On Beneficial Vehicle-to-Grid (V2G) Services

Edward Bentley
Dept. MPEE, Northumbria University
Newcastle upon Tyne, UK
edward.bentley@northumbria.ac.uk

Ghanim Putrus
Dept. MPEE, Northumbria University
Newcastle upon Tyne, UK
ghanim.putrus@northumbria.ac.uk

Gill Lacey
School of Comp., Eng. & Digital Tech.
Teesside University, Middlesbrough, UK
g.lacey@tees.ac.uk

Richard Kotter
Dept. GES, Northumbria University
Newcastle upon Tyne, UK
richard.kotter@northumbria.ac.uk

Yue Wang
Dept. of Eng., Chichester University
Bognor Regis, UK
yue.wang@chi.ac.uk

Ridoy Das
UK Energy Systems Catapult
Birmingham, UK
ridoy.das@es.catapult.org.uk

Zunaib Ali
Dept. MPEE, Northumbria University
Newcastle upon Tyne, UK
zunaib.ali@northumbria.ac.uk

Jos Warmerdam
Faculty of Urban Technology
Amsterdam Uni. of Applied Sciences, Amsterdam, NL
j.m.warmerdam@hva.nl

Abstract

A number of studies have investigated the possibility of extending Electric Vehicle (EV) Lithium-ion battery life by deliberately choosing to store the battery at a low to moderate state of charge. Recently, there has been considerable interest shown in the scheme of a deliberate discharge and subsequent recharge of a battery to yield an overall reduction in battery degradation whilst carrying out Vehicle-to-Grid (V2G) services (so-called 'beneficial V2G'). This paper presents an investigation of the conditions permitting successful operation of this method by examining incremental time variation of the relevant parameters for two types of cells from results of the same physical size and chemistry, and similar capacity. These two types of cells are found in this present analysis to offer differing degrees of suitability for beneficial V2G.

Keywords—Electric Vehicle, Battery Degradation, V2G

I. Introduction

The concept of using the storage capacity of EV batteries via bi-directional chargers to support the power grid for balancing short-term variations in power supply and demand is very attractive. This would be one way of increasing the use of intermittent renewable energy sources. This process as part of V2G can also permit a reduction in peak power demand by 'time shifting' [1]; that is, EVs supplying power at the peak demand time and recharging when aggregate demand is low. This latter use of V2G can postpone (or even partially avoid) the need to reinforce the network [2], as EVs become more commonplace and the power demand due to their charging requirements increases. Thus, as the number of EVs rises, they could be used to support the power network and offset the additional stresses which their charging causes. Other functions of grid support via V2G are also possible, e.g. Firm Frequency Response (FFR) [3] to stabilize the grid and avoid power disruption for which a business case could be most easily made currently (though it does depend on the framework conditions that may change with the increase in EVs) [4]. In this application, an aggregation of EVs would provide power to the grid when the frequency falls below nominal and absorb power when the grid frequency exceeds its nominal value. The projected value of V2G to the economy motivated the UK government in 2017 to provide funding of around £30 million for innovative projects that develop future V2G products, services and knowledge [5]. The UK government's decision [5] had apparently been favourably influenced by recent research reported, such as [6-9] in which laboratory cell testing suggested that, under appropriate conditions, carefully managed V2G could actually extend Li-ion battery life. In a UK Government sponsored meeting for industry and academia in August 2017 [5], which was used to launch the advertised UK £30m V2G initiative, UK Civil Servants indicated that in their view V2G had been shown to be potentially beneficial to an EV battery [6]. It was felt by them to be sensible for the UK to consider largely bypassing the adoption of 'Smart Charging' (whereby EV charging is done at such times as the network has spare capacity) and perhaps to move straight towards the widespread adoption of V2G in the UK. Innovation, research and development and market testing funding was accordingly allocated for this purpose.

Li-Ion batteries used in EVs have a finite lifetime in terms of the number of charge/discharge cycles which they can provide before their storage capacity falls to their end of useful automotive life. The latter is widely taken to be when capacity falls to around 80% of nominal capacity [10,11] and/or their internal resistance rises by 100% [12]. Using an EV battery, whether for driving or for grid support, will therefore tend to reduce its remaining life. The cost of EV batteries is currently still high, around \$137 /kWh as of December 2020[13], so any additional use of the battery over and above its prime purpose for transportation may carry an appreciable cost due to the associated additional battery degradation. If the costs of V2G induced additional degradation exceeding the price obtainable by an EV owner for providing the V2G intervention concerned, then it may not prove to be an economical proposition for that actor.

