Papers Review

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Journal of Power Sources

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Quantifying electric vehicle battery degradation from driving vs. vehicle-to-grid services

CrossMark

Dai Wang, Jonathan Coignard, Teng Zeng, Cong Zhang, Samveg Saxena*

Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., MS90R1121B, Berkeley, CA 94720, United States

Optimal V2G Scheduling of an EV with Calendar and Cycle Aging of Battery: An MILP Approach

Rahmat Khezri, *Senior Member, IEEE*, David Steen, Evelina Wikner, *Member, IEEE*, and Le Anh Tuan, *Member, IEEE*

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서울과학기술대학교 데이터사이언스학과

전기차 충전 요금 체계

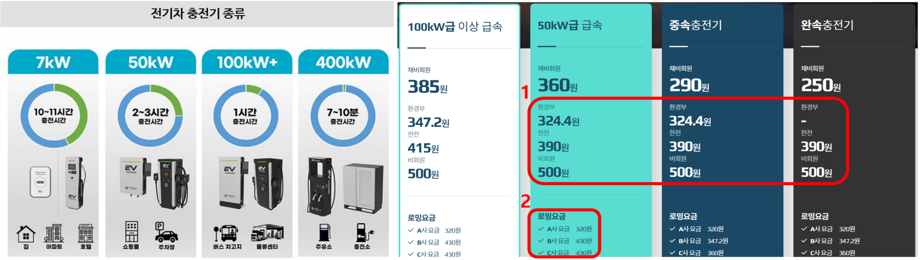
전기차 충전 전력 요금(2023년 5월)			
공용 충전기(원/kWh) – 전년과 동일			
구분	한국전력	환경부	
100kW미만	324.4	324.4	
100kW이상	347.2	347.2	
아파트용 충전기(원/kWh)			
구분	여름	봄/가을	겨울
경부하시간대	289.9	269.7	306.1
중간부하시간대	332.0	280.8	332.0

- 공용 충전기는 충전 속도에 따라 차등 요금 부여
- 아파트용 충전기는 계절과 시간대에 따라 차등 요금 부여

요금 체계 문제점

정책 >

150원에 사온 전기 500원(비회원)에 파는 전기차 충전 플랫폼··· 전문가도 알기 어려운 요금 체계



- 충전요금 체계 개선 필요함
  1. 완속, 중속, 급속의 요금이 모두 같음
  2. 업체별 충전 요금 상이

Abstract_First Paper

Journal of Power Sources 332 (2016) 193–203

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Quantifying electric vehicle battery degradation from driving vs. vehicle-to-grid services

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Dai Wang, Jonathan Coignard, Teng Zeng, Cong Zhang, Samveg Saxena*

Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., MS90R1121B, Berkeley, CA 94720, United States

- EV battery degradation is quantified from driving and vehicle-grid services
- Frequency regulation and peak load shaving do not cause significant degradation
    - There is room for different interpretations of the results

Degradation model

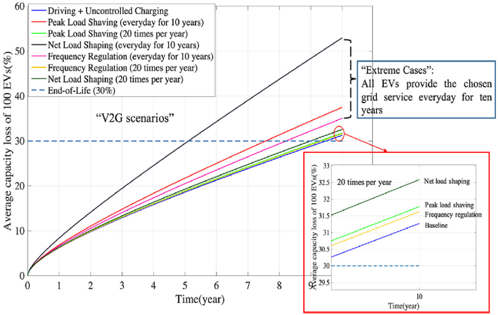
- The **battery degradation model** is divided into **cyclic aging and calendar aging**, designed based on experimental results [Wang (2014), Keil (2016)]
  - **Cyclic aging** is affected by **temperature, C-rate, and energy (Ah) throughput**
  - **Calendar aging** is influenced by **SoC, battery age, and temperature**
- The detailed expressions of the model are reviewed in the second paper

