# Electric Vehicles and Smart Grid Integration: Analysis of Battery Degradation Cost


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***Abstract*— Batteries of plug-in electric vehicles (PEVs) can be used in vehicle-to-grid (V2G) systems for controlled bidirectional power flow between the vehicles and the power grid. Some benefits of V2G include the use of PEVs to provide ancillary services to the grid. However, there are concerns about PEV use for these services, particularly about the degradation of vehicle batteries due to frequent charging and discharging. In this study, a model is used to calculate the total cost of battery degradation for a significant number of vehicles as a result of V2G. Battery degradation is considered to be caused by cycling aging because this type of aging occurs during the V2G process. Simulation is conducted to determine how the battery degradation cost changes based on competing objectives. This study demonstrates the importance of considering PEV battery health during V2G operation and shows how battery degradation can be affected by the different objectives of the aggregator and PEV owners.**



***Keywords*— Vehicle-to-grid, electric vehicles, battery degradation, smart grid, optimization**


## I. Introduction

Global carbon emissions have been on the increase. Compared to other sectors, the transportation sector is the most reliant on fossil fuels and accounts for 37% of $CO_2$ emissions [1]. Despite a decrease in $CO_2$ emissions in 2020 due to the COVID-19 pandemic, the demand for transport is rebounding and is expected to continue to increase at a rapid pace [2]. Plug-in electric vehicles (PEVs) are fast becoming more popular as a viable option for reducing carbon emissions from transport. Despite the advantages of PEVs, integration of a considerable number of PEVs into the power system can lead to an undesirable impact on the power system's quality of electricity if this integration is not adequately managed [3]. As a result, the smart grid network is required to control the charging demand of PEVs to ensure both the needs of PEV drivers and the power grid are met. Although controlled vehicle-to-grid (V2G) can be effective in addressing demand and frequency problems with the power grid and can result in promising economic benefits, the frequent cycling of batteries during V2G operation may lead to battery degradation.

This paper which builds on a previous study by Egbue and Uko [4], presents a V2G optimization model to maximize the aggregator profit and satisfy customer needs while considering the cost of battery degradation in a heterogeneous PEVs population. Furthermore, this study presents a battery degradation model that accounts for the cost of cycling a vehicle battery while conducting V2G services.

## II. Related Work

Several studies have examined V2G as a regulation resource, where aggregators participating in supplementary frequency regulation (FR) employ dispatching strategies to maximize their profits. Egbue, et al. [5] proposed a unit commitment model for a V2G system considering different penetration levels of PEVs and accounting for battery degradation of the vehicles. This study used historical driving patterns and different battery capacities to simulate PEVs demand and calculate the cost of battery degradation due to V2G activities. An earlier study [6], investigated the impact of different penetration levels of PEVs on the optimal economic dispatch problem (EDP). David and Al-Anbagi [7] presented an economic assessment model of PEVs participating in FR and calculated the cost, including battery degradation cost, and revenue for both PEV drivers and the aggregator.

In [8], a high frequency control model is proposed where the regulation dispatch is based on the capacity for regulation in charging stations and the maximum allowable power. Normal distribution was used for plug-in and plug-out times with plug-in time and SOC constraints, however the battery degradation was not considered. Tayarani, et al. [9] introduced a framework for charging and discharging of PEVs implemented in a 21-node distribution system with renewable energy sources included as distributed generation units. Their results show the degradation levels for different scenarios, which included uncontrolled charging, smart grid to vehicle (G2V) charging and smart V2G charging. Though the V2G charging mode was effective in reducing the purchased energy cost in comparison with the G2V mode, the study found that the degradation cost in V2G mode was higher than in G2V mode. In [10], a dispatching strategy was proposed to satisfy driving demand and maximize the aggregator profit while optimizing load frequency control. Required SOC for each vehicle is calculated based on the average daily driving range and the maximum battery capacity. Only PEVs with allowable SOC are selected to participate in FR to meet customer needs and battery degradation was not considered. Triviño-Cabrera, et al. [11] proposed a charging strategy for the operation of a V2G system with a simplified battery degradation model. Their proposal focused on the routing of vehicles to increase their charging revenue. Results show that the optimal routing of the vehicles achieved a significant increase in energy transfer. Battery degradation was also considered in their study.