Whilst battery technology is developing rapidly currently the topic of beneficial V2G is still subject to debate since a number of studies have analysed battery degradation due to V2G and come to differing conclusions [7] [14-18]. In [14-18], the battery degradation cost for V2G provision was calculated as a function of the percentage decrease in equivalent cycles due to the V2G service provision, which would increase the related cost. In [15], batteries were tested under standard profiles and their cycling life was found to be long enough to result in a low battery degradation cost. Another study [16] evaluated the impact of different charging strategies, namely as-fast-as-possible, smart charging and V2G on battery degradation and concluded that V2G always increases the degradation cost, and similar conclusions were reached in [17]. The work in [18] adopted a battery life model for lithium-ion batteries and considered cycling degradation; this resulted in higher costs when V2G was provided, except in the particular case where wind energy utilisation is increased. The models adopted in [14-18] depicted V2G always as additional cycling since battery power exchange is involved, which is detrimental to the battery. Therefore, an economically viable V2G was achievable when the revenues from the V2G services exceeded the associated battery degradation cost. The research set out in [7] on the other hand followed [6] to some extent, showing that performing grid services at low average State of Charge (SOC) arising from bi-diurnal charging can lead to a longer battery life when compared to a case where V2G was not provided and the averaged SOC level was higher due to daily charging activity. In [8], it was shown that smart charging involving limited V2G at low initial SOC, charging before departure, and less frequent charging can extend battery life when compared to uncontrolled charging. In research reported by [9], it was found that calendar degradation and cycling degradation are both reduced at a low SOC. As a result, it was possible - via a V2G design - to minimise the occurrence of high levels of SOC, and thus to increase the life of the cells considered by 60% compared to the results of uncontrolled charging.

Previous studies, such as [19] and [20] which considered the Vehicle-to-Grid (V2G) cycling costs associated with battery degradation, concluded that V2G profits are outweighed by the possible reductions in battery lifetimes. In [19] a battery wear model was created based on manufacturers' test data for the Li-ion battery in a Nissan Altra EV. This allowed direct battery degradation cost assessment. FFR was found to be uneconomic, as degradation costs from the model exceeded revenues. Study [20] calculated degradation costs for $LiFePO_4$ based A123 cells as used in commercial and EV applications [21]. Study [20] used simple regression models based on laboratory data for a limited set of ageing stress factors, namely depth of discharge, and average SOC. Energy arbitrage was not found to be economic for the EV owner. More severe stress factors (e.g. elevated temperature and SOC during cycling and storage) were not considered in that study.

Results were reported in [6], which suggested a means of carrying out V2G while at the same time prolonging the life of the Nickel Cobalt Aluminium Oxide (NCA) cells studied (i.e., beneficial V2G). Conversely, [22] drew the same conclusions as were reached in [14-18], namely that V2G will always cause additional battery degradation. The authors used cells of the same NCA battery chemistry, physical size and similar capacity to those tested in [6], but the associated experimental results demonstrated that V2G would always be adverse to cell lifetime. Given that both [6] and [22] adopted NCA $C_6/LiNiCoAlO_2$ cells and conducted both storage and cycling testing, the diverging outcomes seemed surprising. The lead authors of [6] and [22] published further work [23] in which the discrepancy, inter alia, was argued by them to be anomalous, and was ascribed to the introduction of modelling and simulation in [6]. However, by giving such justification [23] ignores the seemingly inconsistent degradation results reported in [6] and [22].

The present paper analyses the degradation results given in [6] and [22] and addresses this apparent discrepancy. It finds that, based on the cell data given in [6], the availability of beneficial V2G is time dependent. Furthermore, based on the data given in [22], it is not available under similar conditions. For completeness, a brief outline of the various forms of degradation experienced by Lithium-ion batteries is first presented. Then, results from the literature are discussed to ascertain examples of the conditions under which beneficial V2G may be carried out. Conclusions are subsequently drawn, showing that cells can have different suitability for beneficial V2G even when of the same size, capacity and chemistry. The requisite condition – namely that saving in calendar degradation must exceed the associated cycling losses for beneficial V2G - additionally may depend on the degree of prior ageing of the cell, and its initial SOC and temperature. The conclusion reached is that even when a particular cell permits beneficial V2G, this may only be so for a limited part of the cell's lifetime. This has overall consequences for the practice and economics of V2G.

