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Research Paper

Effect on battery life of vehicle-to-home electric power provision under Canadian residential electrical demand

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HIGHLIGHTS

- Physics-based model employed to simulate battery pack performance and degradation.
- Baseline pack lifetimes found as function of driving behaviours through simulation.
- High-resolution electricity profiles for Canadian context represent V2H demand.
- V2H effect on pack lifetime found by simulation and compared to base driving cases.
- Pack lifetime was reduced by two years for a daily 8-h V2H event.

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ABSTRACT

Vehicle-to-Home (V2H) is a support activity using electric vehicles where the electric power stored in their batteries is supplied in response to residential electrical demand. It is understood that supplementary battery use such as V2H will reduce the battery service life. Judicious V2H activity can provide energy benefits at acceptable levels of battery life reduction. The present study employs a fundamentals based battery simulation to explore a range of V2H scenarios to assess the net energy benefits, and weigh these against associated battery life reduction attributable to V2H. The frequency (daily, weekly, monthly), duration and time-of-day of the V2H event were test parameters. Long term (i.e. given roughly 16 year battery calendar life) detailed simulations which included a daily driving regime together with V2H activity based on detailed residential electricity use data were used to determine battery lifetimes. Apart from aggressive driving and fast charging which greatly impact electric vehicle (EV) battery life, the largest contributions to battery degradation were for intense participation in V2H services, such as handling the household electrical load for 8 h daily. A 10.6 year battery life with no V2H, was lowered to about 10.2 years with 1 h daily V2H, and to about 8.5 years with 8 h daily V2H. However, lower intensity, and especially lower frequency use of the EV battery can still provide useful V2H services with acceptable battery degradation.

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1. Introduction

Vehicle-to-Home (V2H) describes an energy system where the battery pack from electric vehicle is used to supply the electricity for residential use. As an energy use strategy as concerns utilities, V2H is aimed at alleviating consumption of power in peak periods when demand is highest. V2H could also provide backup power supply for emergencies, or be used as a temporary electricity supply for infrequently used remote buildings.

It is understood that the battery packs in electric vehicles have been designed for power loads associated with driving. Driving demands in general are more severe than residential energy demands, so it is envisioned that vehicle battery packs could find additional use by supplying power to buildings or homes. The present study has been conducted to investigate the effect of real household electrical loads on electric vehicle battery life. There is general interest from the utility side in North America to make use of V2H to assist with grid stability and to minimize infrastruc-

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tural upgrades and expansion, but at present, electrical vehicles on the market here are not equipped with this capability. Of note, is that in Japan, Toyota and Nissan have implemented V2H functionality in electric vehicles [1].

A number of preliminary studies have been made which describe advantages of V2H, such as peak reduction for household electrical demand. Basic models with batteries represented as a simple energy reservoir, without electrochemical functionality were used to show that V2H can improve the uniformity of power demand [2].

A paper on smart grids, considered V2H in a sophisticated residential energy system [3]. A key finding was that an intelligent management system can derive benefits from V2H, and when combined with renewable energy, there will be elevated demands on the electrical storage units, but the extent of this was not quantified. An even more recent effort in this area was published by Putrus et al. [4], where the importance of battery wear associated with V2H was recognized. The modeling approach employed here was overly simplistic and concluded that controlled smart charging of EV batteries did not cause excessive lifetime degradation. An example of a basic economic case for V2H, with simple technical justification, can be seen in [5].

V2H is a very new practice, and the present study is the first to apply physics based modeling to provide some concrete quantitative results to the generally pondered questions of the effect on automotive battery pack life when also using the vehicle for V2H beyond its normal driving use. From the literature it was understood that V2H was a useful concept and could provide a number of practical benefits, and this paper is the first to report through realistic modeling work, on the cost associated with V2H activity expressed as reduced vehicle battery pack life as a function of various usage parameters.

2. Methodology

Two different modeling procedures were required for this project. The first was a simplified fundamentals-based electrochemical model of the operation of a single Li-ion cell. The output of this first model was collected for a range of currents and condensed into a second model, an engineering type empirical model to represent the function of the total electric vehicle Li-ion battery pack. The models are summarized below, full details may be found in [6].

2.1. Model description: Li-ion battery model

Based on measured charge and discharge data, and a set of material parameters, the fundamental electrochemical single particle model (SPM) [6,7] was used to produce a number of charge and discharge curves at currents ranging from very small currents to very large currents that are beyond practical ranges for experimental tests.

Charge and discharge curves from the SPM then formed the basis of an empirical representation of the Li-ion battery in an equivalent resistance type (Gao) model [8]. The Gao model is then used in vehicle use scenarios to track the operational state of the Li-ion battery. In this project, a constant battery temperature of 30 °C was assumed.

In the Gao model, the voltage during discharging is given by:

$$V(\mathrm{t},\mathrm{DOD},I(t)) = \mathrm{OCV}(\mathrm{DOD}) - I(t)R_{\mathrm{int}}(\mathrm{DOD}) \tag{1}$$

where $I(t)$ is the current and R_{int} is the internal resistance. This equation describes that under load, there is a shift of the voltage as a function of depth-of-discharge (DOD), equal to the internal resistance multiplied by the current.