Although the cost of Li-ion battery has continuously declined over the past decade, batteries are still the most expensive PEV component [12]. This makes battery degradation cost a key factor in customer's decision to participate in V2G. Several factors, such as temperature, state of charge (SOC), time, cycle number, depth of discharge (DOD), cause the battery's power and capacity to decline. The measurement of battery life can be quantified by the calendar life or the number of cycles [13]. Calendar aging estimates degradation due to the ambient conditions. Cycling aging is estimated based on the cycle number, charge rate, and the depth of discharge. Cycling aging occurs during charging and discharging of the battery during driving or in a smart charging scenario such as in V2G implementation [14].

This study presents an optimization model for scheduling the charging and discharging of PEVs and considers vehicle battery degradation caused by cycling during V2G services. For every period, the study accounts for how cycling and depth of the discharge result in degradation of vehicle batteries. Calendar aging is outside the scope of this study.

## III. Problem Formulation

The optimization model is formulated as a multi-objective problem proposed by [4]. The first objective function shown in (1) minimizes the cost of charging for PEV drivers in the system. This is accomplished by charging PEV batteries during periods of low electricity prices when the price for charging is less and discharging the batteries during periods of higher electricity prices where possible.

$$min \sum_{t=1}^{T}\sum_{i=1}^{I} Ccost_t * Cchg_{i,t} - \sum_{t=1}^{T}\sum_{i=1}^{I} Dcost_t * Cdch_{i,t} \quad (1)$$

The total cost of charging is the product of cost of charging at time t, $Ccost_t$ and the charging power of vehicle i during period t, $Cchg_{i,t}$. The total cost of discharging, shown in the second part of the equation is the product of proceeds from discharging at time t, $Dcost_t$ and the discharging power, $Dchg_{i,t}$ . Both the charging and discharging power are assumed to vary between 0 and 6.6 kW. In this study $Dcost_t$ is assumed to be equal to $Ccost_t$. The second objective function shown in (2) maximizes the aggregator's earnings.

$$max \sum_{t=1}^{T} Ptotal_t * (Ccost_t - Cbuy_t) - \sum_{i=1}^{I}(Tsoc_i - Fsoc_{i,t}) * PC_t \quad (2)$$

Where $Ptotal_t$ is the total PEV power flow. The first term of the equation represents the revenue generated by the total power $P_{total}^{t}$ ,while the second term of the equation describes the penalty cost calculation which is based on the target customer SOC, $Tsoc_i$ , the actual SOC at departure, $Fsoc_{i,t}$ , and a penalty cost $PC_t$ which is incurred when vehicles are not charged to their desired SOC.

The depth of discharge (DOD) is considered when accounting for the cycle aging in PEV batteries and was formulated according to the study by Fernández, et al. [15] and Czechowski [16]. In this study, the DOD is determined by considering a cycle where a battery begins discharging to a certain depth and charging back to its initial SOC when the discharge cycle started. The constraint in (3) ensures that at any given time a vehicle status can only be charging, discharging or stable (i.e., neither charging nor discharging).

$$charge_{i,t} + discharge_{i,t} + stable_{i,t} = 1 \ \forall \text{ I} \quad (3)$$

The DOD is only calculated when the current direction changes sign. Therefore, a cycle begins when discharging starts and ends when the current changes direction to charging. The DOD obtained from this formulation is multiplied by 2 to account for the equivalent charging of the battery back to its initial capacity when the discharging cycle began. The constraints below account for the formulation of the cycles and the DOD.

$$cend_{i,t} = 1 \Rightarrow DOD_{i,t} = soc\_start_{i,t} - soc\_end_{i,t} \ \forall \text{ i}, t \quad (4)$$

DOD is determined at the end of the cycle $cend$ by subtracting the SOC at the end of the cycle, $soc\_end_{i,t}$ from the SOC at the beginning of the cycle, $soc\_start_{i,t}$ . Calculation of the cost of degradation was deduced from a model proposed by Ahmadian, et al. [14] shown in (5).

$$Cdeg = \sum_{i=1}^{N} Cbattery * \frac{Dtotal}{\text{Qo} - \text{Quseful}} \quad (5)$$