II. Discrepancy in Findings Regarding the Possibility of Beneficial V2G

A. Costless V2G

The authors of [6] presented a data and simulation study suggesting the idea that, under certain circumstances, V2G involving battery discharge and subsequent recharging (which could include peak shaving and FFR) can actually extend the life of Lithium-ion batteries in EVs. In this work, the authors develop a comprehensive battery degradation model based on long-term ageing data collected from more than fifty long-term degradation experiments on an unspecified type of commercial 3Ah 18650 $C_6/LiNiCoAlO_2$ cell. The model allows for the major known sources of battery degradation - including calendar ageing, Depth of Discharge (DOD), battery temperature, vehicle battery State of Charge (SOC), and C rate (the rate at which a battery is discharged relative to its maximum capacity). Using the developed model, and a driving pattern simulation, study [6] found that lowering the average SOC by discharging energy to the grid in the 'parked' period during the day can reduce capacity fade. The idea here is that the higher the average SOC and ambient temperature, the greater is the degree of calendar degradation. For the battery cells studied it was found that, under certain conditions, the calendar degradation at high SOC could exceed the discharge/charge cycling losses over a period of storage, assumed to be 8.5h. Thus, providing grid support could in these circumstances be actually beneficial to the EV battery. For this result or conclusion to hold, the calendar degradation must be sufficient (namely higher) when compared to the cycling degradation

If valid, this is a most interesting idea since it mitigates the chief objection to V2G, namely that it may inevitably cause expensive additional battery degradation. The scope for profitable V2G business models is greater where the cost of battery degradation is low or possibly even negative. The situation is analysed further in the following sections.

B. Is Costless V2G Possible?

In an apparent contradiction to [6], [22] presented the results of an experimental study on the impact of V2G operations on Lithium-ion battery degradation. These results show that additional cycling to discharge EV batteries to the power grid, even at constant power, is always detrimental to battery lifetime and performance. It was found that the level of calendar degradation of the battery cells studied was too low at typical temperatures ($25^{O}C$) to be able to offset the damage caused by battery cycling. Thus, delayed charging from the grid to the EV battery (G2V) as compared to immediate G2V had no significant effect (<1%) on capacity retention at room temperatures. Given that [6] and [22] use apparently very similar commercially available 18650-type cells, with a capacity of approximately 3Ah, and with Graphite

(GIC)/LiNixCo1−x-yAlyO2 (NCA) negative/ positive electrodes, the seemingly opposing conclusions are not expected and can thus be viewed as controversial [23].The difference in these two sets of findings were discussed in a journal-encouraged joint paper by the lead authors of [6] and [22] in [23]. The conclusion reached was that the discrepancy was due to the use of simulations in [6]. This present paper critiques the presented 'resolution' of the discrepancy as argued in [23], which the present authors do not find convincing.

III. Methodology

The SOC of a battery refers to the percentage of the fully charged battery energy capacity actually stored in a battery. As the battery gradually decays, the maximum energy which it can hold at full charge falls. The conventional way to quantify the effects of capacity degradation is via a term known as 'State of Health' (SOH): a battery that when fully charged would have held X% of the energy it would have held when new and fully charged, would have a X% SOH [24].

Studies [25] and [26] have shown that EV battery degradation may arise from two main causes. The first of these is known as 'Calendar Degradation' and refers to the fact that a Li Ion battery degrades with time, whether or not it is used. The other form of battery degradation occurs when a battery is actually used to store energy via successive charge/discharge cycles, known as Cycling Degradation.

To explore the possibility of beneficial V2G, the results from [6] and [22] were used to establish the degradation associated with the methodology put forward in [6] involving storage for 8.5 hours during the day. This was quantified at a high SOC and at a low SOC at different times as the battery cells aged, at a given fixed temperature. The difference (a saving in degradation over the 8.5 h period at any particular time) was then compared to the cycling degradation cost of discharging the EV battery at the beginning of the 8.5 h period of storage, and then recharging at the end, the overall effect being to reduce the average SOC. To achieve an actual benefit from V2G, the procedure would need to reduce the overall level of battery degradation. Whether this favourable outcome could be achieved at the relevant time and temperature was then evident by comparing the variation in calendar degradation with the incremental variation in cycling degradation with time.

IV. Battery Degradation

A. Calendar Degradation

The rate of calendar degradation, wherein capacity fades and impedance rises, varies with temperature, in accordance with Arrhennius' Law, under which the rate of a chemical reaction doubles with each 100 C rise in temperature, as set out in [27] and [28]. The rate of calendar degradation is also a function of the battery SOC during storage [26]. There is disagreement in the literature over the optimum level of SOC for storage, namely whether it is around 50% [29] or the lower the better [30] though probably not a total discharge.