At a given DOD, an imposed power load P, where $P = IV$, determines a required current $I(t)$ based on the cell voltage. Applying this current over a time step will cause a small voltage drop, and correspondingly advances the DOD via:

$$\Delta\mathrm{DOD} = \frac{-I(t)\Delta t}{\alpha\beta\cdot \mathrm{cap}_{\mathrm{ref}}} \tag{2}$$

In this case, $\mathrm{cap}_{\mathrm{ref}}$ is the battery capacity and α and β are Gao model parameters [8].

2.2. Operating envelope

Conventional cycling methods involve discharging and charging at a fixed current between fixed upper and lower voltage limits. However, both the state of charge and the depth of discharge are properties related to cell capacity rather than voltage. Using fixed voltage limit cycling will result in variable SOC and DOD values for the cycle history of each cell and operating conditions such as temperature and current. To compare partial cycling methods without these biases, fixed percent capacity ranges can be applied to bound charge and discharge stages. For example, to conduct a 5% charge/discharge cycle, 2.20 A h cells would be charged until the relative capacity increased 0.11 A h and then discharged the same amount.

Charging and discharging a battery at constant current based on capacity limits instead of voltage limits poses the question of how to define the limits for continuous cycling. Internal resistance in the cell will shift the potential during operation away from the open circuit potential of the cell in proportion to the applied current. For operation that adheres to the cell manufacturer's recommendations as well as real world performance dictates specified by battery management systems, the voltage was required to stay between 3.0 V and 4.2 V. Working within these limits, initial characterization tests were made on the selected 2200 mA h Lithium-ion cells. Ten cycles of 5% ΔDOD cycles were performed at various currents and SOC centres to probe the safe operating envelope, shown in Fig. 1. The temperature was held to 30 °C ± 0.1 °C for these tests. The operating envelope of Fig. 1 was determined with in-house exploratory data which measured voltage steps that arise from the cell internal resistance when a current is suddenly applied. Under charging conditions, the internal resistance causes a step change increase in potential, while the opposite occurs with discharge.

The experimental setup consisted of 18,650 cells placed inside a temperature controlled chamber and connected to independent channels on an Arbin BT2000 series battery test system. Each channel was both a potentiostat and galvanostat which provided both

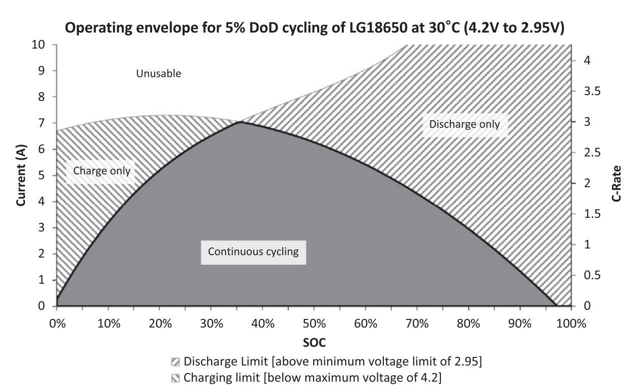

Fig. 1. Operating envelope for 5% range DOD cycling of 2200 mA h Li-NMC 18,650 cells at 30 °C.

voltage and current control for all charging and discharging requirements. For a complete description of experimental setup, please refer to [9].

2.3. Battery testing considerations

Manufacturer data sheets and cell performance testing seen in the literature focus on full DOD cycling [9b]. In some applications such as residential energy storage or with renewables, or in electric vehicles, cells undergo irregular dynamic cycling which may never fully deplete the cells. Relative capacity changes easily determined based on the total amount of current passed. In contrast, a cell's absolute capacity at any one time is unknown and can only be determined by a full charge and discharge cycle. For these tests, absolute capacity is measured using a standard full cycle based on manufacturer specifications (hereto defined as a capacity check cycle) performed every 20 equivalent full cycles (EFC). Absolute discharge capacity will vary with cell age and temperature. When partial cycles are centred around a specific SOC, this SOC point is situated by discharging the cell with a total amount of current that is a specified fraction of the original cell capacity.

As described in the introduction, the classical definition of a cycle does not adequately represent a partial cycle. The concept of EFCs is introduced here as a method to standardize partial cycling methods. The number of EFCs, N_{EFC} is defined as follows,

$$N_{\mathrm{EFC}} == \frac{N_{PC} \cdot \Delta DOD}{Q_{d_i}} \tag{3}$$

where N_{PC} is the number of partial cycles, ΔDOD is the constant state of charge swing of each cycle, and Q_{d_i} is the initial discharge capacity of the cell for the given temperature. In this way, N_{EFC} is a measure of the total energy passed through the cell, regardless of DoD.

2.4. Capacity fade model

Use of a battery will gradually degrade its available capacity. This capacity loss occurs from low-rate irreversible chemical side reactions, which proceed even when the battery is not in use, accounting for the calendar life of a battery. The end-of-life for a battery is typically specified as the point at which the battery capacity falls below 75% of its original value [11]. Battery degradation accelerates in proportion to applied current. Two components of capacity fade must therefore be accounted for; cycling capacity fade and calendar fade.

