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Review article

Economic implications of lithium ion battery degradation for Vehicle-to-Grid (V2X) services

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HIGHLIGHTS

- Comprehensive review of the economic implications of Li-ion battery degradation.
- Calendar Aging is dominant life reducing factor in vehicular applications.
- Battery Degradation Cost is predominately time and temperature dependent.
- Economic analyses of degradation cost should be informed by battery lifetime models.
- V2X services can prolong battery life but cost effectiveness is chemistry dependent.

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ABSTRACT

Electric and Plug-in Hybrid Electric Vehicles are a promising sustainable mobility alternative due to their low emissions impact and the rapidly falling production costs of Li-ion batteries. To lower total vehicle ownership costs, Vehicle-to-Grid/Building/Home (V2X) services aim to derive additional value from the battery asset through dynamic or bi-directional charge control to provide benefits to the electric grid or to reduce/flatten/shift peak energy consumption of buildings. Battery State of Health (SOH) is impacted through reduction of total capacity and/or increase in internal impedance due to various degradation mechanisms which collectively result in Calendar Aging and Cycling Aging behaviors. At moderate temperatures, Calendar Aging is the dominant factor and this understanding paired with the fact that most vehicles are immobile more than 90% of the time, implies that the battery management strategy while at rest will bound lifetime. Evidence suggests that V2X could prolong battery life through integration with optimized management algorithms and that cost effective V2X services may be dependent on battery chemistry. Therefore economic analyses of battery assets should contain sufficient electrochemical detail to account for chemistry specific degradation behavior.

1. Introduction

The transportation sector accounts for around 25% of global energy-related carbon emissions of which light-duty passenger vehicles account for over half and their impact is expected to grow in the coming years [1,2]. It is clear, that to achieve the necessary carbon emission reductions agreed upon in the Paris Climate Accords there must be a substantial contribution from the transport sector [3]. Replacement of light-duty vehicles with Electric Vehicles (EV) and Plug-in Hybrid Electric Vehicles (PHEV) offers a promising alternative to take advantage of synergies between the Energy and Transport sectors, yet their effectiveness as a solution depends on a decarbonized electric grid and the availability of cost competitive battery technology.

Lithium-ion technology provides the highest specific power and specific energy over other commercial battery and storage types [4]. Battery costs have been reduced by a factor of four since 2008 and are set to decrease further; additionally, energy density of lithium ion batteries has increased substantially as seen in Figure S1 in the Supplementary Materials. Over the course of seven years from 2009 to 2015, PHEV batteries experienced an almost 400% increase in energy density [1]. As such, Lithium-ion technology offers the most promising battery solution for the near future.

While PHEVs and other hybrid topologies are already well established in the market, key barriers to large scale EV market penetration include battery costs and vehicle range, both areas where recent technology developments provide encouraging signs. Evidence suggests that

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EVs may reach price parity with Internal Combustion Engine (ICE) vehicles by 2022 [5]. There are several ongoing approaches to these barriers EV adoption.

The first approach is to lower the cost of battery packs thus lowering the Total Cost of Ownership (TCO) of EVs. This strategy is noted as the "Tesla approach", which aims to exhaust economies of scale while improving manufacturing techniques and drastically reducing shipping costs by assembling battery packs in-house.

The second is to invest in research and development of new battery chemistries and new technology. Research is directed towards the development of longer lasting and safer cells with greater energy density, thus lowering per kWh costs. This includes experimentation with new additives in electrolyte and cathode materials for longer lasting Li-ion cell chemistry [6–10]. New technologies include Lithium Sulfur (Li-S) and Lithium Air (Li-O2) battery configurations, the use of solid electrolytes over organic liquid electrolytes for the creation of Solid State Batteries (SSB), and incorporation of new anode materials such as Silicon and Titanate [11–16].

The third approach is related to developing more intelligent Battery Management Systems (BMS) to allow for smaller batteries to satisfy the same mobility demands, thus lowering the TCO of EVs through decreased capacity requirements and the additional cost savings from reduction in vehicle weight [17,18].

The fourth approach, which is the focus of this review, is to develop new revenue streams to offset the high initial cost of EVs through participation in energy markets and provision of grid services, or through diminishing the energy burden of buildings or homes. Vehicle-to-Grid (V2G), Vehicle-to-Building (V2H), Vehicle-to-Home (V2H), Vehicle-to-Load (V2L), and Vehicle-to-Vehicle (V2V) collectively denoted as V2X services, aim to derive additional value from the battery asset during times of non-use in the primary objective of mobility [19].