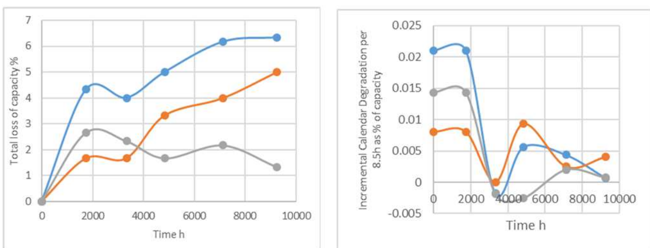
B. Cycling Degradation

Cycling degradation is the term used to describe the loss of capacity and increase of impedance which a battery suffers as it is used to store energy via successive charge/discharge cycles. In [31] it was found possible to experimentally determine the three modes of physical degradation to which Li-Ion cells are subject: loss of active positive electrode material, loss of lithium inventory and loss of active negative electrode material. Cycling degradation takes place in addition to the continuing calendar degradation that may be viewed as an independent phenomenon [24] [26]. It is usually measured by considering the % capacity loss per charge/discharge cycle [26]. Cycling degradation has been found to be a function of the number of cycles, the amount of charge transferred per cycle (effectively this is a function of the DOD) [32], temperature at which cycling occurs [26] [26] [33] [34], average SOC (the lower the average SOC for cycling, the lower the battery degradation), [26] [35] and charge/discharge current during the cycle ('C rate'). If a cell is fully discharged from 100% SOC in 1 hour the C rate = 1C [36-38], while cycling degradation is linearly proportional to the C rate below 1C [39]. As with calendar degradation, the various forms of cycling degradation will vary with cell chemistry and method of manufacture, as explained in [29] and [30].

V. Comparative Battery Degradation Analysis

A. Consideration of the Uddin et al. [6] results

In [6], one may find curves showing the cumulative calendar degradation of the cells used at differing levels of SOC, from which the underlying results may be obtained. Without the need to construct a model of calendar degradation, the experimental results reported may be used to examine the feasibility of beneficial V2G (where the benefits to SOH from storage at low SOC exceed the loss of capacity caused by the extra cycling due to V2G operation) under fixed charge/discharge rates. From the results in [6], the authors produced a curve with Fig. 2(a), showing the difference for the particular battery cells studied between cumulative calendar degradation at 90% SOC and 50% SOC with time, where the cells being stored in a chamber maintained at 25^{o}C. The difference curve gives an indication of the cumulative reduction in calendar degradation arising from storage at 50% SOC as opposed to storage at 90% SOC. As may be seen, the incremental saving associated with storage at low SOC is substantial at around 2000 hours but decreases thereafter. Using the data from [6], the authors of this present paper have derived a curve, Fig. 2(b), showing the incremental difference in calendar loss over the 8.5 hours storage period proposed in [6] as a percentage of cell capacity vs time of storage. This will give a measure of the variation in saving calendar capacity degradation by storage at low SOC over time. The amount of saving shown in Fig. 2(b) falls rapidly after 2000 hours, and more slowly thereafter.



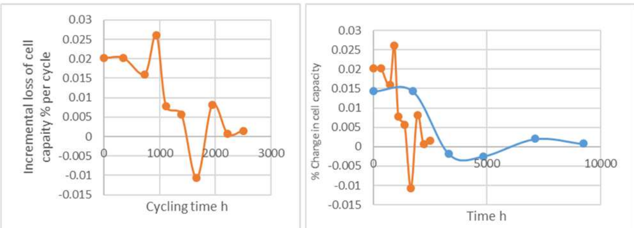
(a) Total Calendar Degradation (b) Incremental calendar degradation

90% SOC 50% SOC Difference

Fig. 1: Total and incremental calendar degradation using the data from. [6].

These results suggest that the methodology used in [6] for beneficial V2G might perform best with these particular cells up to perhaps 3000 hours of the test cells' life and would appear to be less useful both before and after that time. To further explore the possibilities, the amount of cycling degradation was considered. In [6], cycling tests were carried out, inter alia, at a temperature of 250 C, with an initial SOC of 95%, Δ SOC of 30%, discharge rate of 1.2C, and charge rate of 0.3C. This gives a cycle time of 1.25h and a cycle charge throughput of 1.8 Ah for the 3 Ah cells. Cycling testing was carried out until a charge throughput corresponding to 2000 cycles and a total cycling time of 2500 hours was achieved. As the cycling test lasted 2500 hours, an appreciable amount of calendar degradation will have taken place. In [6], the results for calendar degradation at SOC 65% were not published, so the lower degradation figures for SOC 50% were deducted on a conservative basis. Fig. 2(a) shows the incremental degradation calculated by the authors from the data in [6] expressed as a percentage of the original cell capacity vs cycling time. The amount of cycling degradation taking place per cycle varies over the life of the cell. In [6], measurements of capacity were made after various numbers of cycles. Since the testing programme lasted for a number of months, an allowance was made for the effects of calendar degradation. Then, the net variation in cycling degradation after the differing numbers of cycles was calculated. The net cycling degradation per cycle could thus be established.