Cycling capacity fade measurements for the cells modeled here were taken from the literature [12]. At a reference current of C/3, a nominal capacity fade of 0.001833 A h/cycle $(\mathrm{cap}^{\mathrm{REF}}_{\mathrm{fade\ rate}})$ was reported.

Capacity fade is also known to be a strong function of the level of applied current, and the battery DOD, especially when there are rapidly varying power loads that may oscillate from discharging to charging modes [6].

In terms of the ΔDOD, the general expression for the cycling contribution to capacity fade for each time step, can be stated as

$$\mathrm{cap}_{\mathrm{fade}} = \mathrm{cap}^{\mathrm{REF}}_{\mathrm{fade\ rate}} \left(\frac{\Delta\mathrm{DOD}}{2}\right) F_{\mathrm{CUR}}[I(t)] F_{\mathrm{DOD}}[\mathrm{DOD}] \tag{4}$$

Here, $F_{\mathrm{CUR}}[I(t)]$ is a ratio of the extent of fades measured as a function of applied current to the C/3 reference value, and $F_{\mathrm{DOD}}[\mathrm{DOD}]$ is a factor applied to reflect the extent of fade attributable to the instantaneous DOD state. Explicitly, from experimental measurements,

$$F_{\mathrm{CUR}}\ [I(t)] = 0.8581 \cdot \exp(0.0112 \cdot I(t)) \tag{5}$$

For the determination of $F_{\mathrm{DOD}}[\mathrm{DOD}]$, a set of experimental measurements were made where cells were cycled over very narrow DOD ranges for extended periods to estimate capacity fade rates as a function of DOD. Data from these tests are shown in Fig. 2.

$F_{\mathrm{DOD}}[\mathrm{DOD}]$ can be expressed as

$$F_{\mathrm{DOD}}\ [\mathrm{DOD}] = 4.00558 \cdot DOD^2 - 4.89866 \cdot DOD + 2.11414 \tag{6}$$

The values obtained from Eq. (6) have been normalized so that evaluating them across the entire DOD range results in an amount of capacity fade equal to $\mathrm{cap}^{\mathrm{REF}}_{\mathrm{fade\ rate}}$. As the capacity fade is updated dynamically in the simulation, a running total over time of the cumulative capacity fade is also tracked.

The markedly higher capacity fade rates observable at values of DOD lower than about 0.25 are known to occur [13]. A recent study [14] shows significant vehicle battery lifetime loss at high currents when lower DOD recharge values are permitted.

To account for calendar fade ($\mathrm{cal}_{\mathrm{fade}}$, in A h), curve-fitting data from [5–10] provided the following expression,

$$\mathrm{cal}_{\mathrm{fade}} = 1.0565738E - 07 \cdot N_{DAY} + 1.3433717E - 03 \tag{7}$$

In Eq. (7), N_{DAY} is the total number of days the cell has been in existence. In simulations, the calendar fade is determined once daily to update the total cumulative capacity fade at the end of each day.

2.5. Model validation

A representative electric vehicle was chosen for the simulation on the basis of the scope and quality of drive cycle battery discharge data and battery recharge data available. The electric vehicle battery had conventional LiNMC cathode material, with 28 kW h of discharge capacity.

As simulations were run on the cell level, potentials, states of charge, and vehicle power loads were all normalized to single cell values. The voltage where full recharge was considered complete according to the vehicle specifications was 4.02 V, which corresponds to a DOD of 0.04.

The simulation was then validated against dynamometer data provided by Environment Canada for the LA4 (city) Drive Cycle.

Overall, the average error between measured and simulated data was very small, only 0.15%. The largest errors occur during battery relaxation phase, due to time lag and high internal resis-

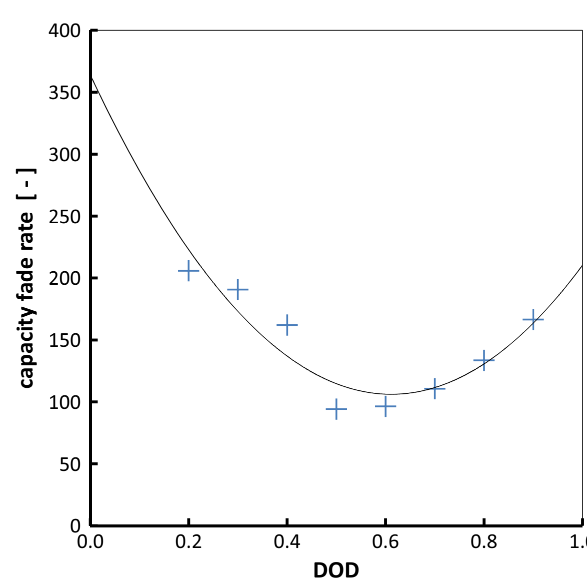

Fig. 2. Capacity fade rates for LiNMC 18,650 cells versus DOD. Data taken at 30 °C, results after 300 equivalent cycles.

tance at low currents. In Fig. 3, a portion of the simulated validation data is shown in great detail in high temporal resolution.

