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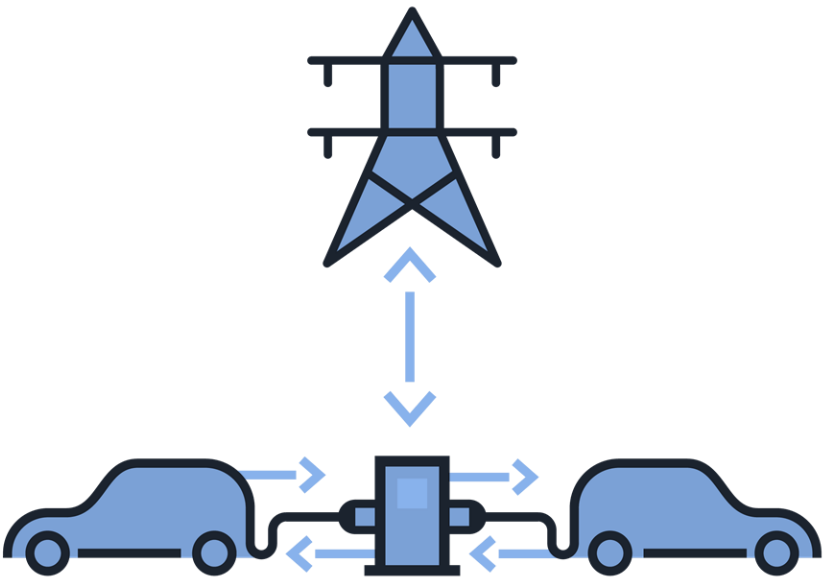
V2G review report - battery aging

Review Report

Issue 1, revision 3, 09.12.2020 **V2GStudy_CSEM_V1_3_Report**



Project RegEnergy AF_ NW E 794, 566-FP.2068_V2G_STUDY.

Content and scope

This document presents the work done in the framework of the project V2G study. The project was officially commissioned by Planair with a convention de sous traitance under Project RegEnergy AF_ NW E 794.

Planair has asked CSEM to realize a study on the impact of V2G modes on the aging of batteries inside the Electric Vehicles (EVs). Specifically, the study should allow the global and specific understanding of the state-of-the-art, to map the R&D work, and pilot projects on the domain.

CSEM has performed the study as requested by Planair. Specifically, Chapter 1 gives an overview of what V2G technology is and what are the service that EVs can provide, through V2G, to the grid. Chapter 2 talks about the different V2G installations and pilot projects that were undertaken across Europe and their results/conclusions, if any. In chapter 3, battery aging is described by giving a short summary of the different parameters that affect the rate of battery aging. Chapter 4 briefly reviews the different scientific studies that have been conducted to quantify the degradation that occurs in batteries as a result of V2G service provision. Chapter 5 contains the conclusions drawn from this review and the outlook for future work in this field. Finally, chapter 6 lists the references used in this report.

The final draft of this document can be found here:
566-FP.2068_V2G_STUDY\Contract_Deliverables\Deliverables

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Issue	Rev.	Date	Modified pages and description/reason
1	1	30/11/2020	First release Sbr
1	2	04/12/2020	Second release Sbr (after review Cbo)
1	3	09/12/2020	Final release Sbr

Abbreviations

CCS	Combined Charging System
CSEM	Centre Suisse d’Électronique et de Microtechnique SA
DoD	Depth of Discharge
EoL	End of Life
EV	Electric Vehicle
FCR	Frequency Containment Reserve
FRR	Frequency Restoration Reserve
PESTEL	Political, Economic, Social, Technological, Environmental, Legislative
SEI	Solid Electrolyte Interface
SoC	State of Charge
SoH	State of Health
V2B	Vehicle to Building
V2G	Vehicle to Gride
V2H	Vehicle to Home

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1 Introduction

V2G is an acronym for 'Vehicle to Grid' and refers to the injection of electrical energy from an electric vehicle (EV) into the grid. The EV involved may be a fuel cell, hybrid or battery EV. The concept of V2G was first introduced by Kempton and Letendre in their paper Kempton et.al. (1997) where they pointed out that EVs could be valuable to electric utility companies by providing distributed generation or storage services. It has since been studied by the scientific community to evaluate its technical and economic viability.

With V2G capabilities, the idea is to sell the storage capacity of the vehicle on the electricity market and earn some revenue. There exist various products that could be sold. These are mainly divided into two categories: generation and ancillary services. Generation involves the production of electricity for the consumption of the end user while ancillary services involve service to preserve the stability of the grid. The products under the generation category are base load and peak load. Base load is a certain amount of electricity that must be provided to the grid 24*7 over a certain period of time (generally months or years) while peak load is the provision of a certain amount of electricity for peak hours (08:00 to 20:00) over a certain period of time. These products are typically provided by various power plants (hydro, coal-fired, nuclear) due to their energy intensive nature, which is also the reason why they cannot be considered as viable V2G products.

There are several products under the ancillary services category. They include regulating power, active power losses compensation and black start/islanded operation capability. Regulating power is procured to maintain the frequency of the grid (50 Hz in Europe). It has 3 main types: primary, secondary and tertiary frequency control. Primary control, also known as frequency containment reserve (FCR) is procured to maintain the frequency of the grid on a second by second basis. The generators providing this service inject energy into the grid if the frequency drops below the set point (50 Hz) and take up energy from the grid if the frequency rises above the set point. Secondary and tertiary control reserves, also called frequency restoration reserve (FRR) are procured to be used in case of a power plant failure. Figure 1 shows the advent of these 3 types of frequency control in such an event. The service providers for this service need to provide energy until the failed power plant can be brought online again. Active power loss compensation is acquired to compensate for the resistive losses that occur during the transmission of electricity over the power lines and is typically acquired for a period of several months. Black start/islanded operation is obtained to bring the entire grid back online in the event of a major blackout. Most of the services, in this category, also are too energy intensive to be provided by EVs. However, the FCR service seems to best suited for V2G provision for two main reasons: one, the depth of discharge involved in this service is typically low, which causes minimal battery degradation and two, the battery SoC over the service provision remains fairly constant, which helps reduce the range anxiety for the EV user. Hence, in this report we focus on FCR service provision.

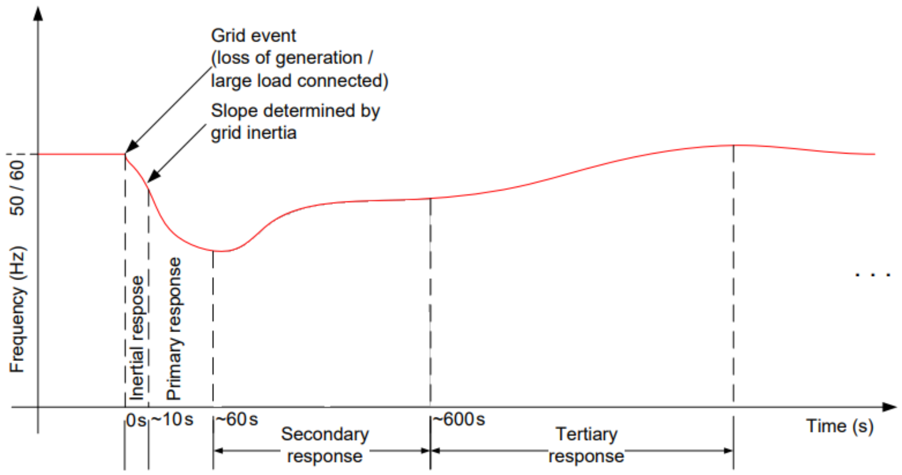

Figure 1: Illustration of primary, secondary and tertiary regulating power activation. Adapted from [1]

Apart from selling products on the electricity market, the EV batteries could also be used for V2H (Vehicle-to-Home) and V2B (Vehicle-to-Building) applications. They could be used as backup power in case of a power outage, for a short period of time. They could also be used to perform energy arbitrage wherein electricity could be bought from the grid when the electricity prices are low and stored in the battery of the EV and be used later the day. The profits from this endeavour would depend on the electricity prices and the charger efficiency. Moreover, EV batteries could be used in conjunction with installed solar power, wherein the excess power generated is stored in them to avoid the low feed-in tariffs offered by the grid and to increase self-consumption. They could also be used to reduce the peak power demands of a (industrial) building, therefore, reducing peak power costs (peak load shaving/tip smoothening) which needs to be paid every month depending on the highest power withdrawn from the grid by the building. Figure 2, for example, shows Y-parc's energy demand from the grid without (in blue) and with (in orange) peak shaving.

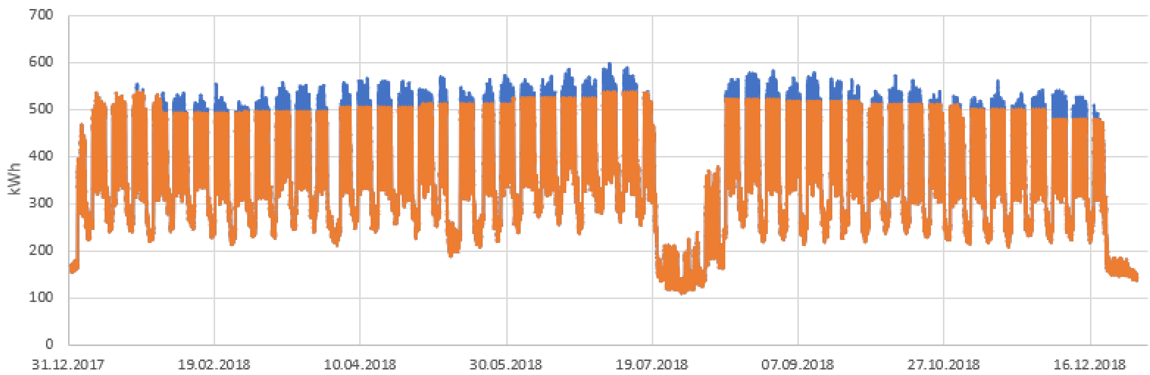

Figure 2: Energy required with and without tip smoothening at Y-Parc

Switzerland is a part of the FCR cooperation which includes other countries like Germany, France, Belgium, the Netherlands, Austria and Denmark. The FCR is procured collectively for these countries. The service must be offered as symmetrical control bands which means that both up and down regulation (energy injection and withdrawal) must be provided by the service provider. Earlier, the service providers were required to bid their services on a weekly basis. However, this has now been reduced to 4-hour blocks (00:00-04:00, 04:00-08:00, etc.). This has led to increased flexibility for the service providers and, thus, among other reasons, contributes to the reduction in the price of the FCR services over the years, as is depicted in Figure 3. The minimum and maximum bid is required to be 1

MW and 25 MW respectively and remuneration is provided for the capacity auctioned, not for the energy actually delivered during service.

