savings.

Cycling effects are also evident through this modeling effort. Battery degradation is accelerated when the battery is maintained at high states of charge, or when fully discharged. The foregoing simulations identified the battery SOC for cases where the vehicle only charged at home (i.e. no V2B), or where the vehicle charged primarily at work and participated in peak shaving through V2B. For each case, the average state of charge for the battery was estimated for an entire year, as well as the equivalent number of charge/discharge cycles. These cycles were estimated based on the total energy transferred from the battery divided by the battery capacity. When the EV only charges at home, the average SOC was estimated to be 86% and the battery experienced 140 equivalent charge/discharge cycles (see Figure 11). When the EV participated in V2B activities at the workplace, the average SOC dropped to 73% while the number of equivalent cycles increased slightly to 153 (see Figure 12). Lower SOC is known to improve battery lifetime through a reduction in parasitic side reactions within the electrolyte and electrode of the cell. By maintaining an average SOC that is closer to 50%, the battery lifetime is expected to increase for the V2B case than for the no-V2B case. However, the increased lifetime from the lower SOC may be offset somewhat by the increased number of cycles that the V2B EV experienced. Reports have been published that describe these interactions[8], but further study is required to fully optimize V2G applications vs. battery lifetime.

[8] K. Uddin, T. Jackson, W.D. Widanage, G. chouchelamane, P.A. Jennings, and J. Marco, Energy 133 (2017) pp 710-722

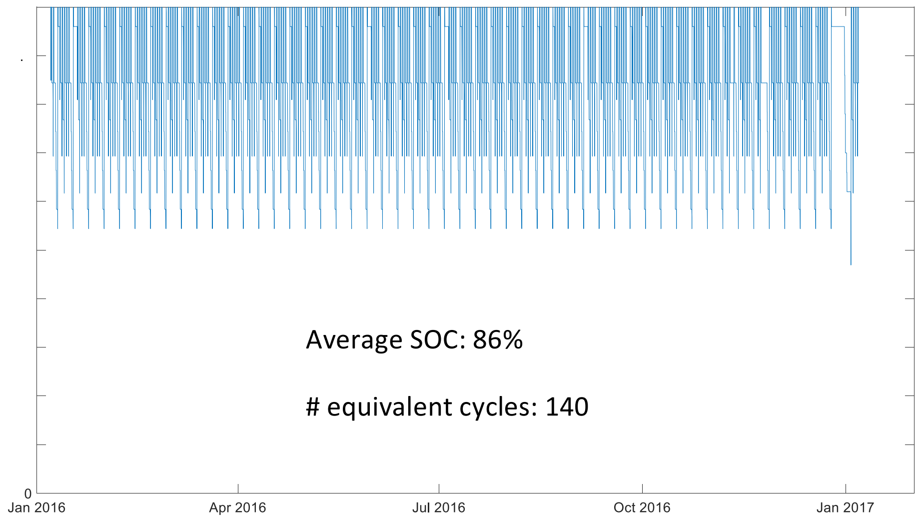


Figure 11. Battery SOC for EV charging only at home, and no V2B

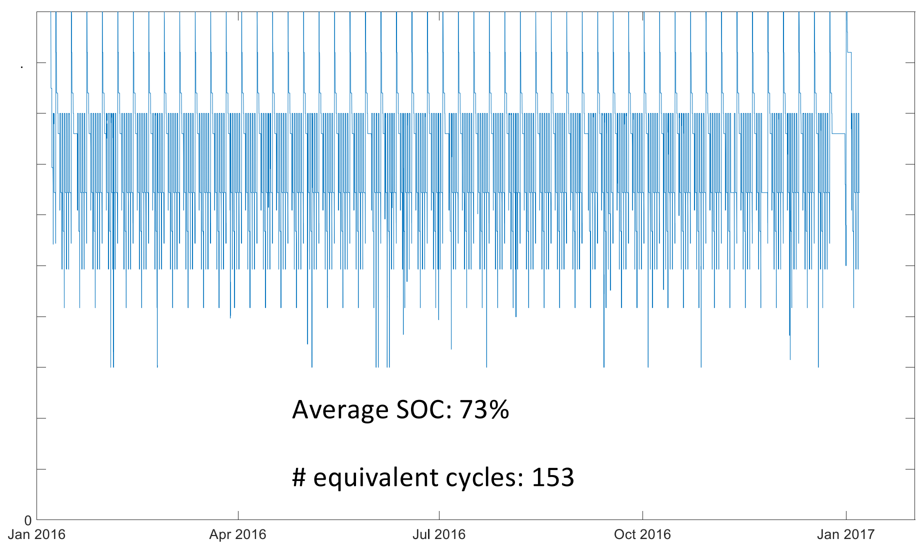


Figure 12. Battery SOC for EV charging mostly at work, and participating in V2B

3. Impacts/Benefits

(1) EV battery usage profiles are identified for a variety of applications, with consideration given to lifetime. As the application changes, the charge/discharge profile on the battery will change, requiring new approaches to determine cycle lifetimes. A good example is for the V2B case, where the average SOC may be lowered, causing a potential increase in battery lifetime. However, the additional cycles may cause a decrease in lifetime, and further study is required to fully characterize this interplay. As EV battery technology matures and more batteries enter the market, it is expected that new applications will be defined, requiring further research.

(2) National travel surveys may be useful in identifying charging behaviors for large adoption rates of EVs. Understanding where EVs will charge is necessary for identifying where charging stations should be located, but also for identifying potential impacts on the local electric grid. Grid capacity is likely sufficient to meet the additional load that EVs will present, but local circuits may be undersized to sufficiently handle the loads. Furthermore, the nature of the charging profiles may result in an increase in electric load at different locations at different times of the day. For example, the analysis presented in this report indicates that workplace charging is likely to experience a significant increase in load early in the day, while home charging will see an increase in the evening hours. Unless controls are implemented to intelligently manage charging behavior, high penetration of EVs has the potential to overload local transformers. There is also the additional impact of costs associated with charging EVs, particularly at sites with commercial demand charges. As EV charging at a commercial site increases, there is a very strong potential that the building's electricity bill will increase, and the additional cost may be passed on to the EV owners. The analysis provided in this report is a step towards understanding and planning for these interactions.