It can be seen in Fig. 3 that when there are very sudden drops in the current demand on the battery, there is a more rapid relaxation back to resting potentials for the simulated values, but in general the correspondence is quite close, generally within 0.01 V.

2.6. Electricity demand profiles

Detailed electricity consumption data for a single Canadian home were taken from a Carleton University study, with electricity use data from the home averaged and recorded over 1 min intervals [15]. The annual demand profile on a daily basis is shown in Fig. 4.

A V2H scenario was tested with residential electrical demand data from IEA Annex 42 [16] over a 4-day period that had 3 s resolution and compared to the same simulation run with one minute aggregates of the 3 s data. For this 4-day period, the total capacity fade was found to be 0.0150392 A h with the 3-s data, versus 0.0150270 A h for the same data in one-minute aggregates. The one-minute aggregate data produced capacity fades that were 99.92% of the 3 s data. This 0.08% error was deemed acceptable for using one minute interval data for long term V2H studies, thus the load data from [15] mentioned above were used in the simulation work.

3. Results of battery life simulation

3.1. Base cases of regular driving and recharging

Any use of a battery has impact on its life. The use of electric vehicles in various scenarios of regular driving and recharging was simulated to establish base cases for comparison to the scenarios in which the electric vehicles would also be involved in V2H activities.

3.2. Driving characteristics

There is a great variation in the way and extent that vehicles are driven. In this study, standard drive cycles representing city driving, highway driving and aggressive driving were used to evaluate the impact of the type of driving on the EV battery life.

For example, Fig. 5 displays the speed profile of the city drive cycle ('LA4', also called 'UDDS') used here. Also used were the highway drive cycle ('HWY'), and the aggressive driving cycle ('US06'). The city drive cycle covers a distance of 12.0 km, the highway drive cycle 16.5 km, and the aggressive driving drive cycle 12.9 km. More information on these standard drive cycles can be found in [17].

3.3. Charging characteristics

Electric vehicles can be recharged using different charge levels. Depending on the charge level, the time to fully recharge the battery will vary, as will the efficiency of the charging process. Table 1 presents the (AC) charge levels and associated charging efficiencies used [8–12]. Most recharging of electric vehicles at home will be done using Level 1, Level 2a or Level 2b. Fast charging at Level 3a or Level 3b is often limited to other locations.

The AC power levels at which the EVs would feed power back into the grid were assumed to be the equal to the AC charge levels. The same applied to the discharge efficiencies.

3.4. Daily EV usage schedule

In each scenario, the electric vehicle was driven 50 km per day and then fully recharged. At the start of the driving on each new day, the EV was made to continue at the point of the drive cycle where it ended the day before, to ensure that all sections of the drive cycles would get equal coverage.

3.5. Battery life impact of regular driving and recharging

First the calendar life of the EV battery was determined using the battery life model. Without any usage of the battery, the EV battery would slowly degrade and after 16.84 years the battery capacity would have dropped to 75% of its original capacity. At this point in time, the battery is assumed to have reached its end of life. In reality, this does not mean that the EV batteries will have to be discarded or recycled. There are good opportunities for secondary usage of EV batteries possible, for instance in less demanding stationary electricity storage applications.

Base case scenarios were run to investigate the additional battery degradation from regular driving and recharging. 15 scenarios were run combining each of the three different drive cycles and the five charge levels. Fig. 6 displays the gradual decrease in EV battery capacity over time for the different drive cycles and recharging at the lowest charge level (1.3 kW). City and highway driving have an approximate equal effect on battery life, reducing its useful life to just over 11.5 years. Aggressive driving results in a much faster degradation of the battery and an additional reduction in battery life of almost 3 years in comparison to the other types of driving.

Fig. 7 presents similar results, but now the EV was always charged at the highest power level (50 kW). Using fast charging will more quickly degrade the EV battery. The battery life for scenarios of city and highway driving decreased by about 1.2 years to approximately 10.5 years in comparison to using the lowest charging power. The aggressive driving scenario showed an additional 1.1 year reduction in battery life compared to recharging at the 1.3 kW level, with the EV battery already reaching the end-of-life point of 75% of the original capacity within 8 years.

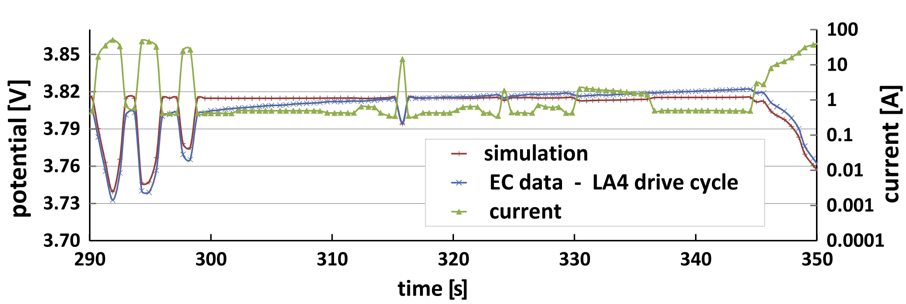

Fig. 3. High temporal resolution measured and simulated battery pack potentials for the test vehicle over a short period of an LA4 drive cycle.