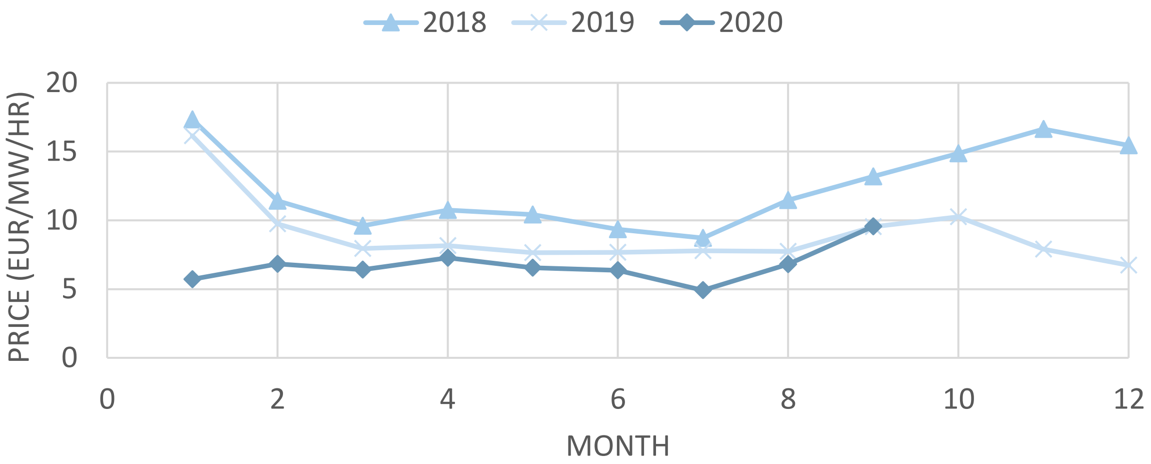

Figure 3: Development of FCR prices over the years for Switzerland

2 V2G installations in Europe

Interest in V2G has led to development of pilot projects all over the globe. These pilot projects have mainly been supported by vehicle manufacturers who are proponents of this technology. The most prominent of these are Nissan, Renault and Mitsubishi. Nissan has been investing in V2G technology ever since the first-generation Nissan Leaf in 2011. Nissan also provided 60+ Leafs to hospitals as backup power during the tsunami and earthquake that struck Japan in 2011. Along with the Leaf, the e-NV200 van from Nissan is also capable of V2G provision. Both the Leaf and e-NV200 have been used in various pilot projects to demonstrate their V2G capabilities. Renault has also been pursuing V2G technology in their vehicles. Although V2G capability is unavailable in their commercially sold vehicles, Renault has been participating in V2G trials in the Netherlands and Portugal with their Zoe. They plan to introduce pilot projects in France, Sweden, Switzerland, Denmark and Germany as well. Mitsubishi provides V2G capability in their Outlander PHEV and participated in a V2G pilot with NewMotion, TenneT and Nuvve in the Netherlands. Recently, Audi also announced that it was exploring the possibilities of V2G provision in their EVs. Along with vehicle manufacturers, utility companies and service providers have also participated in V2G pilot projects to evaluate the gains that they could achieve should this technology be mass adopted. Some of these companies are Enel, Tennet, OVO Energy, Engie, Nuvve and Elia.

In this chapter, the various V2G installations and pilot projects undertaken in Europe have been described briefly, followed by the conclusions/results obtained from them. These have then been summarized in a table.

2.1 Parker Project (Denmark)

LINK: https://parker-project.com

This project was divided into three main topics. The first was grid application investigations in which the grid services that V2G enabled vehicles could provide were studied and shortlisted. Most of these were related to frequency regulation. Furthermore, the V2G hub at Frederiksberg Forsyning was also investigated. A picture of the site is shown in Figure 4. Here, data from ten Nissan e-NV200 vans providing frequency regulation services to the DK2 grid was recorded. The V2G chargers themselves were provided by Enel and were rated at 10 kW. It was found that each van generated an average revenue of € 1860 per year. The second main topic was related to technical capabilities that the EVs and chargers needed to have in order to enable V2G service provision. This included responsiveness (ramp rates), accuracy, precision, set point granularity, etc. Test protocols were developed to evaluate these parameters and it was concluded that the current hardware level was ready for V2G service provision. The third main topic was scalability and replicability of the results obtained in the Frederiksberg Forsyning study. Under scalability, the profits realized from the V2G service provision were calculated considering various costs. The profits varied from -955 €/year to 2304 €/year for the worst- and best-case scenario, respectively, where the worst case scenario considered pessimistic values of FCR price, electricity price, battery degradation, etc. while the best case scenario considered optimistic values. This showed that the profits earned were very sensitive to the various factors that constituted the costs in V2G provision. Under replicability, the barriers that countries like Denmark, Norway, Germany and Sweden face were studied using the PESTEL (Political, Economic, Social, Technological, Environmental, Legislative) analysis. It was concluded that Demark was most conducive for the roll-out of V2G technology followed by Sweden.

Figure 4: Commercial V2G hub at Frederiksberg Forsyning, Denmark

2.2 Nissan and Enel pilot project (UK)

LINK: https://www.v2g-hub.com/projects/uk-vehicle-2-grid-v2g

This pilot project targeted private homeowners who had solar panels on their roof and owned a Nissan V2G enabled vehicle (Leaf/e-NV200) [2]. Typically, in the case of excess solar energy production in the house, the excess electricity must be sold to the grid at a feed-in tariff, which is generally lower than the purchase price of electricity. So, it is advantageous for the homeowner to store the excess energy produced and use it later, than selling it to the grid. The objective of this project was to help homeowners to increase their self-consumption by storing the excess electricity produced in their EV batteries and then, using the V2G chargers provided by Enel, use this energy for powering the house when there is little or no solar energy produced. Frequency regulation would also be provided as an additional income stream. These services would be performed while respecting the driver's energy needs for a particular trip.

2.3 Elia V2G project (Belgium)

LINK: https://innovation.eliagroup.eu/projects/v2g/

This was the first V2G demonstration project in Belgium. It was carried out by Elia and other partner companies which included NewMotion, Enervalis and EVConsult. The objective of this project was to examine the V2G capability of EVs for FCR provision. Both V2G and V1G technology was tested for this purpose. V1G refers to unidirectional V2G. V1G chargers, unlike V2G chargers, cannot inject the energy from an EV back into the grid. However, they can control the charging rate or charging time according to signals from the grid to provide FCR services. For example, when the frequency of the grid is above 50 Hz, the charging rate will be increased while it will be decreased if the grid frequency is below 50 Hz. 40 V1G and 2 V2G chargers were used for this project wherein more than 100 experiments were conducted over the course of a year. It was concluded that both V1G and V2G chargers were compliant with the FCR prequalification requirements. A major outcome of this project was the number of EVs required to provide one unit of FCR service. One unit comprises a service of 1 MW for 4 consecutive hours. It was concluded that 200 to 1200 EVs would be required to provide one unit of FCR service, depending on the fraction of V2G poles. If the number of V2G poles is higher, the number of EVs required will be lower. The effects of V2G service provision on the battery of the EV were not explored.

2.4 INEES project (Germany)

LINK: https://insideevs.com/news/331719/inees-project-v2g-reduces-power-fluctuations-but-is-not-economically-viable/

The INEES project was conducted in Germany from 2012 to 2015 to test V2G service provision by EVs. 20 Volkswagen e-up!1 EVs were modified to provide V2G services and chargers were provided by SMA Solar Technology. Lichtblick, which is an energy and IT company, managed the electricity released from the vehicles. It was concluded that EVs could provide a safe and secure power reserve for the power grid with a short reaction time, but this is not economically viable under current (2015) conditions. No in-depth report for this project was available and the only source of information was press releases by the partner companies. Figure 5 shows the modified Volkswagen e-up!1 EVs for the project

Figure 5: INEES project, Germany

2.5 Electric Nation Vehicle to Grid Project (UK)

LINK: https://electricnation.org.uk/

This is a project hosted by Western Power Distribution with other collaborators like CrowdCharge and DriveElectric (FleetDrive Management) to test the impact of V2G on the low voltage electricity network. This project is expected to run from 2020 through 2022, wherein 100 participants will be provided with V2G chargers and their behaviour will be monitored. The participants will be able to set the minimum amount of energy they require in the EV on the CrowdCharge app, and the EV will be charged during times of cheap electricity and discharged when electricity prices are high, always respecting the SoC limits set by the participants.

2.6 Scirius (UK)

LINK: https://www.ovoenergy.com/electric-cars/vehicle-to-grid-charger

This project was hosted by OVO energy with other project partners like Kaluza and was projected to last from 2018 to 2020. It has a concept very similar to the Electric Nation Vehicle to Grid project where EV owners can participate in the project to experience and benefit from V2G technology. Using the Kaluza app, the owners can set the minimum SoC and the time at which they need the EV to be ready for use.