V2G-Sim with NHTS dataset

Start time	End time	Event type	Distance/charger level	Location
0:00	8:45	Plugged in	L1	Home
8:45	9:45	Driving	39.6 mi	N/A
9:45	16:30	Parked	L2	Work
16:30	17:00	Driving	5.0 mi	N/A
17:00	17:30	Parked	N/A	Restaurant
17:30	18:00	Driving	5.0 mi	N/A
18:00	21:00	Parked	L2	Work
21:00	22:00	Driving	39.6 mi	N/A
22:00	0:00	Plugged in	L1	Home

- The study utilizes a previously developed simulation tool named `V2G-Sim`, with travel itinerary input data sourced from the National Household Travel Survey (NHTS)
- Comparing driving, peak shaving, frequency regulation, and net load shaping
    - **net load shaping** focuses on **managing the variability of renewable energy**

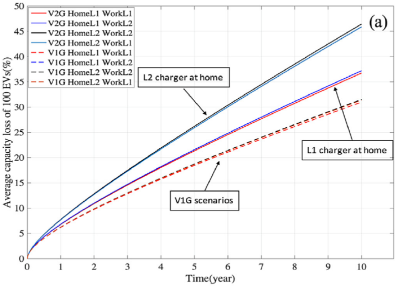
Results



- compares the outcomes of using V2G services at consistent daily times versus using them only 20 days per year
- study asserts that employing **V2G services daily represents an extreme case**, V2G only 20 times per year avoids significant degradation, indicating that **V2G does not inherently degrade performance**

Limitations

1. 연 20일만 V2G를 이용하는 것이 더 극단적인 결과일 수 있음. V2G가 활성화된다면, 비용 절감을 위해 매일 V2G를 이용하는 것이 합리적임
2. 매일 같은 시간에 V2G 를 운용하는 단순한 전략을 취함
3. L1 charger (1.4 kW)와 L2 charger (7.2 kW) 의 충전 속도가 느려 degradation이 현실적이지 않음. L2 charger가 현재 사용되는 아파트용 충전기의 속도와 비슷함



Abstract_Second Paper

Optimal V2G Scheduling of an EV with Calendar and Cycle Aging of Battery: An MILP Approach

Rahmat Khezri, *Senior Member, IEEE*, David Steen, Evelina Wikner, *Member, IEEE*, and Le Anh Tuan, *Member, IEEE*

- presents a Mixed-integer Linear Programming (MILP) to optimize V2G, considering battery degradation
- demonstrates potential cost savings by comparing different scenarios

Motivation

1. The main concern in V2G services is battery degradation, yet it is often overlooked in most existing studies
2. Previous research typically underestimates degradation caused by V2G
3. Most models in previous research employ non-linear approaches, complicating the optimization of V2G scheduling

Objective Function

Operation cost

$$f = \min_{\Xi} \mathrm{Cost}_{\mathrm{EV}}$$

- $\mathrm{Cost}_{\mathrm{EV}}$: Total operation cost

$$\mathrm{Cost}_{\mathrm{EV}} = \mathrm{Cost}_{\mathrm{ch}} - \mathrm{Rev}_{\mathrm{ds}} + \mathrm{Cost}_{\mathrm{deg}}$$

- $\mathrm{Cost}_{\mathrm{ch}}$: charging cost
- $\mathrm{Rev}_{\mathrm{ds}}$: discharging revenue
- $\mathrm{Cost}_{\mathrm{deg}}$: degradation cost

Objective Function

In the equation, **LHS showing home charging costs** and the **RHS workplace charging costs**

Charging cost

$$\mathrm{Cost}_{\mathrm{ch}} = \sum_{h \in H_H} ((\pi_h^{\mathrm{sp}} + \pi^{\mathrm{gu}}) P_h^{\mathrm{ch}} \Delta h) + \sum_{h \in H_W} ((\pi_h^{\mathrm{sp}} + \pi^{\mathrm{gu}} + \pi^{\mathrm{W}}) P_h^{\mathrm{ch}} \Delta h)$$

- P_h^{ch}: charging power at time h
- π_h^{sp}: spot price of electricity
- π^{gu}: grid utilization charge
- π^{W}: additional charging cost at workplace