Superimposing the plot for incremental cycling degradation and the plot for saving in SOH due to low SOC in Fig. 2(b), cycling degradation becomes commensurable with calendar degradation. The x-axis in Fig. 3(b) represents both the time of calendar degradation and the duration of cycling in hours. It is evident from Fig. 3(b) that between about 1000 hours and 2500 hours the saving in degradation due to calendar ageing at low SOC over 8.5 hours exceeds the degradation arising from carrying out V2G cycling. Thus, one condition for beneficial V2G is established on an experimental basis.

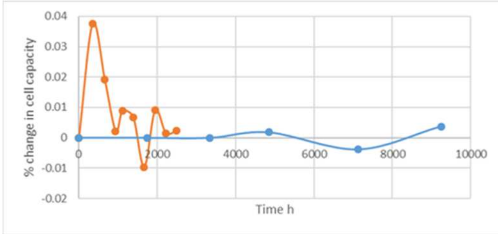


(a) (b)

(a) Incremental cycling degradation vs. cycling time
(b) incremental cycling degradation vs. calendar degradation
Incremental saving in calendar degradation
Incremental cycling degradation

Fig. 2: Incremental cycling degradation using the data from [6].

Uddin et al. [6] found that cycling degradation was higher with Δ SOC of 30% and (start) SOC of 50% than was the case for their cells when (start) SOC was 95%. Accordingly, one might expect that the conditions for achieving beneficial V2G would be harder to achieve under this regime. Fig. 3 shows the results of a similar analysis to that given above for the lower SOC (start point). Here, due to the almost identical reported rate of calendar degradation at 50% SOC and 20% SOC, there is minimal available benefit from storage at low SOC to offset the cycling degradation, which is larger at a start point of 50% SOC than at 95% SOC for □ SOC 30%. Beneficial V2G is not possible under these conditions.

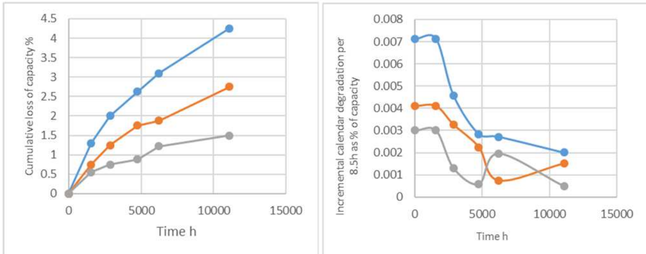


Incremental calendar degradation
Incremental cycling degradation

Fig. 3: Incremental cycling degradation vs. incremental calendar degradation

B. *Consideration of the Dubarry et al. [22] results*

In [22], a study was made of calendar degradation for NCR 18650B 3.35Ah cylindrical cells under various conditions including storage in a chamber maintained at 250 C with SOC of 100% and 50%. The results using data obtained by the authors from [22] (Fig. 4(a)) allow a comparison with the Uddin et al. [6] work – using degradation at the nearest comparable SOC to that used in [6], i.e. 100% will be expected to be slightly greater than at the 90% SOC of the Uddin et al.'s [6] results.



(a) Total calendar degradation (b) Incremental calendar degradation
100% SOC 50% SOC difference

Fig. 4: Total and incremental calendar degradation using the data from [22]

Fig. 4(b) (arrived at in the same way as Fig. 2(b) by the present authors) shows the incremental calendar degradation results and the reduction arising from storage at low SOC for 8.5 h. This allows a comparison with the work described in [6] – calendar degradation at 100% SOC will be expected to be slightly greater than at the 90% SOC of the results given in [6], but not greatly so.

These results suggest that the Uddin et al.'s technique [6] has less scope with the battery cells studied in [22], since the potential reduction in calendar degradation arising from storage at 50% SOC rather than at 100% SOC shown in Fig. 5(b) are much less than those shown in Fig. 2(b)

Dubarry et al. [22] also carried out real cycling degradation tests to represent the effects of two fixed profile driving cycles per 24 hour period, together with a number of different behaviours. A useful pair of experiments for the present purpose involved one series of tests with a single V2G intervention per 24 hours with Δ SOC =30%, initial SOC =100%, T= 25^{O}C, C=0.25, and another series of tests on an identical basis but with no V2G intervention. The difference in degradation between the two runs would yield the cycling degradation involved with a single V2G intervention. The cycling testing lasted for 8.25 months, 5940 hours, and each cycle lasted for 11 hours.