The EV is then charged when the electricity price is low and discharged back to the house when the electricity is expensive. If the electricity cannot be taken up by the house, it is sold back to the grid. The V2G charger provided for the trial is rated 6kW for charging and discharging and comes with a CHAdeMO cable.

2.7 Utrecht Science Park (The Netherlands)

LINK: https://smartsolarcharging.eu/en/press-release-utrecht-science-park-first-campus-bidirectional-charging-network/

The collaboration between Utrecht University, HU University of Applied Sciences Utrecht and other companies like LomboXnet, We Drive Solar and Smart Solar Charging resulted in the installation of 32 bi-directional chargers which charge according to the ISO 15118 standard at the Utrecht Science Park campus. These chargers will be combined with 8000 solar panels, which are on campus as well, and 6 We Drive Solar shared cars. This will enable the EVs to charge, using solar energy during the day, and discharge at night thus maximizing solar energy utilization. Figure 6 shows a photograph of the site.

Figure 6: V2G installation at Utrecht Science Park

2.8 FCA-ENGIE EPS Vehicle-to-Grid pilot project (Italy)

LINK: https://insideevs.com/news/444527/fca-inaugurated-v2g-pilot-project-mirafiori/

Fiat Chrysler Automobiles have, very recently (September 2020), completed the first phase of their V2G pilot project at the Mirafiori factory in Turin. FCA has partnered with ENGIE EPS and Terna, the Italian energy supplier to realize this project. This first phase consists of the installation of 32 V2G chargers, each of which can charge two EVs at a time. The second phase, which is scheduled to finish by the end of 2021, will see the installation of enough V2G chargers to charge up to 700 EVs, making this the world's largest V2G facility. This will allow the facility to provide up to 25 MW of regulating power. "The project is acting as our laboratory to experiment on and develop an offering to add value in the energy markets," said Roberto Di Stefano, Head of EMEA e-Mobility at FCA. In addition to the V2G chargers, solar panels are also going to be installed on the facility to provide 6.5 MWh of electricity every year. Figure 7 shows the V2G facility built in Turin.

Figure 7: FCA-ENGIE EPS V2G project, Turin

2.9 Summary

Table 1 summaries the main findings of the V2G pilot projects presented in the above sections. Besides the dimension of the project, which can be exemplified by the number of poles installed, the assessment of the impacts on battery aging and the economic viability have been chosen as main point of interest in the present study.

Table 1: Main findings from pilot project in the field of V2G

Project	Country	Timespan	Type of V2G service provided	No. of chargers	Aging impact on battery assessment	Economic viability assessment
Parker project	Denmark	2016-ongoing	Frequency Response	10	No	Yes
Nissan and Enel pilot project	UK	2016-ongoing	Frequency Response, increased self-consumption	N/A	No	N/A
Elia V2G project	Belgium	2018-2019	Frequency Response	42	No	No
INEES project	Germany	2012-2015	Frequency Response	20	No	Yes
Electric Nation V2G project	UK	2020-2022	Reserve, DSO Services, Time shifting	100	No	Yes

Scirius	UK	2018-ongoing	Arbitrage, Time shifting	N/A	No	Yes
Utrecht Science Park	The Netherlands	2019-ongoing	Increased self-consumption	32	No	N/A
FCA-ENGIE EPS V2G project	Italy	2019-2021	N/A	700	N/A	N/A

As we can see from Table 1, V2G pilot projects have been undertaken from as early as 2012, as in the INEES project, and are still being undertaken today, like the FCA-ENGIE EPS V2G project. Apart from the projects mentioned, many other smaller projects have also been done with a lesser number of V2G chargers in Europe and around the world. The most extensively tested V2G service, however, seems to be frequency regulation, which is reasonable, seeing how it can manageably be provided by EVs. Most projects investigated the technical and economic feasibility but battery degradation due to the service provision has been overlooked.

Moreover, it has been found that one of the main bottlenecks to the adoption of V2G technology is the availability of V2G chargers. Very few companies produce chargers that support V2G provision. Some of them are Nuvve, Wallbox, Delta Electronics and EVTEC. V2G is supported by the CHAdeMO standard alone. The more widely used CCS standard does not currently support V2G. However, it has a roadmap that envisions V2G support by 2025.

3 V2G and battery aging

There have been various V2G pilot projects undertaken in Europe, as has been shown in the previous chapter, and many more around the world. However, most of them have studied/demonstrated the technical or economic viability of this service. As anticipated in the previous chapter, the battery, which is a large chunk of the cost of the vehicle, is also affected by V2G service provision, but the effects of V2G provision on the battery have not been investigated in the pilot projects. It is important to take this degradation into account to design an appropriate business model around V2G.

Just like all things, batteries degrade with time and usage. The degradation due to time is termed calendar aging and the degradation due to usage is called cycle aging. There are a few phenomena such as solid electrolyte interface (SEI) layer growth and lithium plating on the electrodes, loss of active material and the like. However, various factors affect the rate at which these phenomena occur, in turn, affecting the rate of degradation of the cell. These are factors such as the temperature of the cell, power drawn from or given to the cell, the depth of discharge (DoD), state of charge (SoC), the charging protocol used, the chemistry of the cell and so on. Not all these parameters may be relevant from the point of view of V2G provision. For example, the cell chemistry is not a relevant factor since EVs do not vary vastly in the cell chemistry of the cells used in their battery packs. As can be seen in Figure 8, the EV sector is dominated by the NMC chemistry. The most important factors related to V2G provision have been discussed below.

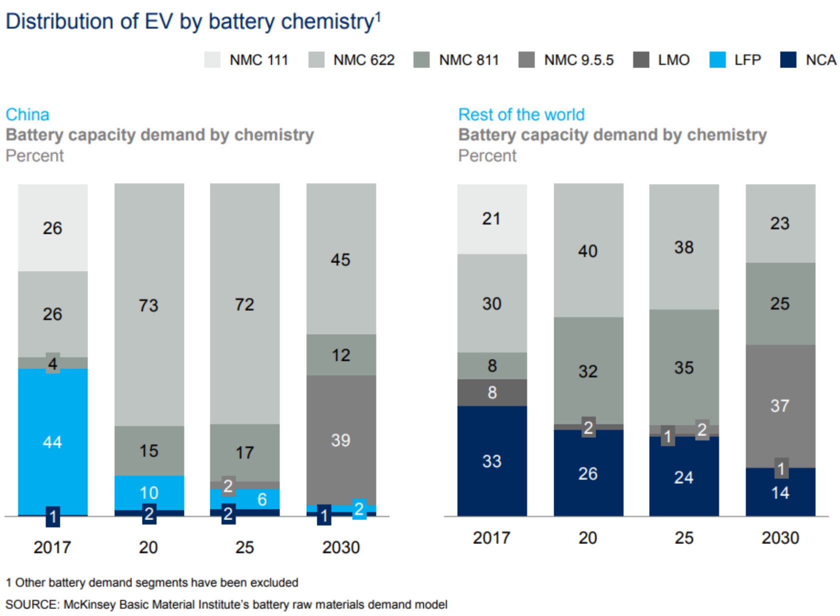

Figure 8: Battery chemistry distribution (current and predictions) in EVs in China and the rest of the world. SOURCE: MCKinsey Basic Material Institute's battery raw materials demand model

3.1 Temperature

Temperature is one of the most important factors for any chemical reaction. Increasing the temperature generally increases the rate of the reaction. Hence, high cell temperatures lead to faster SEI layer growth which leads to rapid cell degradation. Very high cell temperatures may also cause thermal runaway of the cell which is a phenomenon in which the cell temperature rises spontaneously until it catches fire. This poses a safety hazard. Operating the cells at very low temperatures is not healthy for the cell either. At very low temperatures, lithium plating on the electrodes increases which leads to a loss in the cyclable lithium in the cell and, hence, loss in cell capacity. Moreover, this lithium plating leads to the formation of dendrites which can cause internal short circuits in a cell and are a safety hazard. Low temperatures also cause material embrittlement which results in loss of active material (graphite) and, hence, capacity loss [3].

These trends have been proven by experimental work. [4] conducted elaborate experiments and observed that very low and very high temperatures caused higher degradation as compared to cells operated at moderate temperatures especially at higher c-rates. However, more recent papers show that higher temperatures are good for the cell. [5], for example, cycled NMC cells at 20°C and 45°C and observed that the cell cycled at the higher temperature degraded slower as compared to the one at lower temperature. [6] also performed cycling experiments on NMC cells at 1C c-rate, 100% DoD and various operating temperatures. They too observed that the capacity fade was lower in cells that operated at higher temperatures, as shown in Figure 9. They, nonetheless, concluded that this temperature effect was cell chemistry dependent, as they also tested LFP cells and found that capacity fade, in this case, was lower for lower temperatures. The capacity fade at extremely low temperatures has also been studied. [7] tested NMC cells at different low temperatures (-10°C, 0°C and 10°C) and showed that the degradation was highest for the cell operated at -10°C. Post mortem analysis was also done to show the lithium plating that had occurred on the anode of this cell.