Where $Dtotal$ is the sum of calendar aging and cycle aging. To determine the cycle aging, this paper assumes a linear approximation of the relationship between aging per cycle and cycle depth of discharge. The cost of the battery for calculating the degradation cost was obtained from a study by [17]. The modified battery degradation model is shown in (6).

$$Cdeg = \sum_{i=1}^{N}(\text{Cbattery} + \text{Clabor}) * 2 * \frac{\sum_{t=1}^{48} Dv2g_{i,t}}{\text{Qo} - \text{Quseful}} \quad (6)$$

Where Clabor is the replacement cost of the vehicle battery, Quseful is the useful capacity of the battery and is assumed to be 80% of the battery's capacity, $Dv2g_{i,t}$ accounts for the DOD due to cycling during V2G operation as well as a factor to capture the linear approximation of the relationship between the DOD and aging per cycle.

Driver attributes such as the average commute distance to several destinations and the dwell time at each destination are based on data obtained from the National Household Travel Survey [18]. The electricity pricing information was obtained from ComEd [19].

## IV. Results and Discussion

Based on the simulation results, the impact of the optimization objective to minimize the total cost of customer participation in the V2G system and the objective to maximize the aggregator profit on battery degradation costs can be observed. Similar to the study by Egbue and Uko [4] three points on the Pareto front for both objectives are selected for further examination. These include the point that represents the minimum customer cost (Case 1), a point close to the midpoint between the highest and lowest points on the Pareto front (Case 2), and the point representing the maximum aggregator profit (Case 3). In addition, a case where V2G does not occur is considered (Case 4). Optimization or discharging of vehicle batteries do not occur in case 4.

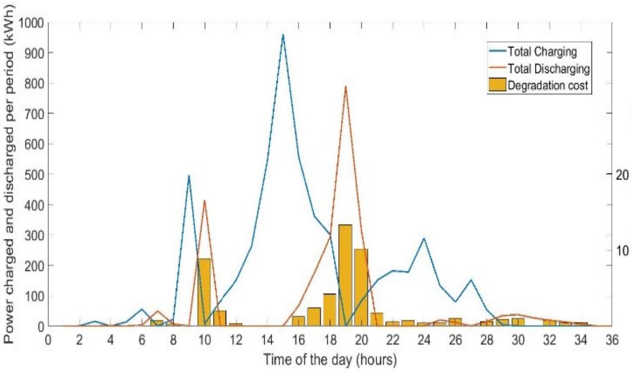


Fig. 1. Total charged power, total discharged power, and degradation cost for case 1.

Fig. 1 illustrates the charging and discharging behavior of vehicles as well as the degradation cost for case 1. As can be observed, the degradation cost follows the discharging pattern. Therefore, the more discharging that occurs, the higher the degradation cost. Since the objective is to minimize the customer cost, PEVs mostly charge the least amount possible in order to keep costs low. Vehicles that arrive with an SOC higher than their minimum required SOC discharge their batteries to reach this minimum level in order to reduce their costs.

Fig. 2 shows the total amount of power charged and discharged in case 2 where both aggregator and PEV drivers' objectives are strongly considered. As the figure shows, there is more discharging occurring in this case as the priority of the aggregator's profit maximation is increased. As shown in Fig. 3, there is also an increase in discharging in case 3 compared to case 1 because, in this case, the aggregator maximizes profit by carrying out more cycling of the PEV batteries.

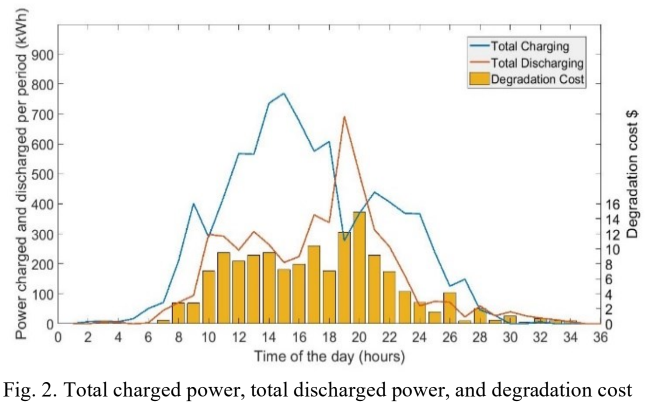


Fig. 2. Total charged power, total discharged power, and degradation cost for case 2.