It is then possible to plot the benefits of reduced calendar degradation over the 8.5 hours period against the costs of 1 cycle of V2G, Δ SOC =30%, initial SOC =100% and T = 25

°C. The C rate used by Dubarry et al. [22] was lower than that used by Uddin et al. [6] and given that a low C rate promotes a lower degree of degradation [39] the results would underestimate the degree of cycling degradation when compared to the C rates used in the Uddin et al. [6] study, thus favouring beneficial V2G. The present authors' comparison is shown in Fig. 5.

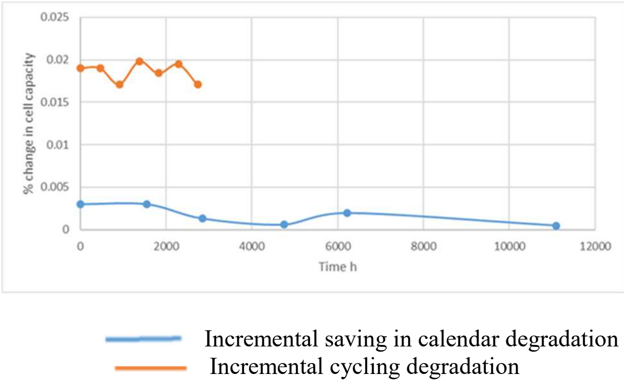


Fig. 5 Incremental cycling degradation vs. calendar degradation

It may be seen that the benefits of reduced calendar degradation from storage at low SOC never compensate for the degradation costs of the necessary cycling. With the cells used in [22], beneficial V2G does not appear to be feasible.

VI. CONCLUSIONS

It is evident from the analysis presented in this paper that the possibility of beneficial V2G exists but that this depends upon the actual battery cell properties, such as their history, storage, method of manufacture, operating temperature, and their relative propensity to calendar degradation and cycling degradation - in addition to the size, capacity and chemistry of the battery cell. It seems that insufficient weight to the combined effect of these factors is given in the literature discussed in this paper. Battery cells may differ in respect of their degradation process during storage and cycling, despite being of the same size, chemistry and capacity. In addition, the initial level of SOC and temperature at which V2G is implemented are important, as is the Δ SOC. The battery cell's degree of ageing (history) prior to a V2G intervention is also very important. An accurate real-time dynamic model of an EV battery will therefore be required to determine when and if a given battery (with given cells) can ever carry out beneficial V2G. Not all battery cells offer this capability; one needs a suitable ratio of calendar degradation at a given time to cycling degradation at that time. Previous work has investigated the possibility of extending battery life via storage at low SOC, but this paper demonstrates for the first time the time dependence of the phenomenon of beneficial V2G.

VII. ACKNOWLEDGEMENTS

This work has been supported by EU – Interreg North Sea Region programme through the Smart, clean Energy and Electric Vehicles for the City (SEEV4-City) project [J-No.: 38-2-23-15]. The work is also supported by the British Council under grant contract No: IND/CONT/GA/18-19/22. The authors would like to thank Mr Bert Witkamp (at the time at AVERE, The European Association for Electromobility) for his assistance in this research.

VIII. REFERENCES

[1] He Y, Chen Y, Yang Z, He H, Liu L. A review on the influence of intelligent power consumption technologies on the utilization rate of distribution network equipment. Protection and Control of Modern Power Systems 3:18; 2018. https://doi.org/10.1186/s41601-018-0092-2

[2] Daim TU, Wang X, Cowan K, Shott T. Technology roadmap for smart electric vehicle-to-grid (V2G) of residential chargers. Journal of Innovation and Entrepreneurship 5:15; 2016. https://doi.org/10.1186/s13731-016-0043-y

[3] Meng J, Mu Y, Jia H, Wu J, Yu X, Qu B. Dynamic frequency response from electric vehicles considering travelling behavior in the Great Britain power system. Applied Energy 162: 966–979; 2016. https://doi.org/10.1016/j.apenergy.2015.10.159

[4] Cenex UK. Understanding the True Value of V2G, report for Innovate UK, May 2019. https://www.cenex.co.uk/app/uploads/2019/10/True-Value-of-V2G-Report.pdf

[5] Department for Transport, Office for Low Emission Vehicles, Innovate UK, Department for Business, Energy & Industrial Strategy, and Jesse Norman MP. New Story, £30 million investment in revolutionary V2G technologies, 12 Feb. 2018 https://www.gov.uk/government/news/30-million-investment-in-revolutionary-v2g-technologies