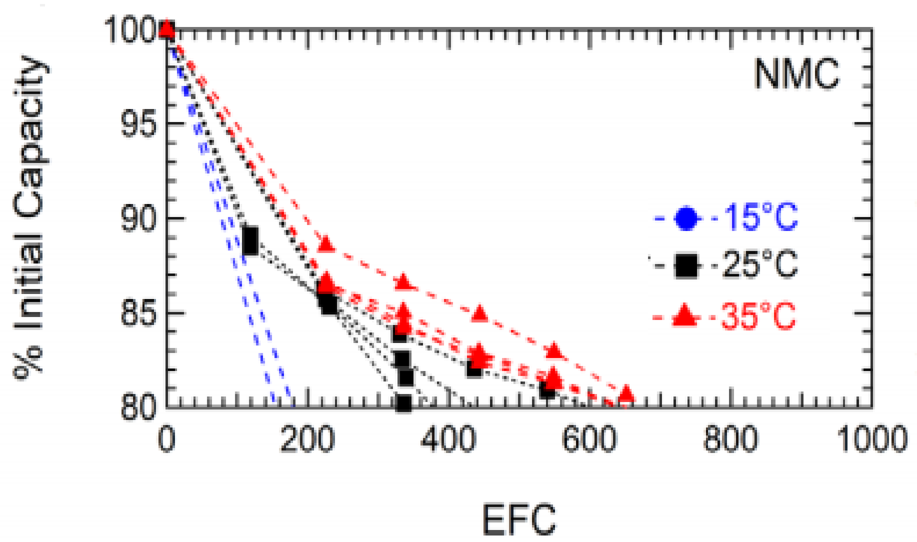

Figure 9: Effect of temperature on capacity fade as shown by [6]

3.2 State of charge (SoC)

The SoC of the cell also determines the amount of degradation it undergoes. Most people like to keep their devices at very high SoCs so that they can be used for the longest possible time. However, storing cells at high SoCs has shown to cause higher degradation as compared to storing them at low SoCs. This is since the SoC determines the voltage of the cell, which, in turn, determines the voltage of the cathode and the anode. The voltage of the cell is given by the equation:

$$V_{cell} = V_{cathode} - V_{anode}$$

Hence high SoCs lead to high cell voltages which demands high cathode and low anode voltages. It has been seen that high cathode voltages cause electrolyte oxidation and cathode decomposition, while low anode voltages accelerate side reactions like SEI layer growth and lithium plating [3].

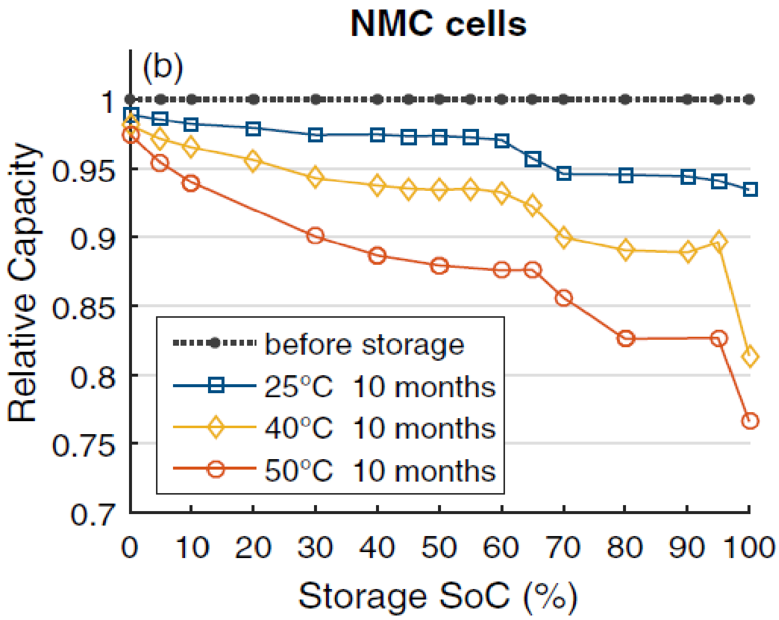

Figure 10: Effect of SoC on calendar aging of NMC cell shown by [8]

Various calendar aging studies on different cell chemistries can be found in the literature. [9] performed calendar aging for NMC cells at 50°C for various SoC levels and it was observed that storage of the cells at high SoCs led to higher degradation. A more recent study, [8] stored cells of different chemistries at different temperatures for 10 months and monitored their capacity fade. It was observed that irrespective of the cell chemistry, storage at higher SoCs led to higher capacity fade. Figure 10 shows the calendar aging over 10 months at different SoCs from their paper. However, the amount of capacity fade differed with cell chemistry (NMC showing the highest fade). They concluded that the capacity fade observed was due to SEI layer formation and electrolyte reduction which stemmed mainly from the low anode voltage in the cells stored at high SoCs.

3.3 Depth of discharge (DoD)

The DoD is an important parameter for cell degradation from a V2G perspective since there exist the V2G services vary in their DoD requirements. For example, FCR provision is typically characterized by a low DoD requirement while services like peak shaving demand higher DoDs. DoD has an impact on cell degradation in that it determines the amount of volume change the electrode undergoes during intercalation and deintercalation. High DoDs lead to higher volume changes which result in high stress in the electrodes and the growth of microcracks. As these microcracks grow, they provide more area for the SEI layer to form which ultimately causes loss of lithium ions and capacity [3].

[10] performed cycle aging tests on NMC pouch cells at various temperatures, DoDs, mean SoCs and c-rates. Here, it was observed that higher DoDs led to higher cell degradation. Their results are shown in Figure 11. In a more recent paper, [6] had similar observations. These results show that low DoD applications like FCR provision would be less degrading for the cells as compared to high DoD applications like peak shaving.

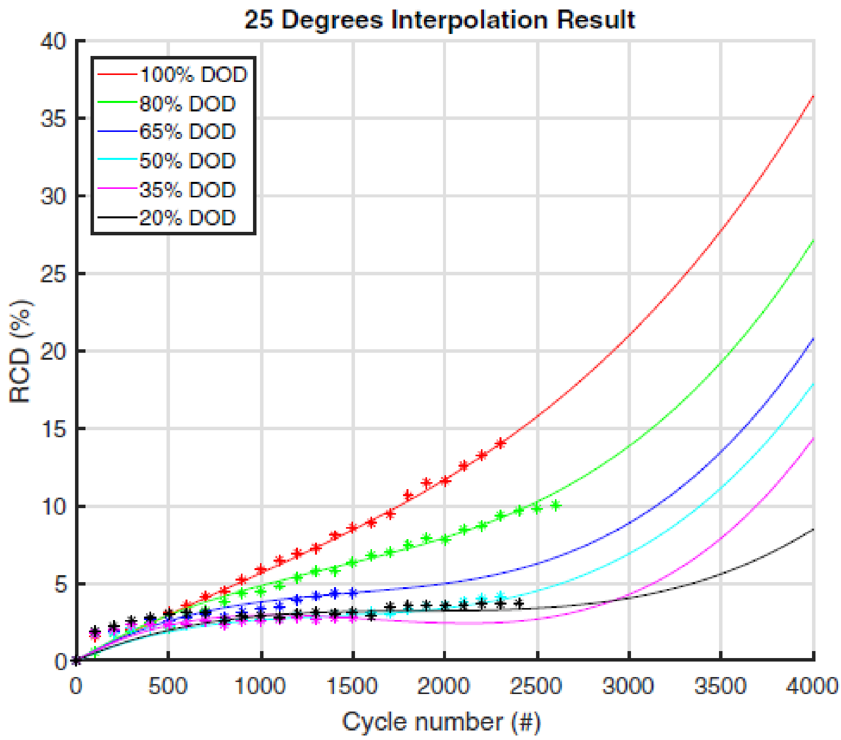

Figure 11: Effect of DoD on the capacity fade of NMC cells as shown by [10]

3.4 Charging/Discharging rate

The charging/discharging rate is also an important factor to be considered for battery degradation. This is the current injected in to or withdrawn from the battery and is generally shown as c-rate, so that the current is normalised to the battery capacity. It is given by the formula:

$$C - rate = \frac{current\ [A]}{cell\ capacity\ [Ah]}$$

High c-rates are typically degrading for the battery for several reasons. High c-rates result in higher joule heating which increases the temperature of the cell, accelerating the side reactions that cause degradation. High c-rates also cause very high or very low local potentials which can accelerate degrading phenomena. Moreover, large c-rates also lead to high rates of intercalation/de-intercalation which can result in high stresses in the electrode material causing LAM [3].

It is seen that very high c-rates at very low temperatures are especially degrading for the cell. [4] observed the degradation of the cell at various discharge c-rates and temperatures and confirmed that while at high temperatures, the c-rate did not greatly affect the degradation, its effect became apparent at lower temperatures. [11], on the other hand, cycled NMC cells at different charging c-rates (1C to 4C) while keeping the discharge rate constant at 1C. The cells were cycled at 35°C and between 20% to 80% SoC. It was observed that at low c-rates, the c-rate did not impact the much. However, at 3C and 4C, rapid degradation of the cell could be seen. The capacity fade and resistance rise observed is shown in Figure 12.

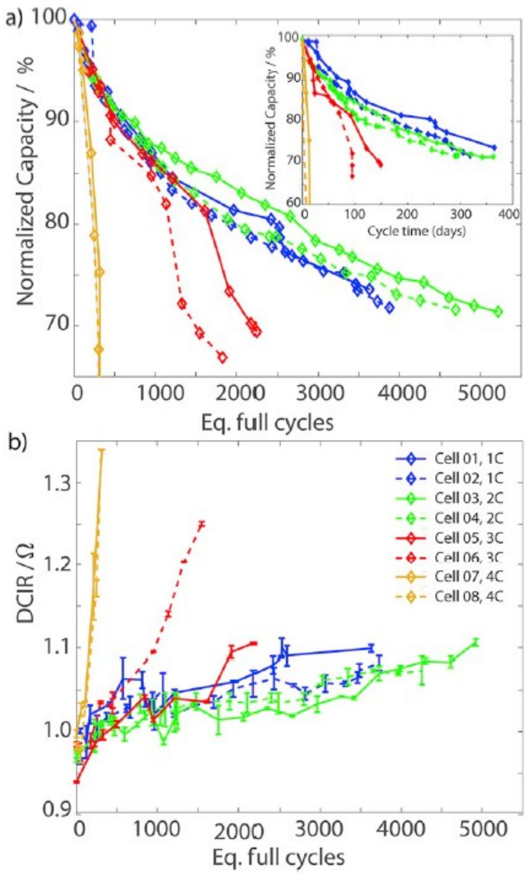

Figure 12: Capacity loss and resistance increase at different c-rates, from [11]

3.5 Example of aging modelling

Experimentation is the most reliable method of studying cell aging as the cell tested goes through real profiles and its degradation can physically be measured. But this is a very lengthy process. It takes several months of testing before significant data can be produced for some analysis. Due to these complications of experimental works, most authors use empirical models to calculate the aging of the cells. These empirical models also must be obtained by intensive testing, but it is a one-time investment. Once the model is built, the cell can be simulated and tested under various conditions. However, the empirical models also have a limit. They can be used only for the conditions that the cell has been tested in. For example, if the cell aging test has only been done for temperatures below 40 degC, the model obtained may not be applicable for a simulation in which the cell is exposed to temperatures above 40 degC.

