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Evaluation of the second-life potential of the first-generation Nissan Leaf battery packs in energy storage systems

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ABSTRACT

Nissan Leaf was the first mass-produced electric vehicles (EV) using lithium-ion batteries (LiB). Most of the first generation (Gen 1) battery packs have been retired after approximately 10 years of operation, and some of them are repurposed to build battery energy storage systems (BESS). However, the health condition of the battery packs at the time of retirement, the battery aging trajectory, and the service life in second-life application are unclear. To answer these questions, this paper conducts a comprehensive study on the retired Nissan Leaf Gen 1 batteries. First, over 100 retired battery packs were investigated to evaluate their state of health (SOH). Secondly, a battery aging test was conducted on two battery cells which completed 7380 aging cycles. Lastly, the battery aging trajectory was analyzed. The result shows that although most retired Nissan Leaf Gen 1 battery packs have only 60 %–67 % remaining capacity, they can operate 12–20 years in second life. Whole-battery-pack utilization is preferable due to good battery consistency. A retired battery pack with a cost of $1000 can generate a $16,200 value in its second life, suggesting a good return on investment (ROI).

1. Introduction

The sales of electric vehicles (EVs) are in exponential growth in recent years. In 2022, 10.5 million new EVs and plug-in hybrid electric vehicles (PHEVs) were sold globally, and the market share of EVs jumped from 9 % to 14 % from 2021 to 2022 [1]. The EV sales in 2030 is expected to exceed 20 million and reach 35 % of the market share. The EV battery packs will be retired after 8–15 years of operation due to faded capacity and power [2,3]. Therefore, in future decades, millions of LiB packs (hundreds of GWh) will be retired from EVs every year. Such a considerable number of retired LiB packs creates a potential business opportunity for second life application of these batteries.

Second life utilization of LiB will not only reduce the cost of battery energy storage systems (BESS) and promote renewable energy penetration, but will also reduce EV ownership costs [4] and mitigate the environment impact in producing new batteries [5]. However, second-life applications of LiBs face many uncertainties and challenges [2,6,7]. The health condition of the batteries at the time of retirement is unknown. How long these second-life batteries can last in BESS is uncertain. The battery aging trajectory and their commercial viability are also unclear. Furthermore, different battery types have different aging performance. Some batteries, like $LiFePO_4$ (LFP), tend to have balance issues [8,9]. Some batteries have aging knee problems [10,11]. Some studies have proposed to use whole battery packs without disassembling them [12–14], while others declared that using battery modules has more advantages than using whole packs [3,8,15,16]. The complicated situation increases the uncertainty of using second-life LiBs. Therefore, a large-scale study on different types of retired EV batteries is necessary, so we can understand their state of health (SOH), second-life potential, aging trajectory, technical challenges, and commercial viability.

There are a few projects using retired EV batteries to build second life battery energy storage systems (SLBESS). Joseph et al. [15,17] developed a 262 kW h BESS using retied Nissan Leaf Gen 1 battery modules for a microgrid at the University of California, Davis in 2019, which successfully reduced the peak-time energy use by 39 %. Energy company B2U Storge Solutions built a 25 MW h BESS at a solar farm in California using retired EV battery packs, including Nissan Leaf, GM Bolt and Tesla Model 3 [12]. This project uses whole battery packs instead of reassembling battery modules, which significantly reduces the repurposing cost. Xu et al. [18] used retired LiBs in a fast-charging station, which can achieve a cost saving of about 50 %. BMW built an SLBESS using eight 2nd life BMW i3 battery packs (90 % SOH) to buffer high power demand for an EV charging station [13,14]. Other automakers, including GM, Audi, Nissan, and Toyota also have similar 2nd life battery projects [4].

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These projects prove the feasibility of building BESS with 2nd life LiBs. However, due to the limited operation time, the battery operation data are rarely reported, so are the degradation process, end of second life, and ROI.