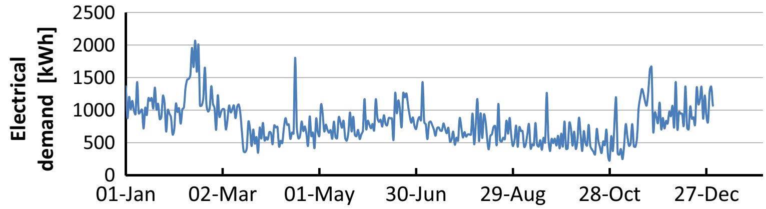

Fig. 4. Daily residential electricity demand from [15].

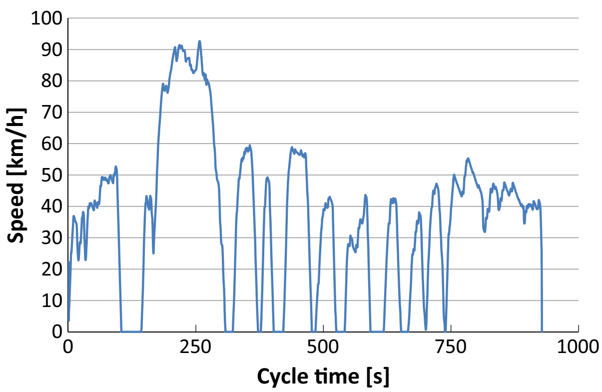

Fig. 5. Speed profile of city driving test cycle (LA4/UDDS).

Table 1
EV battery life (in years) for various drive cycles and levels of charge and discharge power.

Charge level	Charge power (kW)	Charger efficiency (%)	Drive cycle		
			LA4	HWY	US06
L1	1.3	0.84	11.56	11.75	8.81
L2a	3.3	0.935	11.52	11.70	8.77
L2b	6.6	0.89	11.45	11.64	8.71
L3a	25	0.92	11.01	11.21	8.35
L3b	50	0.94	10.30	10.52	7.75

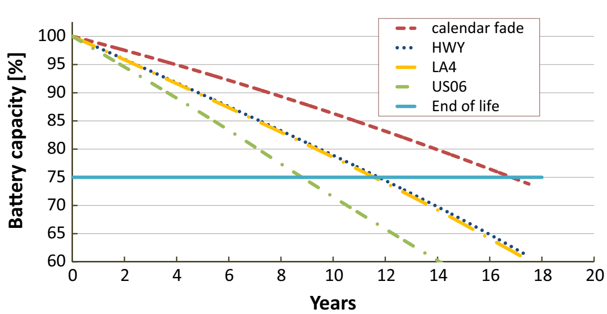

Fig. 6. EV battery life for various drive cycles for Level 1 (1.3 kW) charge and discharge power.

The battery life results for all 15 scenarios are summarized in Table 1.

The drive cycles for city driving and highway driving were created in 1972. Current real world traffic is significantly more aggressive than 40 years ago. To use a more representative drive cycle for current day driving, a 'mixed' drive cycle was defined. In the mixed drive cycle, the EV would drive one third of its daily 50 km using the city driving cycle, one third following the highway drive cycle, and it would use the aggressive driving drive cycle for the last third of its daily kilometres. Fig. 8 displays the battery life results for

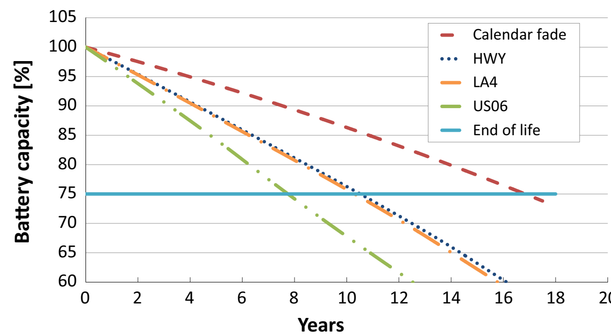

Fig. 7. EV battery life for various drive cycles for Level 3b (50 kW) charge and discharge power.

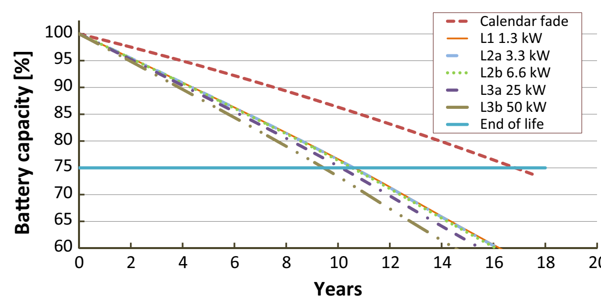

Fig. 8. EV battery life for the (33%/33%/33%) mixed drive cycle for various levels of charge and discharge power.

using this mixed drive cycle and for all charge levels. The numeric results are included in Table 1.

The expected battery life for scenarios using the mixed drive cycle falls in between the results for the city/highway drive cycles and the aggressive drive cycle and ranges from 10.64 years for Level 1 charging to 9.44 years for Level 3b charging.