There are various models for battery aging, but one model seems to be used more than the others. This is the Wang model that is used for the simulation of NMC cells. [4] conducted various tests on NMC cells and constructed a semi-empirical model to compute the calendar and cycle aging of the cells. The equations of the model are as follows:

$Q_{losscal,\%} = 14876 * \exp(-24500 / (R * T)) * days^{0.5}$ (calendar aging)

$Q_{losscyc,\%} = (a*T^2 + b*T + c) * \exp[(d*T + e) * I_{rate}] * Ah_{throughput}$ (cycle aging)

Where,
R = 8.314 J/K
T = temperature of the cell in K
$a = 8.61 * 10^{-6}$

$b = -5.13 * 10^{-3}$
$c = 0.763$
$d = -6.7 * 10^{-3}$
$e = 2.5$
I_{rate} = C- rate

The equations above give the percentage of capacity loss due to calendar or cycle aging. The total capacity loss of a cell at a given point of time was considered to be the sum of the cumulative calendar and cycle aging until that point of time.

To come up with an aging model, extensive testing of cells had been performed. Figure 13 shows a part of the whole testing matrix, wherein the DoD, temperature and c-rate at which the cells were cycled are depicted. [4] cycled various NMC cells at different DoDs and c-rates. It was observed that higher DoDs caused more degradation as compared to lower DoDs at 2C and 3.5C c-rates. At a higher c-rate (5C) it was seen that the low DoDs was more degrading that the high DoDs. They conducted elaborate experiments and observed that very low and very high temperatures caused higher degradation as compared to cells operated at moderate temperatures especially at higher c-rates. At lower c-rates, higher temperature caused higher degradation while lower temperatures caused lower degradation. These conditions are then input into the model to get the model predictions. Figure 14, for example shows the model prediction (dotted line) and experimental data (markers) of the capacity loss of the cell cycled at various c-rates and keeping the temperature constant at 10°C and DoD constant at 50%.

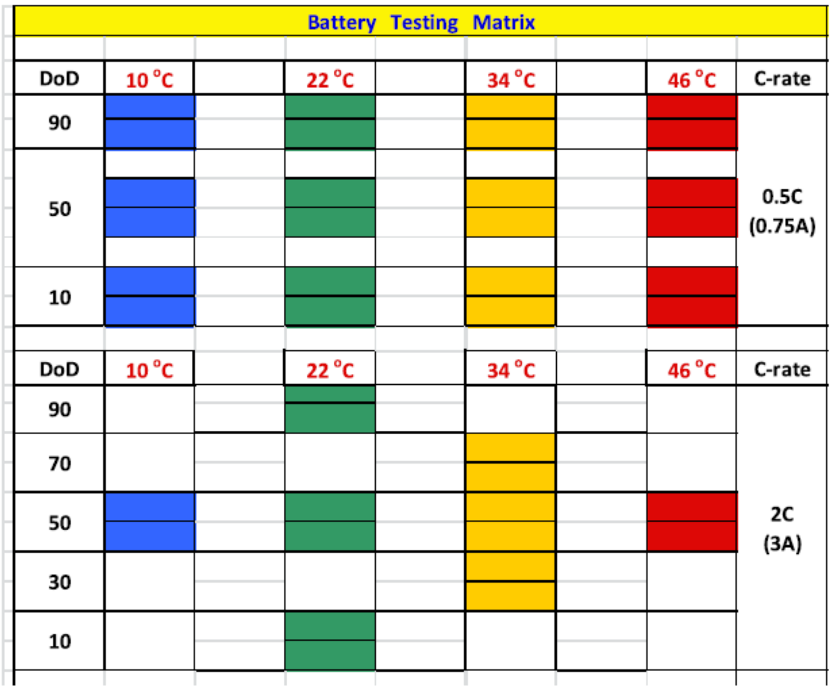

Figure 13: Battery testing matrix from [4]

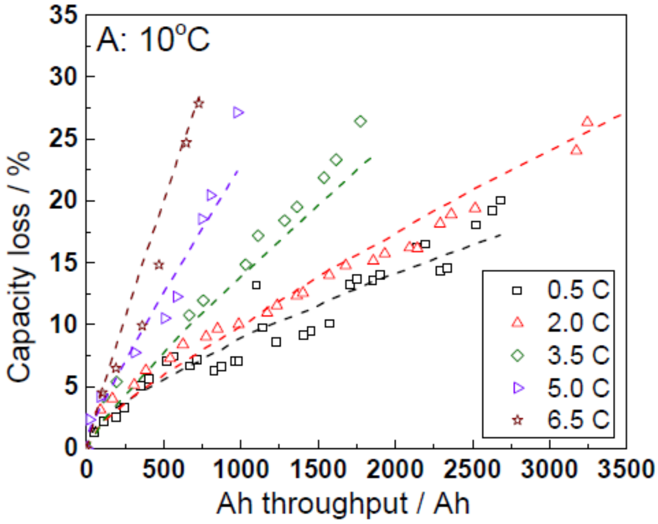

Figure 14: Model predictions(dotted line) and experimental results (markers) of cells cycled at various c-rates, keeping temperature constant at 10°C and DoD constant at 50%, from [4]

4 V2G studies

As has been shown in chapter 2, various V2G pilot projects have been undertaken to establish the viability of this technology. However, most of these projects overlook the inevitable EV battery degradation caused due to V2G provision by the vehicle. Hence, we turn to scientific literature on the impact of V2G service provision on battery aging, which unfortunately, is not ample in number.

Battery aging is very path dependent and non-linear. In the sphere of the V2G literature too, there has not been a lot of experimental work conducted. To the best of the author's knowledge, there are only 2 works, [12] and [13], that have tested vehicle profiles and V2G profiles on real cells. There have been more simulation-based studies where a battery model is used along with synthetic profiles to mimic the cycling of a battery and compute the degradation caused. The experimental and simulation studies have been described below.

4.1 Experimental studies

[12] is an old work and the results obtained may not be valid for cells today. Moreover, the tests were performed on LFP cells, which are not heavily used in the automotive industry, except for in China. Nevertheless, their approach is worth mentioning and taking inspiration from. The authors first obtained a drive cycle to test on the cell. They found the median number of trips in a car and also the average velocity and duration of each trip. Then they took parts of the UDDS cycle that best fit these parameters for each trip and joined them to make one profile. This profile, which was a velocity vs time profile, was converted to a power vs time profile using a simple physics model of a car and subsequently converted to a c-rate vs time profile. These profiles were tested, with and without additional V2G profiles, on LFP cells up to various depths of discharge and it was found that the degradation did not depend as heavily on the DoD as was previously thought from the VARTA curves. Also, degradation was a stronger function of the energy throughput, so the higher throughputs due to V2G resulted in higher degradation. This is shown in Figure 15. However, the V2G profiles used here were simple discharges at a constant current, and it was shown that degradation due to the more dynamic drive cycle was double as compared to degradation due to V2G (per normalized Wh).

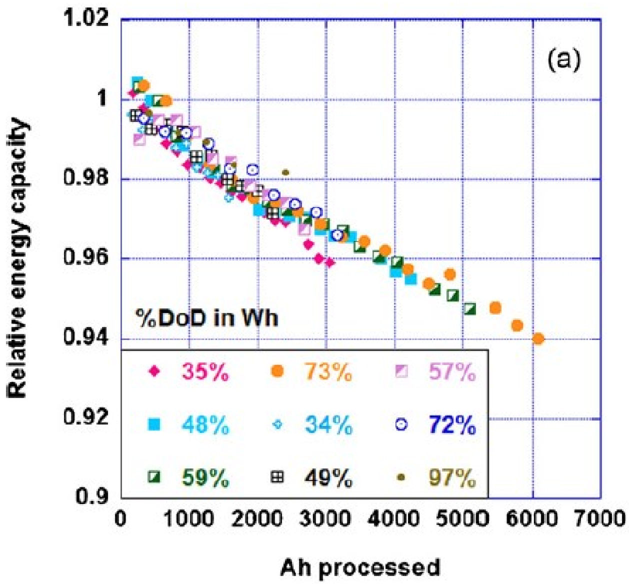

Figure 15: Graph illustrating the low dependence of capacity on DoD and higher dependence on Ah processed as shown in [12]

[13], on the other hand, tested NCA cells. The V2G profile they tested was also a simple constant current discharge. The drive cycle was taken from an in-house database. This drive cycle was a 1h round trip cycle which contained all types of road conditions. The V2G profile was described which was a simple discharge at P/4 where P is the rated power of the pack. The V2G was performed once or twice a day for 1 h periods where the price of electricity peaked. The charging protocol was defined where level 2 charging was available at home while fast charging was available at work. The car was constrained to be charged at least once a day at home. The following is a description of the various daily loads tested. DCR, CR, RC and R were defined which meant discharge charge rest, charge rest, rest charge and rest, respectively. Each of these loads could either be performed at home or at work. A matrix of 12 different tests was made based on various combinations of these loads and accelerated tests, an equivalent of 18 months, were performed on the NCA cells. Examples of 4 out of the 12 profiles tested is shown in Figure 16. It was found that the capacity fade was highest for vehicles that provided V2G services twice a day, and lowest for vehicles that did not provide V2G services and charged twice a day. These results are shown in Figure 17. It was concluded that providing V2G services twice a day could reduce the lifetimes of the battery packs to less than 5 years.