Table 1 summarizes costs for the various cases analyzed in this study. As can be observed from the table, the highest battery degradation cost of $144.03 occurs in case 2. In this case, the aggregator's profit is increased while the customer charging cost is kept significantly lower than in cases 3 and 4. These conditions require an increase in the number of cycles performed on the battery, which increases the battery degradation cost. In comparison, case 4 which does not include any charging/discharging optimization or V2G activity, had the worst performance in terms of minimizing customer cost. In terms of the aggregator's profit, case 4 has the second highest amount.

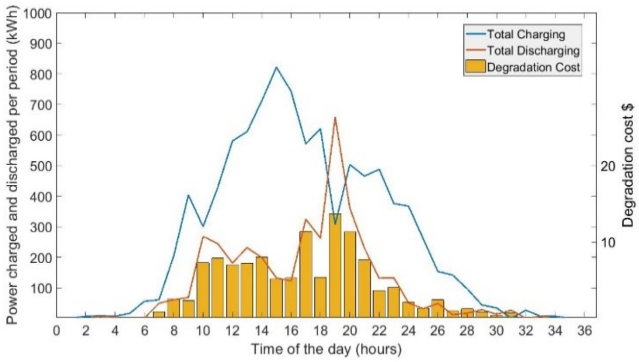


Fig. 3. Total charged power, total discharged power, and degradation cost for case 3.

Table 1: Summary of V2G and Non-V2G Costs

| Case # | Customer cost ($) | Aggregator profit ($) | Battery degradation cost ($) |
|---|---|---|---|
| Case 1 | 1339.73 | 564.16 | 53.38 |
| Case 2 | 1821.59 | 2468.06 | 144.03 |
| Case 3 | 2755.99 | 3645.90 | 121.183 |
| Case 4 (No V2G) | 2982.65 | 2306.13 | 0 |

Case 4 demonstrates the effectiveness of the customer charging cost reduction objectives and the aggregator profit maximization objectives when compared to a case where no optimization takes place. Furthermore, the results indicate that degradation costs are higher in cases with significant consideration for maximization of aggregator profit.

## V. CONCLUSIONS

The multi-objective optimization model in this study considers objectives for PEV drivers and the V2G system aggregator. Optimization was conducted with the aim of determining how battery degradation cost vary with shifts in priorities. The objectives were solved together employing a Pareto front of the best non-dominated solutions. By having different optimal solutions generated on a Pareto front, system planners and administrators can choose the best solution based on the system requirements or priorities. Finally, the results show the effectiveness of the optimization model in achieving the objectives compared to a non-V2G case where no optimization takes place.

Future work includes the consideration of the impact of calendar aging on the cycling aging of PEV batteries during V2G operations. In addition, future work can determine the optimal number of cycling for individual PEV based on factors such as battery capacity and battery age.