1.1. V2X Services

Unlike the standard load demands that EV battery packs which are designed for mobility-only undergo, the resultant load demand from a V2X product is inherently dependent on the underlying energy service. Thus V2X should be considered an umbrella term under which several distinct energy services can be provided therefore a generalized V2X load profile does not exist. It is however possible to develop load profiles for individual V2X products depending on the connection topology (V2G, V2B, V2H, V2L, and V2V) and the energy service being provided (Frequency Regulation, Energy Arbitrage, Emergency Back-up Power, etc.) as elaborated in the following sections 1.1.1 and 1.1.2.

V2X can be generalized into energy based products and power based products. Bulk energy transfer products such as performing V2G energy arbitrage (charging/buying electricity during times of low energy prices and discharging/selling during periods of high energy prices), providing V2G spinning reserves (bulk energy discharge or dynamically altering charge rate in response to grid requirements), acting as a Demand Response (DR) resource, or serving as emergency back-up power (V2H/V2B), all result in similar load profiles in that a large energy throughput is required which translates to long periods of charging or discharging for a vehicle battery. Frequency of use, daily timing, and utilization rates for each service will differ however and are further elaborated in Section 5.2.2. Power products however (most notably V2G frequency regulation) where fast response time is crucial will result in significantly less energy exchange as the inherent energy service is charge/discharge flexibility. Fig. 1 below is a visual overview the various V2X topologies which shows interaction type with grid operators and operating location either in the High Voltage (HV), Medium Voltage (MV) or Low Voltage (LV) networks [20]. Note that a V2B topology is similar to the V2H pictured with the addition of multiple vehicles or a fleet which implies a more sophisticated building energy management system but the concept is the same. Additionally the V2L and V2V topologies are similar.

1.1.1. Vehicle-to-Grid (V2G)

Vehicle-to-Grid services relate to utilizing an electric vehicle battery as either a Distributed Energy Resource (DER) or as storage for the electric grid. V2G is envisioned to predominately provide Ancillary Services due to the inherent characteristics of an EV resource which include a near-instantaneous response time and limited energy capacity. Four potential products exist in current energy markets for V2G services: Spinning Reserves, Peak Power Shaving (also known as Energy Arbitrage), Frequency Regulation (or Regulation Reserves), and Demand Response [21–23].[1] While the other Ancillary Services have been shown to be economically competitive in certain situations, Frequency Regulation has been identified as the first most promising and lucrative market due to its inherent characteristics which include a seconds-time interval response requirement and a low net energy requirement with relatively high market prices [21,24]. Figure S2 in the Supplementary Materials is an example frequency regulation load profile which compares PJM's Reg A (Ordinary Regulation, net energy variable) and Reg D (Fast Response Regulation, net energy neutral) signals and their impact on battery State-of-Charge (SOC) of a Battery Energy Storage System (BESS) [25]. Due to the inherent nature of the usage case (high frequency charging/discharging load profile) a low net energy exchange and a shallow charge/discharge cycle results which is known to be less detrimental to batteries as will be explained in Section 3.

The US Frequency Regulation Market is highly volatile which often experiences price spikes of over 100 ($/MW-h) while typical prices can range from 5 to 65 ($/MW-h) depending on the regional market. Market revenue has grown from under $20 million in 2009 to over $380 million in 2014; however Frequency Regulation is a relatively shallow market with an average capacity requirement of 410 MW [26]. Due to these characteristics, it is envisioned that V2G would likely provide Frequency Regulation first while descending the technology learning curve until market saturation and later expand into larger markets.

Lazard's Levelized Cost of Storage (LCOS) analysis has identified that non-subsidized stationary lithium-ion Battery Energy Storage Systems (BESS) on the high-end have already achieved cost competitiveness with conventional gas peaker plants for Frequency Regulation services as of 2015, with projected 5-year developments likely to lead to full cost competitiveness across all installations [27]. Subsequent analysis showed an estimated 5-year capital cost reduction of Lithium-ion Batteries between 26 and 29% [28]. The question remains however, if lithium ion technology in an electric or plug-in hybrid vehicle configuration can deliver a similar value proposition.

Current Ancillary Service regulation requires a minimum capacity to bid into the market ranging from 100 kW–5 MW [29,30]. These rules constitute a barrier to entry for small capacity resources yet reflect the reality that only significantly large loads are economically worth controlling during real-time grid operation. While an EV charging at even the lowest L1 charging power will draw roughly 2 kW which would double the instantaneous power requirement of a household, it is a negligible amount in the context of the transmission grid. However, 100 EVs charging simultaneously would be well above the minimum capacity requirement regardless of the charging level used. As such, V2G is likely to be employed by an aggregator which intelligently coordinates several distributed resources to provide grid-significant capacity [31,32].

[1] These Ancillary Service products are from US energy market definitions. In Europe these Ancillary Services have recently been redefined as Frequency Containment Reserves (FCR), Frequency Restoration Reserves (FRR), and Replacement Reserves (RR) in efforts to harmonize the various definitions across EU Member States [112]. Other international markets may have additional definitions for Ancillary Services.