[6] Uddin K, Jackson T, Widanage WD, Chouchelamane G, Jennings PA, Marco J. On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system. Energy 133: 710-722; 2017. https://doi.org/10.1016/j.energy.2017.04.116

[7] Jafari M, Gauchia A, Zhao S, Zhang K, Gauchia L. Electric Vehicle Battery Cycle Aging Evaluation in Real-World Daily Driving and Vehicle-to-Grid Services. IEEE Transactions on Transportation Electrification 4(1): 122-134; 2018. DOI: 10.1109/TTE.2017.2764320

[8] Lacey G, Putrus G, Bentley E. Smart EV charging schedules: supporting the grid and protecting battery life. IET Electrical Systems in Transportation 7(1): 84 – 91; 2017. DOI: 10.1049/iet-est.2016.0032

[9] Lunz B, Yan Z, Gerschler JB, Sauer DU. Influence of plug-in hybrid electric vehicle charging strategies on charging and battery degradation costs. Energy Policy 46: 511–9; 2012. https://doi.org/10.1016/j.enpol.2012.04.017

[10] Casals LC, Barbero M, Corchero C. Reused second life batteries for aggregated demand response services. Journal of Cleaner Production 212: 99-108; 2019. https://doi.org/10.1016/j.jclepro.2018.12.005

[11] Hesse H, Martins R, Musilek P, Naumann M, Truong C, Jossen A. Economic Optimization of Component Sizing for Residential Battery Storage Systems. Energies 10(7): 835; 2017. DOI: 10.3390/en10070835

[12] Keil P, Jossen A. Aging of Lithium-Ion Batteries in Electric Vehicles: Impact of Regenerative Braking. World Electric Vehicle Journal 7: 41-51; 2015. DOI: 10.13140/RG.2.1.3485.2320

[13] Bloomberg News Articles, 16 December 2020 https://www.bloomberg.com/news/articles/2020-12-16/electric-cars-are-about-to-be-as-cheap-as-gas-powered-models

[14] Gough R, Dickerson C, Rowley P, Walsh C. Vehicle-to-grid feasibility: A techno-economic analysis of EV-based energy storage. Applied Energy 192: 12-23; 2017. https://doi.org/10.1016/j.apenergy.2017.01.102

[15] Han S and Han S. Economic Feasibility of V2G Frequency Regulation in Consideration of Battery Wear. Energies 6: 748-765; 2013. doi:10.3390/en6020748

[16] Schuller A., Dietz B, Flath C.M., Weinhardt C. Charging Strategies for Battery Electric Vehicles: Economic Benchmark and V2G Potential. IEEE Transactions on Power Systems 29(5): 2014-2022; 2014. DOI: 10.1109/TPWRS.2014.2301024

[17] Ma T, Mohammed O. Economic analysis of real-time large scale PEVs network power flow control algorithm with the consideration of V2G services. IEEE Transactions on Industry Applications 50(6): 4272-4280; 2014. DOI: 10.1109/IAS.2013.6682513

[18] Ahmadian A, Sedghi M, Mohammadi-ivatloo B, Elkamel A, Golkar MA, Fowler MW. Cost-Benefit Analysis of V2G Implementation in Distribution Networks Considering PEVs Battery Degradation. IEEE

Transactions on Sustainable Energy 9(2): 961-970; 2018. DOI: 10.1109/TSTE.2017.2768437

[19] Han S, Han S, Aki H. A practical battery wear model for electric vehicle charging applications. Applied Energy 113: 12–23; 2014. DOI: 10.1109/PESMG.2013.6672402

[20] Peterson SB, Whitacre JF, Apt J. The economics of using plug-in hybrid electric vehicle battery packs for grid storage. Journal of Power Sources 195(8): 2377-2384; 2010. https://doi.org/10.1016/j.jpowsour.2009.09.070

[21] A123 cells used for EV propulsion http://www.a123systems.com/automotive/markets/plug-in/

[22] Dubarry M, Devie A, McKenzie K. Durability and reliability of electric vehicle batteries under electric utility grid operations: Bidirectional charging impact analysis. Journal of Power Sources 358: 39-49; 2017. https://doi.org/10.1016/j.jpowsour.2017.05.015

[23] Uddin K, Dubarry M, Glick MB. The viability of vehicle-to-grid operations from a battery technology and policy perspective, Energy Policy 113: 342–347; 2018. https://doi.org/10.1016/j.enpol.2017.11.015