Zhang et al. studied the LFP batteries retired from an EV after 50,000 km driving distance [8]. The remaining capacity of the 12 battery modules ranges from 75 % to 98 %, which shows a significant variance. The capacity of one battery module dropped from 94 % to 64 % after 3200 cycles. The degradation rate is 9.4 % per 1000 cycles. Tong et al. used second-life LFP batteries to build a BESS for an off-grid system [19]. The remaining capacity of the battery modules is between 60 % and 90 %. The battery capacity dropped from 80 % to 65 % after 1400 aging cycles, with a capacity fading rate at 10.7 % per 1000 cycles. Ramirez-Meyers et al. studied the retired A123-26650 LFP hybrid batteries retired from electric buses, which shows that the battery cell capacity is between 25 % and 75 % of new batteries [16]. The research shows that most retired LFP batteries have inhomogeneous or balance issues and need to be regrouped or refurbished for a second life utilization. Uitz et al. studied the aging of Tesla's 18,650 LiNCA batteries [20] which shows that the battery capacity fades 12 % in 500 cycles at 25 °C, namely 24 % per 1000 cycles. If the temperature is raised to 40 °C–60 °C, the battery would enter the aging knee and die quickly after 500 cycles. These studies on LiBs retired from real EVs provide valuable information to assess their second life. However, due to the variety of LiB types, materials, and use conditions, the existing studies are insufficient to depict a whole perspective for LiB second life applications. More study on different types of commercialized LiB is still needed [4].

Nissan Leaf was the first mass-produced EV using LiBs, and the first generation (Gen 1) was introduced to the market in 2010. Many of the 24 kW h Gen 1 battery packs have been retired from vehicles. Therefore, we have a chance to conduct a large-scale study on the retired battery packs to evaluate their second life potential. The innovation of this paper includes the following aspects. First, over 100 mass-produced EV battery packs were investigated, illustrating the SOH of retired EV battery packs. Secondly, this study clarified the feasibility of using whole battery packs for second-life applications. Thirdly, the battery aging trajectory of first life and second life was elaborated, showing a second-life potential of 12–20 years. It also proposed some guidelines on how to prolong the battery life. Fourthly, the ROI is provided. This study shows a positive prospect for the LiB's second life applications, which is valuable for the energy storage industry and government policymakers.

The remainder of this paper is structured as follows: In Section 2, one hundred retired Nissan Leaf Gen 1 battery packs are investigated to evaluate their SOH. Two battery packs are tested in the laboratory for a more detailed study. Then, a battery aging test is conducted on two battery cells. In Section 3, the particle swarm optimization (PSO) based battery parameter identification method is introduced. In Section 4, the SOH of the battery packs at the time of retirement, the batteries' aging trajectory, and the ROI for the 2nd life LiB utilization are analyzed. Conclusions are drawn in Section 5.

2. Experimental setup

2.1. Specification of the Nissan Leaf Gen 1 battery pack

The Nissan Leaf Gen 1 battery pack consists of 48 battery modules, and each battery module is composed of two parallel, two series (2P–2S) connected battery cells. The whole battery pack is of 2P–96S configuration. The cathode material is $LiMn_2O_4$ with $LiNiO_2$ and the anode is graphite. The specification of the battery cell is listed in Table 1 [21]. The nominal capacity of the battery pack is 66.2 A h/24 kW h at 0.3C rate. However, the capacity of the pack is set to 65.6 A h in the battery management system (BMS) due to higher current rate in the vehicle. The peak output power of the battery pack is 90 kW (3.75C), and the quick charging power is 50 kW (2C) between 16 % and 80 % SOC. In the rest of this paper, the two parallel connected battery cells are regarded as one battery cell for ease of discussion.

Table 1
Specification of the Nissan Leaf Gen 1 battery.

Capacity (Two Parallel)	66.2 A h (0.3C)
Internal Resistance (Two Parallel)	1 mΩ
Voltage Range	2.8V–4.2 V (3.8 V mean)
Weight of Module (2P–2S)	3.8 kg
Module Energy Density	213 W h/L
Module Specific Energy	132 W h/kg

2.2. Obtain the SOH of 100 Nissan Leaf battery packs

Nissan provides an 8 year/100,000 miles warranty for the Leaf Gen 1 battery packs. If the SOH indicator on the dashboard drops from 12 bars (100 % SOH) to 8 bars (66.25 % remaining capacity), Nissan will replace the battery pack for free [22]. Many battery packs were retired around 2020 due to warranty issues. Fig. 1(a) shows the retired battery packs that belonged to BigBattery, a battery pack manufacturer in Los Angeles, CA that supplies small battery packs for golf carts. These retired battery packs were planned to be disassembled into battery modules and repurposed to build golf cart battery packs. The price of each retired battery pack was about $1000.