3.6. Summary of base case results

Drive style and charge level both have a significant impact on the EV battery life. While daily charging at Level 2 (3.3 kW or 6.6 kW) does not substantially reduce the EV battery life compared to charging at Level 1 (1.3 kW), this cannot be said of fast charging. Daily fast charging at a power level of 50 kW reduces battery life by 1.1–1.3 years.

The impact of drive style is even greater. Aggressive driving can reduce EV battery life by 2.6–2.9 years compared to a gentler driving style.

3.7. V2H cases

This study set out to investigate the effect of adding V2H activities to regular vehicle use. A number of scenarios were designed that involved controlling a set of parameters that could be incorporated into the simulation. These included; a daily distance of 50 km driven by the vehicle; the type of driving (a drive cycle mix consisting of 33.3% each of LA4, HWY, US06 cycles); a daily V2H event (as opposed to weekly or monthly); a daily operational regime composed of driving, battery recharging, V2H event and a second battery recharging (DRVR); and recharging with a 6.6 kW L2b unit. Independent effects of some of these variables kept constant can be seen in [14].

The above parameters were kept constant for all simulations, while a number of other parameters were varied in order to establish their effects. Given the temporal nature of the electric demand profiles, the V2H events were assigned various daily start times, and a range of durations. These values are detailed in Table 2.

The particular electric vehicle under consideration had a pack architecture of 92 cells in series and 2 in parallel, with a nominal driving range of about 120 km. This was designated as BEV 120. Two other hypothetical vehicles with larger battery packs were also simulated, BEV 200 (3 × 92 pack, ~200 km range) and BEV 300 (5 × 92 pack, ~300 km range).

Fig. 9 gives an overview of the battery capacity as simulated over the lifetime of the standard electric vehicle, BEV 120. The 0 h V2H duration curve corresponds to the L2b curve in Fig. 8, as this shows a driving-only effect on battery life. In general as the duration of V2H service increases from 1 h to 8 h, the extent of battery life loss is roughly proportional. A nominal value of about 0.36 years-life-loss/hour-of-V2H was calculated for 1 h V2H cases, and this value was found to extend to 4 h with a small reduction, and dropped to 0.24 for the 8 h period. This indicated that there is time-of-day functionality at work here, the later hours of the 12h00–20h00 8-h block present a lower electrical demand than the earlier hours. In any event, a daily 8-h V2H event represents a 1.90 year cost in vehicle battery life. Note that if the V2H frequency was weekly or monthly, the life-loss cost would be roughly 3 months (0.27 years) or 3 weeks (0.06 years) respectively.

Table 2
Simulation parameters for V2H scenarios.

BEV 120 [2 cells parallel]				
V2H			Duration [h]	Years
START	8	am	0	10.55
			1	10.18
			2	9.86
			4	9.34
			8	8.65
	10	am	1	10.13
			2	9.83
			4	9.35
			8	8.58
	12	am	1	10.15
			2	9.86
			4	9.35
			8	8.54
	14	pm	1	10.16
			2	9.83
			4	9.26
			8	8.55
	16	pm	1	10.10
			2	9.73
			4	9.19
			8	8.71
	18	pm	1	10.07
			2	9.75
			4	9.31
			6	9.11
			8	9.00
	20	pm	1	10.15
			2	9.89
			4	9.62
	22	pm	1	10.31
			2	10.17

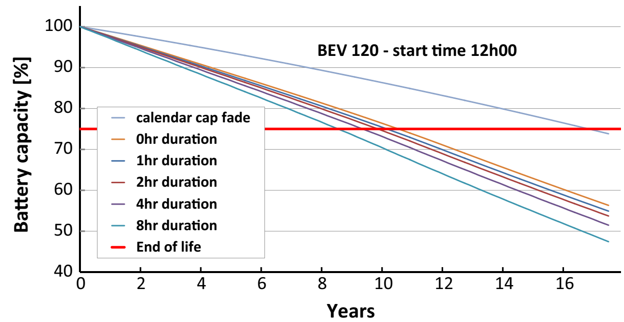

Fig. 9. EV battery life for various daily durations of V2H service for the BEV120.

The effect of V2H on different sizes of battery packs was also simulated. Additional parallel sets of cells were added to the simulation to test hypothetical electric vehicles with nominal driving ranges of 200 and 300 km (BEV 200 and BEV 300). With batteries 50% and 150% larger than in the standard electric vehicle, it can be seen in Fig. 10 that a 50 km/day driving requirement produces much less wear on the battery pack. The BEV 300 will have a battery life of 13.68 years and the battery in the BEV 200 will last 12.16 years. This expanded capacity also assists with managing the demands of V2H service. In Fig. 10 the additional battery life loss due to 8 h of daily V2H service is 2.10 years for the BEV 120, 1.98 years for the BEV 200, and 1.68 years for the BEV 300. The difference in life for these three battery sizes is not too substantial compared to the capital costs associated which would be directly proportional to capacity. The factor that works against any economy associated with a larger battery pack is the calendar fade, which is constant and independent of size.