Objective Function

Discharging revenue

$$\text{Rev}_{\text{ds}} = \sum_{h \in H_H} (\pi_h^{\text{sp}} P_h^{\text{ds}} \Delta h) + \sum_{h \in H_W} ((\pi_h^{\text{sp}} - \pi^{\text{W}}) P_h^{\text{ds}} \Delta h)$$

- P_h^{ds}: discharging power at time h
- π^{W}: additional discharging cost at workplace

Degradation cost

$$\text{Cost}_{\text{deg}} = \sum_{h \in H} \pi_h^{\text{deg}} \Delta h$$

- π_h^{deg}: degradation cost at time h

Battery Degradation Cost

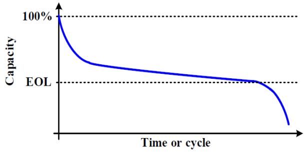


Fig. 1. General trend of degradation for LIBs based on time or cycle.

The degradation cost expressed as:

$$\pi_h^{\text{deg}} = \pi_{\text{bes}} \frac{D_h^{\text{tot}}}{100\% - \mu}$$

- π_{bes}: Present value of the battery
- D_h^{tot}: Total degradation
- μ: capacity at EOL

if D^{tot} = 100% - μ then $\text{Cost}_{\text{deg}} = \pi_{\text{bes}}$, battery should be replaced

present value of the battery

The **present value of the battery** is calculated using **engineering economic principles**:

$$\pi_{\text{bes}} = \pi_{\text{rep}} + \pi_{\text{om}} - \pi_{\text{sv}}$$

- π_{rep}: Present replacement cost
- π_{om}: Present operation and maintenance cost
- π_{sv}: Present salvation value

present value of the battery

$$\pi_{\text{rep}} = \frac{C_{\text{rep}}}{(1+i)^{\phi}}$$

$$\pi_{\text{om}} = C_{\text{om}} \frac{(1+i)^{\phi} - 1}{i(1+i)^{\phi}}$$

$$\pi_{\text{sv}} = \frac{C_{\text{sv}}}{(1+i)^{\phi}}$$

- C_{rep}, C_{om}, C_{sv}: Costs associated with replacement, operation and maintenance, and salvation
- i: Discount rate
- ϕ: Nominal battery life in years.

Degradation model

The total degradation, D_h^{tot}, is defined as the sum of calendar and cycle aging:

$$D_h^{\text{tot}} = D_h^{\text{cal}} + D_h^{\text{cyc}}$$

$$D_h^{\text{cal}} = f(S_h, \theta_h, d)$$
$$D_h^{\text{cyc}} = f(\theta_h, I_h^c, A_h)$$

- This study utilizes an empirical aging model developed by [Wang (2014)] for cycle aging and [Keil (2016)] for calendar aging

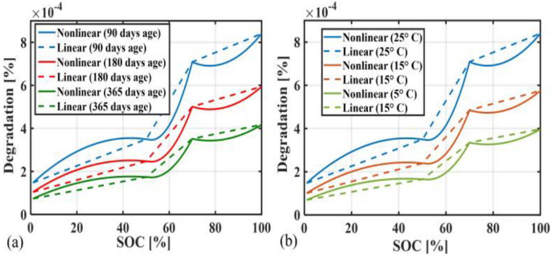
Calendar aging

The calendar aging of the battery, expressed as:

$$D_h^{\text{cal}} = G(S_h) e^{-\frac{E_a}{R\theta_h}} d^{0.5}$$

- $G(S_h)$: function of SOC (S_h)
- θ_h: Temperature (Kelvin)
- d: Time duration

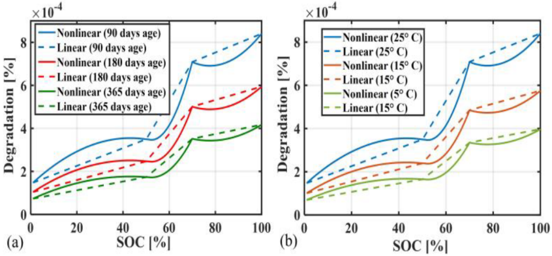
linearize Calendar aging



$G(S_h)$ is a **piecewise quadratic function of SOC (solid line)** :