Nissan provides a cellphone App named "Leaf Spy", through which the battery information can be read. We used a small 12 V lead-acid battery, a Bluetooth OBD-II adapter, and a cellphone with "Leaf Spy" to read information from the retired battery packs, as shown in Fig. 1(b). The 12 V battery provides power to the Leaf BMS through the signal connector. The OBD-II adapter communicates with the Leaf BMS through CAN network and sends data to the cellphone through Bluetooth. In this way, the information of each battery pack can be obtained, as shown in Fig. 1(c). The data includes "AHr"- the remaining capacity of the battery pack in ampere-hour (Ah); SOH = AHr/Pack Capacity (65.6 A h) = 66.36 %; maximum cell voltage difference dV = 35 mV, which indicates the balance state of the battery pack; Serial Number (SN) 230JT111A3000113; Hx = 44.24 % indicating the battery conductivity; battery pack voltage and current; four temperature readings, and a bar chart showing the 96 battery cell voltages. The red bars indicate the battery cells undergoing balancing (discharged).

Fig. 2 shows the SOH of the 100 battery packs. Only one battery pack has an SOH above 70 %, while most battery packs' SOH is between 60 % and 67 %, which is very close or below the 66.25 % warranty line. Fig. 2 also shows the dV of the battery packs whose mean cell voltage is above 3.7 V (>30 % SOC). Here, dV < 50 mV indicates a good balance state, and dV > 100 mV indicates severe balance issues or battery failure. Fig. 2 shows that only three battery packs have a dV above 100 mV, and all others are below 50 mV, which means most battery packs are in good balance states.

2.3. Testing of two Nissan Leaf battery packs

The data read from the Leaf BMS only provides some basic information, which is insufficient to draw a whole picture of the battery packs' health condition. The battery pack capacity loss could be caused by battery cell capacity degradation, balance issues, and high impedance. To further evaluate the health condition of the battery packs, two battery packs were tested in the laboratory to obtain the charge/discharge characteristics, capacity, and impedance. The test system is shown in Fig. 3.

Chroma 62100H-600 DC Power Supply is used to charge the battery pack. The maximum charging current is 17A. Chroma 63,210 Electronic Load is used to discharge the battery pack. The maximum power is 14.5 kW (Maximum 600 V, 150A). The current of the DC Power and Load can be controlled in real-time through RS232. The dSPACE Autobox is used