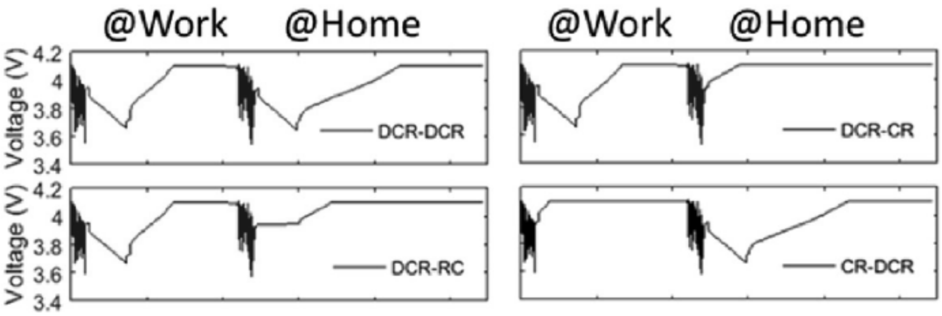

Figure 16: An example of 4 out of the 12 profiles tested on the cells, as shown in [13]

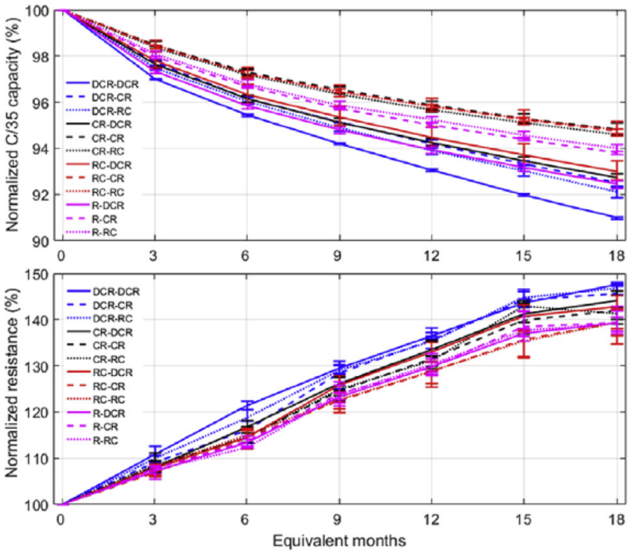

Figure 17: Capacity fade for cells tested with different protocols, [13]

4.2 Simulation studies

[14] conducted a study in which they simulated different V2G services to find their effect on battery degradation. Services like peak load shaving, frequency regulation and net load shaping were simulated using an in-house simulator 'V2G Sim'. The Wang model was used for modelling battery degradation in

conjunction with a thermal model. The V2G services were simulated to be provided 20 times for 2 hours each, or to be provided every day for 2 hours each. It was concluded that most degrading V2G service was net load shaping, followed by peak load shaving and frequency regulation. Also, the battery lasted 9.5 and 8 years without and with V2G service provision, respectively. The results of these simulations are given in Figure 18. The end-of-life (EOL), must be noted, was defined at 70% state-of-health (SOH).

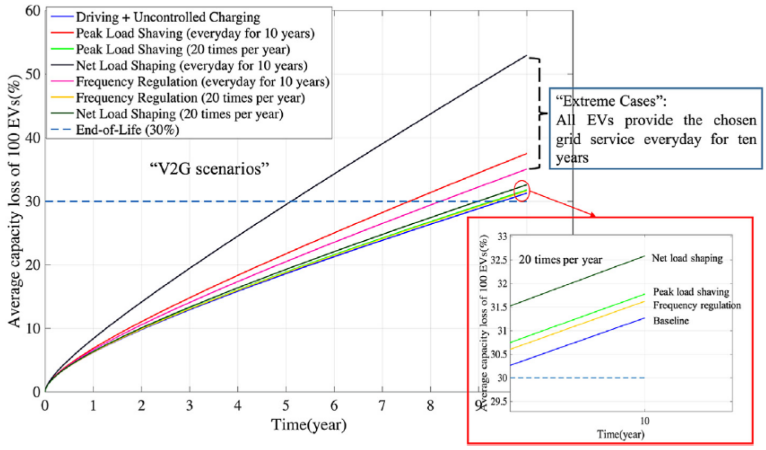

Figure 18: Capacity fade as seen in the simulations of different V2G scenarios carried out by [14]

In a more recent study, [15] studied the effect of primary frequency regulation on battery aging in Denmark. This was also a simulation study in which the V2G service was provided only in the evening when the vehicle was plugged in (14 hours of service provision). The model used for this study has not been explicitly mentioned, however, they have mentioned calendar aging, cycle aging, thermal modelling in the paper and also provided a diagram which shows these to be some of the components of the model used. This diagram is shown in Figure 19. Moreover, they have also mentioned charger efficiency which they have integrated into their calculations. They simulated two scenarios: one without FCR provision, and one with. In both scenarios there are two instances of driving, each for 30 minutes and charging for 1 hour (up to 80% SoC). However, in the "only driving" scenario, the charging takes place immediately when the owner reaches home, while in the "FCR provision" scenario, the vehicle provides V2G services once the owner reaches home (from 17:00, for 14 hours). Charging is delayed to just before the owner leaves for work. Simulations showed that degradation due to V2G service provision was very low. After 5 years of usage, the battery would degrade by 7% and 9% without and with V2G service provision, respectively. The evolution of the battery degradation over time can be seen in Figure 20.

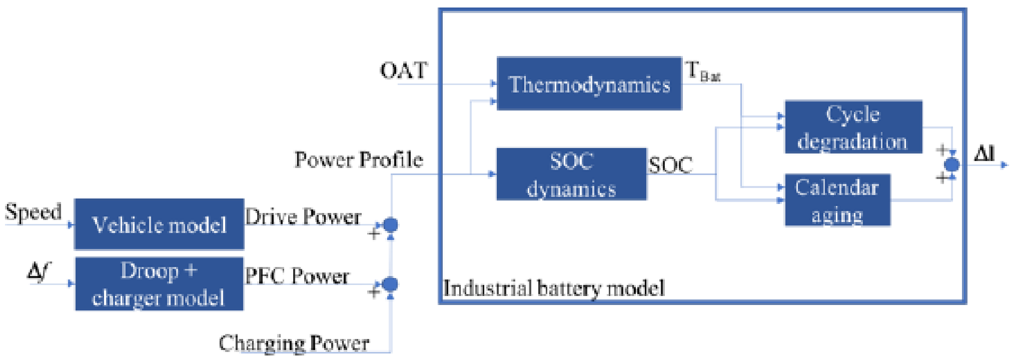

Figure 19: Illustration of model used, from [15]

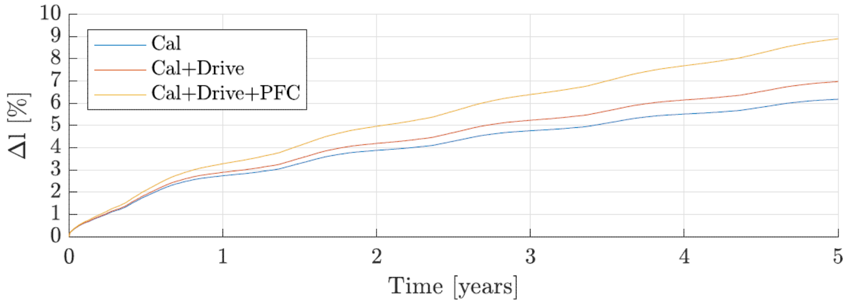

Figure 20: Cell degradation with respect to time depicting only calendar aging, calendar aging along with cycle aging and calendar and cycle aging along with aging due to V2G provision. From [15]

[16], too, studied the effect of primary frequency regulation service provision on battery aging. However, they also studied the effects of other factors like the electricity prices, charger efficiency, mean SoC and grid frequency characteristics on the battery aging and profit. The simulation scenarios were similar to that of [15] and a modified Wang model was used. The vehicle provided V2G services while it was parked at home and was charged before leaving for work. From the simulations, conclusions about the various factors was made. It was observed that the simulation at the lower average SoC led to lower degradation and higher battery life. This is shown in Figure 21. Economic results showed that V2G service provision was profitable for providers if the electricity was bought at industrial prices. At domestic electricity prices, the service provision leads to losses. These results are provided in Figure 22. The cost of battery degradation only due to V2G provision was 10% - 20% of the cost of total (drive + V2G) battery degradation.