$$G(S_h) = \begin{cases} a_1 S_h^2 + a_2 S_h + a_3 & \text{if } 0 \leq S_h \leq 50 \\ b_1 S_h^2 + b_2 S_h + b_3 & \text{elif } 50 < S_h \leq 70 \\ c_1 S_h^2 + c_2 S_h + c_3 & \text{elif } 70 < S_h \leq 100 \end{cases}$$

linearize Calendar aging



piecewise linear approximation (dotted line) is used for optimization purposes:

$$G(S_h) = \begin{cases} k_1 S_h + k_2 & \text{if } 0 \leq S_h \leq 50 \\ m_1 S_h + m_2 & \text{if } 50 < S_h \leq 70 \\ n_1 S_h + n_2 & \text{if } 70 < S_h \leq 100 \end{cases}$$

Cyclic aging

The cycle aging model is:

$$D_h^{\text{cyc}} = Z(\theta_h) e^{q_4 I_h^c A_h}$$

- $Z(\theta_h)$: piecewise quadratic function of Temperature
- I_h^c: C-rate
- A_h: Ah-throughput

where temperature function $Z(\theta_h)$ is:

$$Z(\theta_h) = q_1 \theta_h^2 + q_2 \theta_h + q_3$$

By using piecewise linear approximation and binary variables, aging functions are linearized

Case study

Analyze the performance of five distinct models:

- **V2G (Main Model):** minimize operational costs while using V2G

$$f_1 = \min_{\Xi}(\mathrm{Cost}_{\mathrm{ch}} - \mathrm{Rev}_{\mathrm{ds}} + \mathrm{Cost}_{\mathrm{deg}})$$

- **Immediate Charging (Uncontrolled Model):** EV is charged immediately after each journey until the battery is fully charged

$$f_2 = \max_{\Xi}(S_h)$$

- **Smart Charging (Controlled Model):** minimize costs, without V2G

$$f_3 = \min_{\Xi}(\mathrm{Cost}_{\mathrm{ch}} + \mathrm{Cost}_{\mathrm{deg}})$$

Case study

- **V2G without Battery Degradation Cost:** ignores the battery degradation cost, focusing on the economic viability of V2G

$$f_4 = \min_{\Xi}(\mathrm{Cost}_{\mathrm{ch}} - \mathrm{Rev}_{\mathrm{ds}})$$

- **V2G by Battery Degradation Cost as the Objective Function:** minimize the battery degradation cost only

$$f_5 = \min_{\Xi}(\mathrm{Cost}_{\mathrm{deg}})$$

Results_Total cost

Model	Year	Tot. cost [€] in (2)	Charg. cost [€]	Disch. rev. [€]	CYAC [€]	CAAC [€]
V2G (Main Model)	2022	171	1,449	-1,527	47.7	201
	2021	567	662	-263	24.4	143
Uncontrolled Model	2022	1,421	945	0	18.1	458
	2021	1,086	632	0	18.2	436
Smart Charging	2022	647	450	0	18.1	179
	2021	632	473	0	18.3	143
V2G without Deg. Cost	2022	235	1,437	-1,548	48.9	346
	2021	699	643	-286	25.7	317
V2G with Deg. as Obj.	2022	1,078	955	0	17.5	106
	2021	741	622	0	17.9	101

CAAC: Calendar aging cost, CYAC: Cycle aging cost

- The main V2G model significantly reduces costs compared to other models
  - one-fourth of the controlled model
  - only one-eighth compared to the uncontrolled model

Results_Degradation

Model	Year	Cal age. [%]	Cyc. age. [%]	Tot. ch. [kWh]	Tot. dis. [kWh]
V2G (Main Model)	2022	0.99	0.24	10,137	5,508
	2021	0.71	0.12	4,924	980
Uncontrolled Model	2022	2.26	0.09	3,823	0
	2021	2.16	0.09	3,823	0
Smart Charging	2022	0.93	0.04	3,796	0
	2021	0.71	0.05	3,796	0
V2G without Deg. Cost	2022	1.48	0.24	10,359	5,677
	2021	1.56	0.13	5,097	1,125
V2G with Deg. as Obj.	2022	0.52	0.08	3,796	0
	2021	0.50	0.08	3,796	0