Another consideration for V2H is the quality and continuity of the power supplied to the home by the vehicle. In the face of the electrical demand profiles, there could be times where the V2H service is unable to meet the instantaneous demand. In particular, there are two circumstances where the demand is not met. The first would be by a demand peak, where a power draw above 6.6 kW is sought. The L2b charging system is limited to power transfers of this level. Thus, any instantaneous demand above 6.6 kW cannot be met, and this quantity of power is tracked as undelivered due to peak height. A second condition can occur, normally towards the end of the V2H service period, which is when the battery becomes depleted before the end of the V2H period. This quantity of power is tracked as undelivered due to battery capacity. This second type of supply failure in principle would

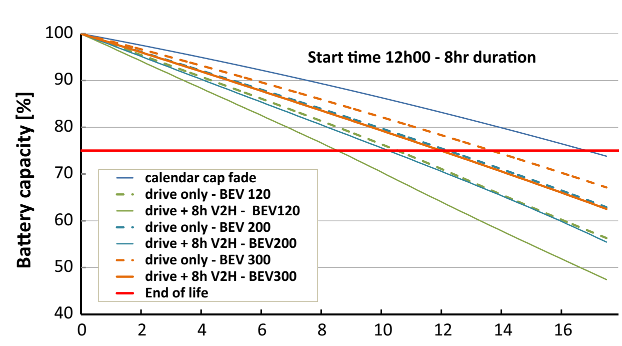

Fig. 10. EV battery life for an 8 h daily duration of V2H service three different sizes of battery packs.

become more common as the battery capacity fades over its lifetime.

The effect of V2H service can also be shown in terms of how vehicle performance would evolve over time. Fig. 11 shows the possible driving range over time for the vehicle determined under two scenarios, the first with 50 km daily mixed-cycle driving, the second with the same driving demands, as well as a daily 8 h V2H service, started at 12h00. It can be seen in Fig. 11 that the driving range decreases over time, and it decreases at a slightly greater rate when heavy V2H use occurs. For reference, with the V2H usage as simulated, 3.2% more of the driving range is lost after 2 years, 7.3% after 6 years, and about 18% at the battery end-of-life point of 10.5 years. It should be mentioned that these percentage additional losses would scale roughly in proportion to frequency of V2H service and duration of V2H service. Thus, for a vehicle deployed once a week for 2 h of V2H, the percentage range loss after 10.5 years would be about 0.65%, a fairly insignificant difference.

Life-cycle analysis (LCA) for automotive battery packs is an in-depth subject related to all phases of battery materials production, manufacturing, battery use, energy inputs, emissions and disposal considerations [18]. LCA concerns are of great interest to battery users and the general public. While LCA was not within the scope and objectives of the present project, V2H activity should have a near net-zero energy use and environmental effect, since the main difference would arise from efficiency losses connected to power flows back and forth between the vehicle and home. A daily 8 h V2H service scenario, would represent 2.1% of the total power flow which can be considered to be extremely high V2H usage, so lesser, more realistic V2H loads would show a fairly negligible LCA impact.

Fig. 12 shows the fraction of the residential electric power demand that is met by the V2H service performing 8 h V2H service over its lifetime. Up until about the 4 h service mark, all three curves overlap, which indicates that the undelivered power was not a function of battery capacity, but rather is attributed to peaks above 6.6 kW. The peak power limit is common for all three battery sizes. The effect of the battery pack sizes becomes significant in the later part of the V2H period. For the case of the BEV 300, the fraction power delivered actually increases over the final four hours, likely due to the character of the daily profiles, where excessive peaks occur less frequently. A substantial drop-off is seen with BEV 120, as the duration of the V2H service is depleting the battery, and this becomes exacerbated as the battery ages. Towards the end of the battery lifetime, in terms of noticeable power lapses, the BEV 120 would miss delivery of the electrical demand at a rate about four times greater than the BEV 300 under the same V2H requirements.

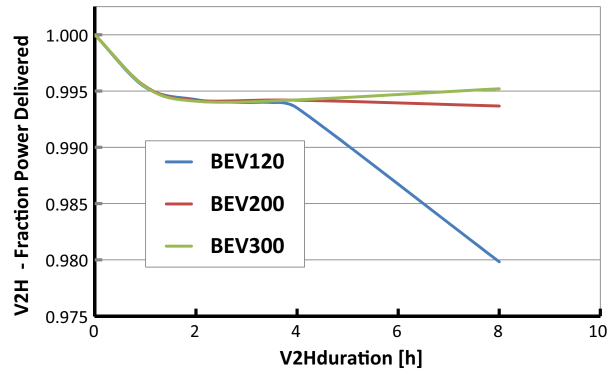

Fig. 12. Fraction of total power demand delivered for 8 h daily V2H for the three electric vehicles shown at end-of-life point.

This situation discussed above regarding two causes of undelivered power is depicted in Fig. 13, where the proportion of undelivered power due to battery capacity is plotted against time for the three electric vehicles.