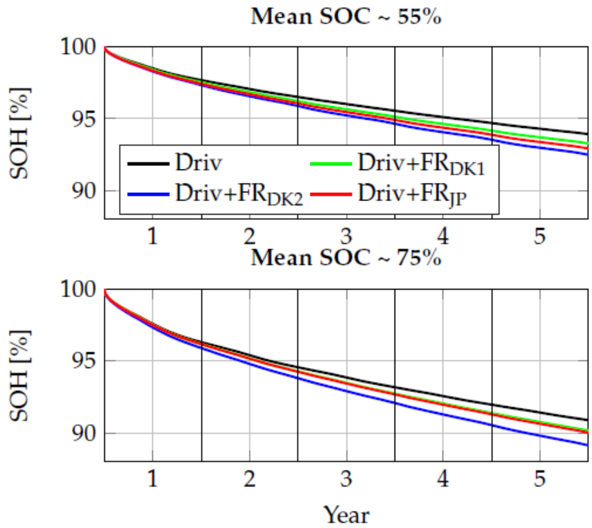

Figure 21: Graph depicting the effect of mean SoC on the degradation of the cell. Taken from [16]

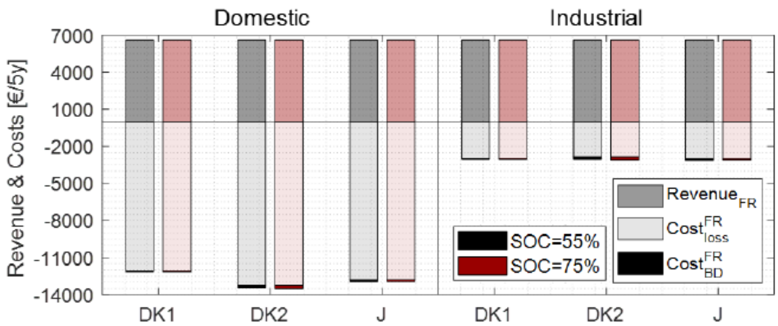

Figure 22: Distribution of costs and revenues considering industrial and domestic electricity prices in different regions as shown in [16]

There was also a paper by [17], wherein they performed simulations to see the effect of different factors like driving style, charging strategies and temperature on the degradation of the battery of an EV. The effect of different V2G services was also studied. The model used for the simulations was one which was developed for LFP cells. It concluded that aggressive driving styles were, understandably, more degrading than mild or gentle profiles. Regarding charging strategies, the levels of charging simulated (L1, 1.5kW and L2, 7.6kW) did not affect the battery degradation (presumably because the E-rates by this level of power is very low). However, controlled and uncontrolled charging caused different amounts of degradation. Uncontrolled charging, which consisted of charging the vehicle after every trip, caused more degradation as compared to controlled charging which involved charging the vehicle after midnight. This was probably a result of low storage SoC in the controlled charging scenario. The effects of V2G service provision were also compared. Two V2G services were simulated, peak shaving and frequency regulation. However, they were not compared against one another. Instead, degradation due to frequency regulation was compared against degradation due to a combination of peak shaving and frequency regulation and against no V2G service provision. The results of the simulations are shown in Figure 23. A greater amount of V2G service resulted in greater amount of throughput and degradation. However, another comparison between a scenario without V2G provision and another scenario with frequency regulation service provision along with charging every other day revealed that the latter showed lower degradation even though the energy throughput was higher. Finally, for the effect of temperature, it was concluded that higher temperatures led to higher degradation (comparing temperatures in Phoenix, Miami and Ann Arbor) and an active thermal management system would result is lower degradation than a passive one.

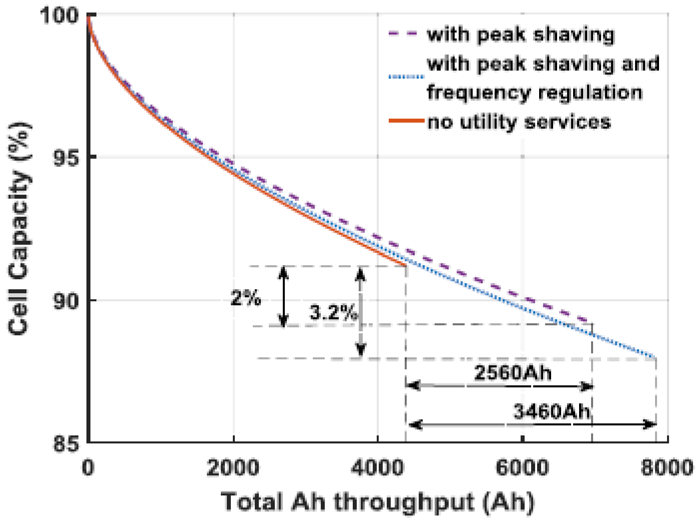

Figure 23: Cell degradation resulting from no utility service provision, only peak shaving and peak shaving with frequency regulation. From [17]

The papers above have studied battery degradation in a single car. However, a couple of papers have considered and studied the battery degradation in a whole fleet. [18], for example, simulated V2G services provided by a fleet of electric vehicles for a year. The V2G service provided was not unlike peak load shaving. The grid was considered cognizant of the power required to be drawn from the fleet. It would then send a set of discharge profiles to each vehicle. The BMS in the vehicle would send back the least degrading profile back to the grid. The grid would then choose the set of profiles which cause minimum degradation in the whole fleet while fulfilling the grid requirements and send this finalized set back to the fleet. A pictorial representation of the BMS algorithm is shown in Figure 24. A set of different scenarios was constructed with different temperatures and vehicle selection methods. Two temperature scenarios are the environments of Dubai and Aachen, while the vehicle selection methods are optimized, wherein the vehicles are chosen such that the overall degradation is minimized, and random, wherein the vehicles are chosen randomly. To reflect reality more closely, the fleet simulated was composed of two types of cars: one type using LFP cells while the other using NMC cells. A total of 100 cars were simulated with 50 cars of each type. The battery degradation in each EV in Dubai in the optimized selection method is shown in Figure 25. The analysis of the results showed that the SoH of the LFP cells was at least and at max 3.93 and 14.63 percentage points higher, respectively, in the optimized case as compared to the random selection case. The NMC cells, in comparison, showed a much lower dependence of the selection criteria on the SoH. The optimized selection resulted in a SoH 1.51 percentage points lower to 0.34 percentage points higher than the random selection case. Regarding the temperature, NMC cells showed higher degradation in a hotter (Dubai) climate than a colder (Aachen) climate.

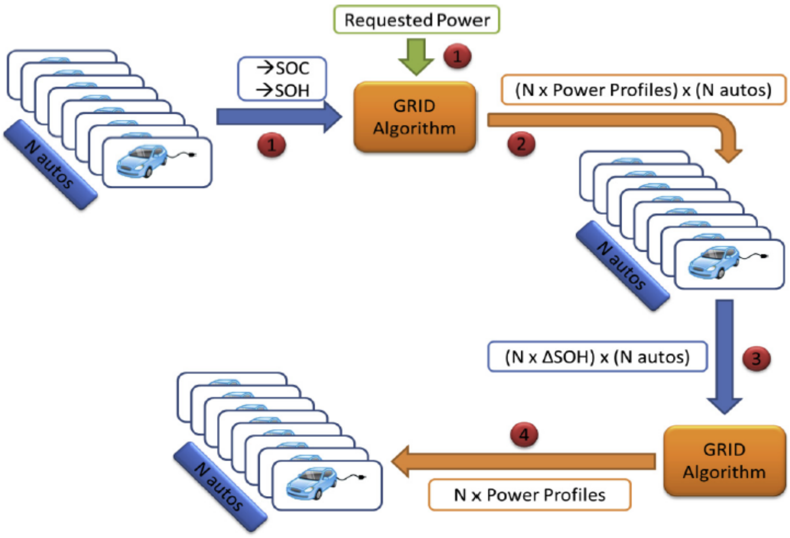

Figure 24: Algorithm for power profile selection from [18]

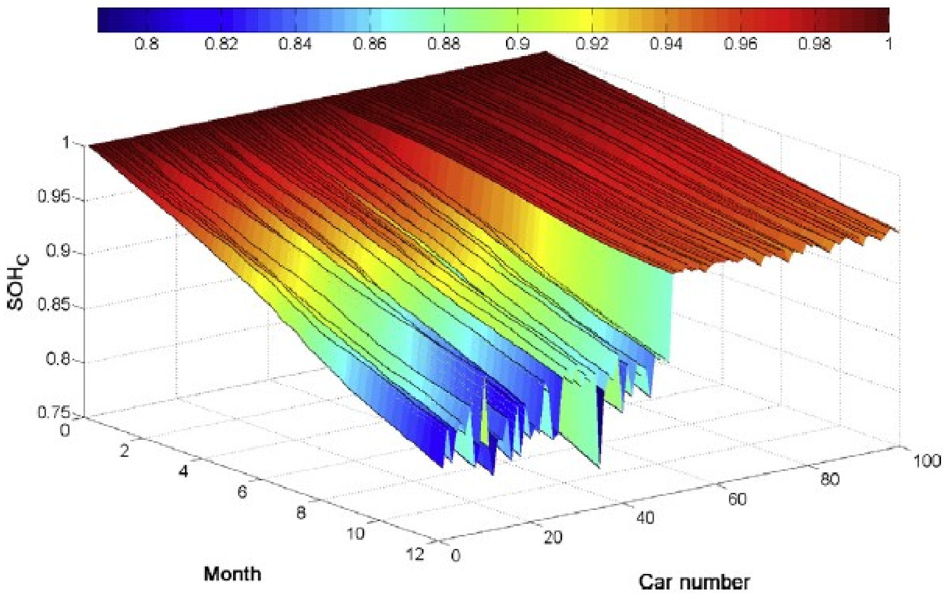

Figure 25: SoH degradation trend for each car over the whole year in the case of SoH optimised selection mothod in Dubai, from [18]

Another paper by [19] claimed that V2G provision could actually result in lower degradation as compared to no V2G provision. The V2G service considered here is the simple injection of energy from the EV battery into the grid. In their paper, they first, describe the development of the battery model used for the simulation. Next, they describe the algorithm that they employ in the BMS for the V2G provision. This algorithm then decides if the V2G service should be provided by the EV or not. The premise for the algorithm is that the V2G service will be provided only if it results in lower degradation. It first checks if the energy to be injected into the grid can be provided without compromising on the driver's energy requirements. If this is satisfied, the BMS checks if the degradation resulting after the V2G provision is lower than that resulting without V2G provision (this could indeed be possible since after injecting into the grid, the EV battery will be at a lower SoC, and so calendar aging will be lesser). If this is the case, the V2G injection is executed. A real-world scenario was also simulated where a part of the energy requirements for International Digital Laboratory building in the University of Warwick was requested from EVs (120 in number) parked in the parking spaces in the vicinity of the building. It must be noted that all vehicles had different DoD for driving, i.e., all vehicles had different driving energy requirements from 0% to 40%. The results showed that this algorithm was able to reduce the capacity fade and power fade by up to 9.1% and 12.1%, respectively, as compared to the case where no V2G service was provided. These results are shown in Figure 26. Moreover, not all the parked EVs participated since the algorithm concluded that those vehicles would degrade more if they provided V2G services.