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## REFERENCES

[1] International Energy Agency, "Transport. Improving the sustainability of passenger and freight transport, IEA 2022 Ministerial Meeting ", 2022. [Online]. Available: https://www.iea.org/topics/transport
[2] S. McBain and J. Teter, "Tracking Transport 2021," 2021. [Online]. Available: https://www.iea.org/reports/tracking-transport-2021
[3] D. Ascher and G. Hackenberg, "Integrated transportation and power system modeling," in *2015 International Conference on Connected Vehicles and Expo (ICCVE)*, 19-23 Oct. 2015 2015, pp. 379-384, doi: 10.1109/ICCVE.2015.23.
[4] O. Egbue and C. Uko, "A Multi-Objective Optimization Model for Vehicle-To-Grid Systems," in *Industrial and Systems Engineering Annual Conference and Expo*, Orlando FL, May 18-21 2019, 2019.
[5] O. Egbue, C. Uko, A. Aldubaisi, and E. Santi, "A Unit Commitment Model for Optimal Vehicle-to-Grid Operation in a Power System," *International Journal of Electrical Power & Energy Systems,* vol. 141, p. 108094, 2022.
[6] C. Uko, O. Egbue, and D. S. Naidu, "Economic Dispatch of a Smart Grid with Vehicle-to-Grid Integration," in *2020 IEEE Green Technologies Conference(GreenTech)*, Oklahoma City, OK, 1-3 April 2020, pp. 148-152, doi: 10.1109/GreenTech46478.2020.9289782.
[7] A. O. David and I. Al-Anbagi, "EVs for frequency regulation: cost benefit analysis in a smart grid environment," *IET Electrical Systems in Transportation*, vol. 7, no. 4, pp. 310-317. [Online]. Available: https://digital-library.theiet.org/content/journals/10.1049/iet-est.2017.0007
[8] H. Liu, K. Huang, Y. Yang, H. Wei, and S. Ma, "Real-time vehicle-to-grid control for frequency regulation with high frequency regulating signal," *Protection and Control of Modern Power Systems,* vol. 3, no. 1, p. 13, 2018/05/21 2018, doi: 10.1186/s41601-018-0085-1.
[9] Tayarani, Jahangir, Nadafianshahamabadi, Golkar, Ahmadian, and Elkamel, "Optimal Charging of Plug-In Electric Vehicle: Considering Travel Behavior Uncertainties and Battery Degradation," *Applied Sciences,* vol. 9, no. 16, 2019, doi: 10.3390/app9163420.
[10] C. Peng, J. Zou, L. Lian, and L. Li, "An optimal dispatching strategy for V2G aggregator participating in supplementary frequency regulation considering EV driving demand and aggregator's benefits," *Applied Energy,* vol. 190, pp. 591-599, 2017/03/15/ 2017, doi: https://doi.org/10.1016/j.apenergy.2016.12.065.
[11] A. Triviño-Cabrera, J. A. Aguado, and S. d. l. Torre, "Joint routing and scheduling for electric vehicles in smart grids with V2G," *Energy,* vol. 175, pp. 113-122, 2019, doi: 10.1016/j.energy.2019.02.184.
[12] M. S. Ziegler and J. E. Trancik, "Re-examining rates of lithium-ion battery technology improvement and cost decline," *Energy & Environmental Science,* 10.1039/D0EE02681F vol. 14, no. 4, pp. 1635-1651, 2021, doi: 10.1039/D0EE02681F.
[13] J. Guo, J. Yang, Z. Lin, C. Serrano, and A. M. Cortes, "Impact Analysis of V2G Services on EV Battery Degradation -A Review," in *2019 IEEE Milan PowerTech*, 2019, pp. 1-6, doi: 10.1109/PTC.2019.8810982.
[14] A. Ahmadian, M. Sedghi, A. Elkamel, M. Fowler, and M. Aliakbar Golkar, "Plug-in electric vehicle batteries degradation modeling for smart grid studies: Review, assessment and conceptual framework," *Renewable and Sustainable Energy Reviews,* vol. 81, pp. 2609-2624, 2018, doi: 10.1016/j.rser.2017.06.067.
[15] I. J. Fernández, C. F. Calvillo, A. Sánchez-Miralles, and J. Boal, "Capacity fade and aging models for electric batteries and optimal charging strategy for electric vehicles," *Energy,* vol. 60, pp. 35-43, 2013, doi: 10.1016/j.energy.2013.07.068.
[16] K. Czechowski, "Assessment of Profitability of Electric Vehicle-to-Grid Considering Battery Degradation," Master Programme in Mathematics, KTH Royal Institute of Technology, 2015. [Online]. Available: www.kth.se/sci
[17] D. Coffin and J. Horowitz, "The Supply Chain for Electric Vehicle Batteries," *Journal of International Commerce and Economics,* 2018. [Online]. Available: https://www.usitc.gov/publications/332/journals/the_supply_chain_for_electric_vehicle_batteries.pdf.
[18] Federal Highway Administration. "National Household Travel Survey." U.S. Department of Transportation. Federal Highway Administration. https://nhts.ornl.gov/ (accessed November 30, 2018).
[19] ComEd. "ComEd's Hourly Pricing Program." https://hourlypricing.comed.com/ (accessed November 10, 2019).