As V2H service periods go beyond 2 h, battery capacity limits are reached with the BEV 120 and the fraction rises above zero. The onset point is around 4 h for the BEV 200 and no delivery lapses due to battery capacity are ever observed for the BEV 300. Thus, Fig. 13 shows that the power quality derived from V2H service is greatly enhanced with larger battery packs.

Fig. 14 shows a the fraction of undelivered power demand over the course of an 8 h V2H event. A high-demand day was selected (February 16) where there were demand peaks above L2b charging level capacity, as well as a large overall demand. The undelivered power is shown for these V2H events in the first, fifth and ninth year of battery service. The amount of power undelivered due to demand peaks is the same in each year, as these data are only a function of the electrical demand. As the battery ages, the point in time where the battery can no longer satisfy all demand becomes progressively earlier, near the 5 and a half hour point in the first year, and lasting about 3 and half hours in the ninth year. For reference, the end-of-life value for the battery pack used for this V2H scenario (12h00 start time, 8 h duration) was 8.54 years.

The same scenarios were run using a DVR operational regime and the battery became exhausted before the end of the first hour of the V2H event for February 16 in the ninth year of service. Additionally, the total amount of undelivered power in the ninth year rose to over 30%. Even in the very first year of service, the V2H duration was limited to 3 h, and the amount of undelivered power was about 17% on this date. The lesser amount of battery use in changing from the DRVR regime depicted in Fig. 14, to a DVR regime came with longer net battery life of 8.88 years.

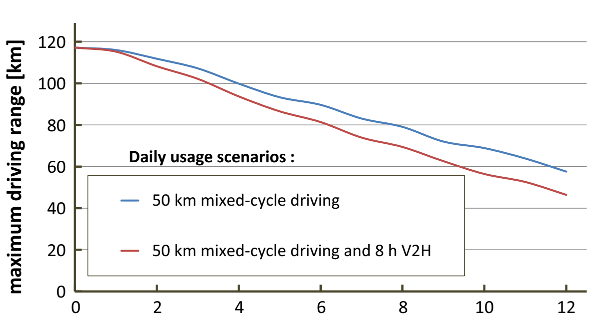

Fig. 11. Driving range vs. time for 50 km mixed-cycle driving scenario for cases with and without 8 h daily V2H service.

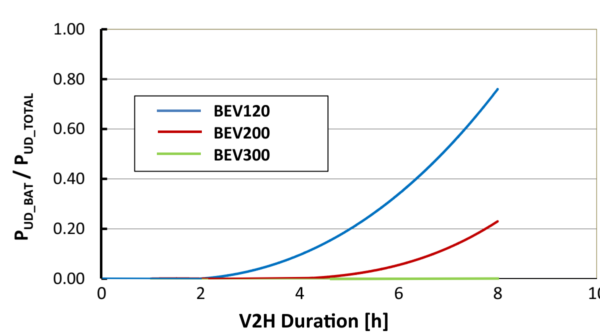

Fig. 13. Fraction of undelivered power due to battery capacity for 8 h daily V2H.

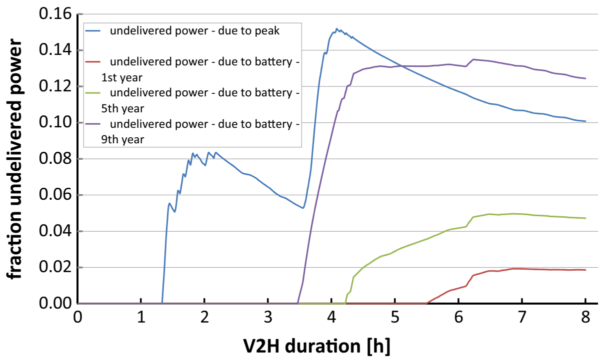

Fig. 14. Fraction of undelivered power demand over an 8 h V2H event on the same high demand day, shown for the first, fifth and ninth year of battery service.

4. Conclusions

The present study was a novel investigation into the effect of vehicle-to-home activities on the expected service life of a battery pack in an electric vehicle. A number of scenarios were explored, and in general, a battery pack built with 192,41 A h cells had an estimated service life of about 10 and half years used solely for 50 km/day of mixed-cycle driving. When V2H service was added to the battery use, the pack lifetime was reduced by as much as two years for a daily 8-h V2H event. Shorter or less frequent V2H use lessened the pack life proportionally.

Hypothetical simulations were run with vehicles having battery packs 50% and 150% larger than the selected test vehicle. At a 150% increase in pack size, the pack life can be extended by 3 years for driving-only use. For such a large battery, daily V2H reduced the pack lifetime by 1.7 years.

In addition to battery pack service life, the question of the power quality delivered by V2H was also studied. It was found that the fraction of total power delivered for daily V2H event is reliable for a 4 h period for all battery sizes over the battery lifetime. The smaller capacity BEV 120 vehicle was unable to meet about 2% of total demand for an 8 h period by the end of its service life. In terms of power interruptions in a residence, this level is of quality is not ideal.

The prospects for V2H use are positive. In general, the 28 kW h battery pack in the test vehicle simulated here, while serviceable, is a little on the small side. For real life residential electrical demands, V2H operation would be more stable and reliable with a battery pack in the 35–40 kW h size range.

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