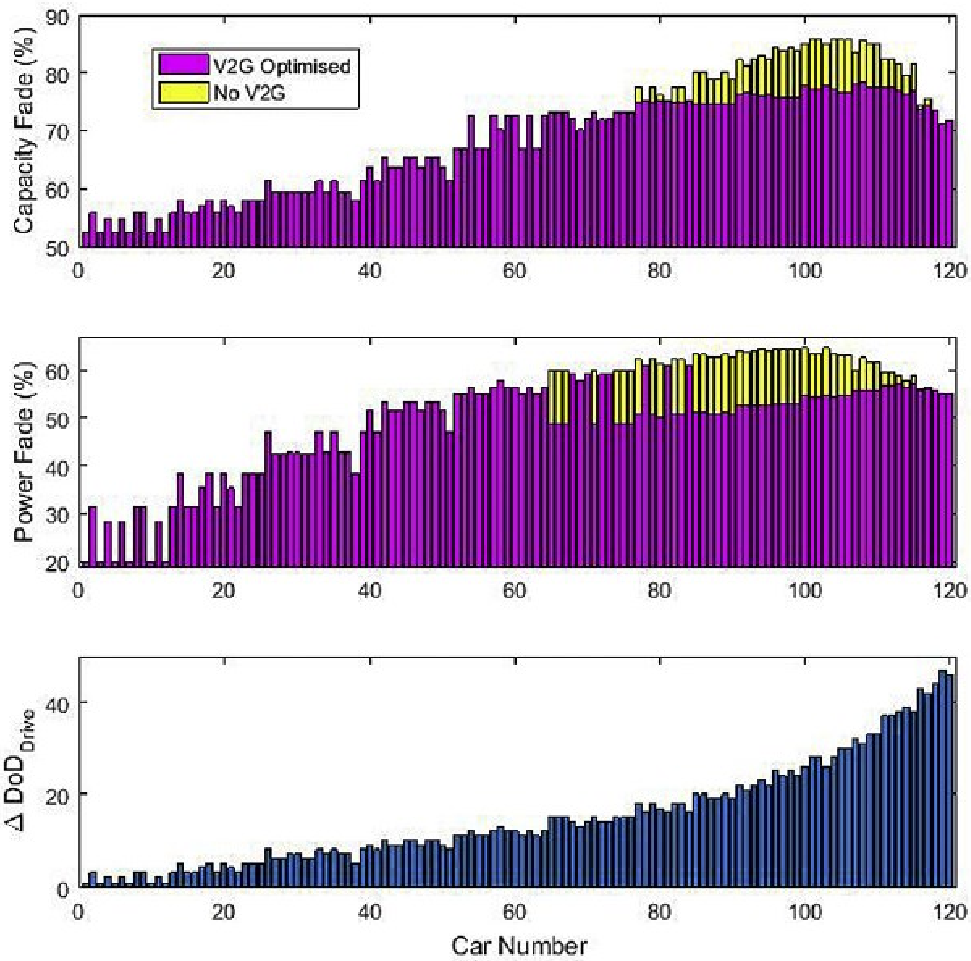

Figure 26: Capacity fade, power fade and driving DoD for each EV simulated in the study resulting with and without optimized V2G provision. From [19]

4.3 Summary

Table 2 summaries the main findings about the literature review conducted in the previous section.

Table 2: Main findings from research works in the field of V2G.

Paper	Year of publication	Experiment/ Simulation	Fleet involved?	Results
[12]	2010	Experiment	No	• Degradation directly dependent on energy throughput • Dynamic profile more degrading than static ones
[13]	2017	Experiment	No	• V2G provision could decrease lifetime of cells to lesser than 5 years
[14]	2016	Simulation	No	• Frequency regulation least degrading of the V2G services simulated • Batteries reached 70% SoH after 9.5 and 8 years without and with V2G provision (frequency regulation) respectively
[15]	2019	Simulation	No	• After 5 years, battery SoH at 7% and 9% without and with V2G provision (frequency regulation) respectively
[16]	2020	Simulation	No	• The simulation at the lower average SoC led to lower degradation • V2G provision (frequency regulation) could be profitable at low prices of electricity, if applicable
[17]	2018	Simulation	No	• Higher amounts of energy throughput generally lead to higher degradation • Delayed or alternative day charging reduces degradation • The warmer weathers simulated resulted in greater degradation
[18]	2015	Simulation	Yes	• Optimized selection of EVs from fleet led to reduced degradation in the overall fleet battery • Simulations of hotter climate resulted in higher degradation
[19]	2017	Simulation	No	• V2G provision could lead to lower battery degradation than no V2G provision. Simulation showed up to 9.1% lower capacity fade and 12.1% lower power fade in EVs providing V2G services

Given the Y-Parc case study, there are three main points of relevance, which should be taken into account:

1. FCR is the V2G service that is least degrading of the battery of the EV due to its low DoD requirements. Since the SoC remains fairly constant throughout service provision, it also becomes less unfavorable for EV owners who may, already, be troubled by range anxiety. Moreover, depending on the compensation rules from the electricity grid operator (whether consuming electricity while providing FCR is charged money or not), a profit could be made, as shown in Calearo et.al (2020), since Y-Parc would be considered an industrial site and would pay electricity at an industrial price.
2. Tip smoothening may also be a viable option for V2G provision. However, as mentioned earlier, DoD is an important factor governing the amount of degradation in a cell. Hence, the viability of this service can be established depending on the DoD that it demands from the battery. Further studies could be done to quantify this and the economic returns that could be received from this service.
3. The optimization of self-consumption using EVs is a strategy which was outlined in the RegEnergy report may harm the battery and reduce its lifetime. The strategy was to discharge 20% of the battery when the vehicle arrives at Y-Parc, charge 60% using PV generated power for 4 hours and then discharge 20% again before the EV leaves the premises, as shown in Figure 27. Dubarry et.al (2017) performed tests on cells using similar profiles but concluded that such treatment can reduce the lifetime of the battery to less than 5 years (Nissan offers a warranty of 8 years on its EV battery, without V2G provision).

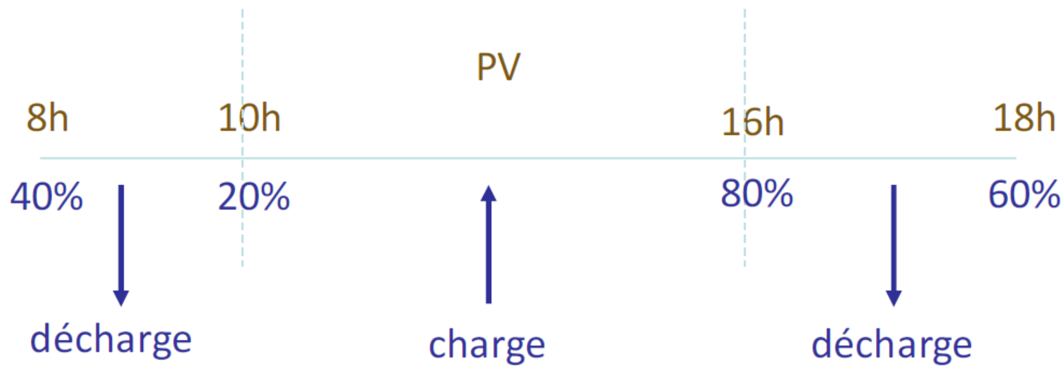

Figure 27: Optimization of self-consumption strategy as outlined in PLANAIR's RegEnergy report

5 Conclusion and Outlook

In conclusion, FCR provision seems to be the most suitable V2G service since most other options are too energy intensive from the perspective of an EV battery. Other V2H and V2B options also seem feasible. However, more experiments/simulations need to be performed to assess the minimum, maximum and average cell degradation that results from these services to put a price on the excess cell degradation and to also bring its economic viability into perspective.

The “V2G installations in Europe” section shows that there have been many pilot projects that have been undertaken in Europe. There have been a few in other part of the world as well. There are also examples of very recent installations like the FCA-ENGIE EPS V2G pilot in Turin, Italy. This goes to show that this may indeed be a viable technology. However, despite the high number of pilot projects, investigations in the direction of battery degradation due to the provision of these services are rare. Most of the projects focus on testing the technical viability, such as the Elia V2G project, and the revenue obtained, albeit disregarding cell degradation.

The amount of scientific literature on the topic of battery degradation due to V2G service provision is also very limited. However, it is fairly clear that higher cycling, as will be the case in V2G services, the battery is degrading more. Therefore, it is very important to put a price on battery degradation so that EV owners, who participate in V2G, can be compensated adequately. Failing to do so will discourage EV owners from participating in such services.

The outlook for the future is that, considering the dearth of literature that overlaps V2G and battery aging, there exists the need, scope and opportunity to perform an in-depth study regarding this. The varying results obtained in the studies also point to the fact that the opportunity for the deployment of a better battery model also exists. Better the predictions of the battery models, more accurate will be the compensation that can be decided for V2G service provision and better will be the comparison with other storage technologies.

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