[24] Zou Y, Hu X, Ma H, and Li SE. Combined State of Charge and State of Health estimation over lithium-ion battery cell cycle lifespan for electric vehicles. Journal of Power Sources 273: 793-803; 2015. https://doi.org/10.1016/j.jpowsour.2014.09.146

[25] Schmalstieg J, Käbitz S, Ecker M, Sauer DU. A holistic aging model for Li(NiMnCo)O2 based 18650 lithium-ion batteries. Journal of Power Sources 257: 325-334; 2014. https://doi.org/10.1016/j.jpowsour.2014.02.012

[26] Ecker M, Nieto N, Käbitz S, Schmalstieg J, Blanke H, Warnecke A, Sauer DU. Calendar and cycle life study of Li(NiMnCo)O2-based 18650 lithium-ion batteries. Journal of Power Sources 248: 839-851; 2014. https://doi.org/10.1016/j.jpowsour.2013.09.143

[27] Käbitz S, Gerschler JB, Ecker M et al. Cycle and calendar life study of a graphite/LiNi 1/3Mn1/3Co 1/3O 2 Li-ion high energy system. Part A: Full cell characterization. Journal of Power Sources 239: 572-583; 2013. https://doi.org/10.1016/j.jpowsour.2013.03.045

[28] Bloom I, Jones SA, Polzin EG, Battaglia VS, Henriksen GL, Motloch CG, Wright RB, Jungst RG, Case HL, Doughty DH. Mechanisms of impedance rise in high-power, lithium-ion cells. Journal of Power Sources 111 (1): 152-9; 2002. DOI: 10.1016/S0378-7753(02)00302-6

[29] Ashwin TR, Barai A, Uddin K, Somerville L, McGordon A, Marco J. Prediction of battery storage ageing and solid electrolyte interphase property estimation using an electrochemical model. Journal of Power Sources 385: 141–147; 2018. https://doi.org/10.1016/j.jpowsour.2018.03.010

[30] Keil P, Schuster SF, Wilhelm J, Travi J, Hauser A, Karl RC, Jossena A. Calendar Aging of Lithium-Ion Batteries. Impact of the Graphite Anode on Capacity Fade. Journal of The Electrochemical Society 163(9): 1872-1880; 2016. DOI: 10.1149/2.0411609jes

[31] Birkl, CR, Roberts, MR, McTurk, E, Bruce, PG, Howey, DA, Degradation diagnostics for lithium-ion cells. Journal of Power Sources 341: 373-386; 2017. https://doi.org/10.1016/j.jpowsour.2016.12.011

[32] Peterson SB, Apt J, Whitacre JF. Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization. Journal of Power Sources 195 (8): 2385-2392; 2010. https://doi.org/10.1016/j.jpowsour.2009.10.010

[33] Duleep G, Van Essen H, Kampmann B, Grunig M, Assessment of Electric Vehicle and Battery Technology. Impacts of Electric Vehicles. Deliverable 2. ICF/CE Delft/Ecologic Institute, Delft 2011. https://www.ecologic.eu/13512

[34] Schmalstieg J, Kabitz S, Ecker M, Sauer DU. From Accelerated Aging Tests to a Lifetime Prediction Model: Analyzing Lithium-Ion Batteries, World Electric Vehicle Symposium and Exhibition (EVS27), Barcelona; 2013. DOI: 10.1109/EVS.2013.6914753

[35] Lunz B, Walz H, Sauer DU. Optimizing vehicle-to-grid charging strategies using genetic algorithms under the consideration of battery aging. Proceedings of the IEEE Vehicle Power and Propulsion Conference, Chicago, IL, 1-7; 2011. DOI: 10.1109/VPPC.2011.6043021

[36] Koller M, Borsche T, Ulbig A, Andersson G. Defining a Degradation Cost Function for Optimal Control of a Battery Energy Storage System, IEEE Powertech Conference, Grenoble; 2013. DOI: 10.1109/PTC.2013.6652329

[37] Millner A. Modeling Lithium-Ion battery degradation in electric vehicles, IEEE Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply (CITRES), Waltham, MA, 349-356; 2010. DOI: 10.1109/CITRES.2010.5619782

[38] Majima M, Ujiie S, Yagasaki E, Koyama K, Inazawa S. Development of long-life lithium-ion battery for power storage. Journal of Power Sources 101: 53-59; 2001. https://doi.org/10.1016/S0378-7753(01)00554-7

[39] Ning G, White RE, Popov BN. A generalized cycle life model of rechargeable Li-ion batteries. Electrochimica Acta 51 (10): 2012-2022; 2016. https://doi.org/10.1016/j.electacta.2005.06.033