- The V2G model exhibits significantly lower performance degradation compared to the uncontrolled model

Disccusions_price volatility and V2G

Model	Year	Tot. cost [€] in (2)	Charg. cost [€]	Disch. rev. [€]	CYAC [€]	CAAC [€]
V2G (Main Model)	2022	171	1,449	-1,527	47.7	201
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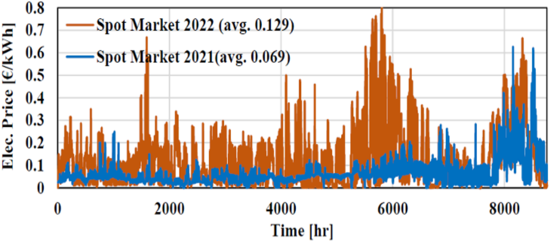
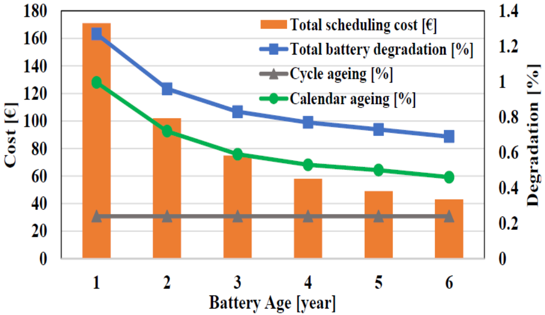
CAAC: Calendar aging cost, CYAC: Cycle aging cost



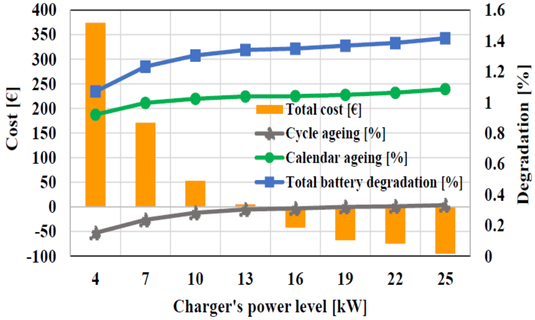
- In 2021, when the average electricity price was lower, models excluding V2G showed lower total costs
- The **V2G model significantly reduces costs in 2022**, a year characterized by **high electricity price volatility**

Disccusions_Calendar aging



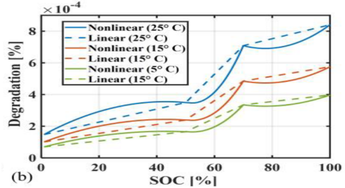
- cycle aging is constant for different battery ages
- **calendar aging is two times higher when the EV is new** compared to when it has been used for three years
  - vigorous chemical reaction

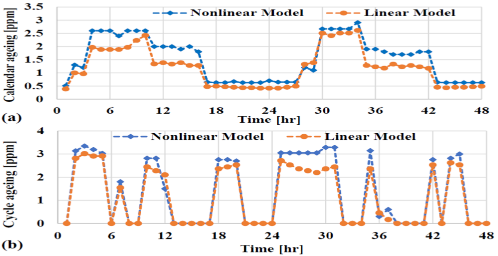
Disccusions_Total cost and Charger power



- **As the charger's power increases, the total scheduling cost decreases**
- higher charger power gives a better opportunity to EV owners to make more profits, however, it increases the battery degradation

Limitation_Linearized Aging function





- 논문의 저자는 linear model과 non-linear model의 average of differences가 calendar and cycle aging 에서 각각 0.3 ppm, 0.2 ppm 으로, 추정 오차가 매우 적다고 주장함
- 그럼에도 선형화 과정에서 각 구간 내 local optima point가 무시되므로, degradation 을 포함한 최적화 결과에 많은 영향을 미칠 수 있음

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"Thank you for listening"
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