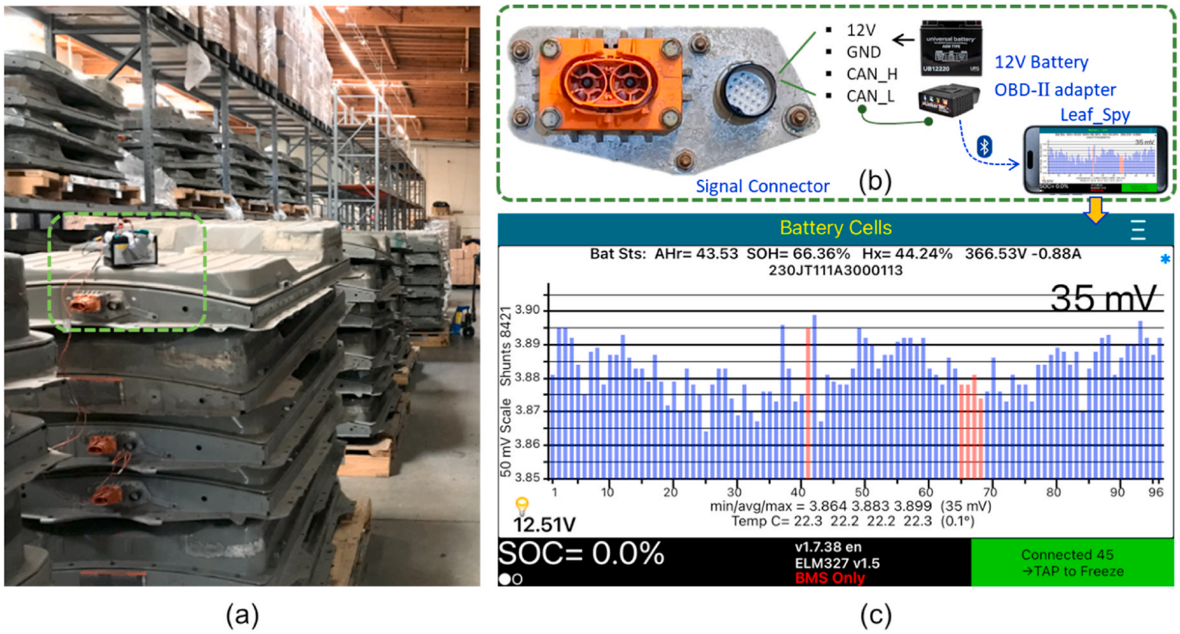

Fig. 1. Evaluation of 100 Nissan Leaf Gen 1 battery packs. (a) The retired battery packs; (b) The setup to read the battery SOH information; (c) Leaf Spy data of the battery packs.

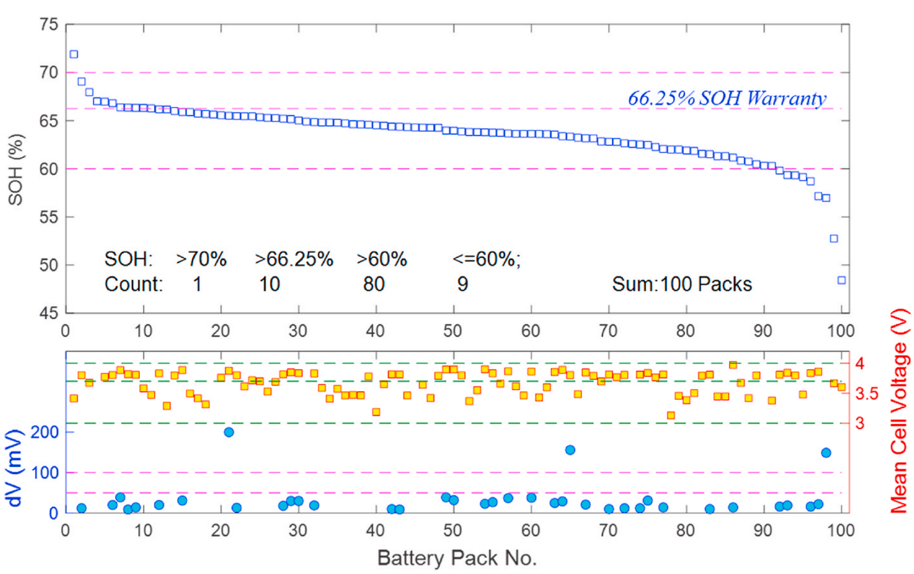

Fig. 2. Statistics of the SOH of 100 retired Nissan Leaf battery packs.

as the test controller. The test process is designed in Matlab/Simulink and runs in the Autobox. It collects data from the BMS-Gateway, the DC Power, and DC Load, then sends commands to the DC Power and DC Load to control the test process. The BMS-Gateway is designed to communicate with the Leaf BMS through CAN network to obtain battery data, including 96 battery cell voltages and four temperatures. The communication protocol is the same as Leaf-Spy, and the data is updated every 0.5 S. The BMS-Gateway also measures the pack DC voltage and current in a 0.1 S time step, controls the DC contactors and conducts system protection to prevent over-charge, over-discharge, communication lost, etc. All the data are sent to dSPACE Autobox through another CAN channel. The RS232-CAN converter is designed to translate the commands and data between the CAN communication of Autobox and the RS232 protocol of Chroma equipment. The dSpace ControlDesk is used for the user interface. It also records the test data with a 0.1 S timestep.

The test data of Pack 01 is shown in Fig. 4. It consists of two charge and discharge cycles and one discharge cycle with current pulses at different SOC. The current pulses are used to calculate the impedance of the battery cells. The charging current is 17A (0.38C) and the discharge current is 35A (0.78C), which is limited by the test equipment. The cycling voltage range is 2.8 V–4.2 V, which is 100 % depth of discharge (DoD). The charge and discharge Ah and energy (kWh) of each cycle is labeled in Fig. 4. The tested battery pack capacity is 44.71 A h, and the SOH is 44.71 A h/65.6 A h = 68.16 %, which is 1.8 % higher than the Leaf BMS reading of 66.36 %. The coulombic efficiency is close to 100 %, and the energy efficiency is approximately 96.4 %. Compared to the 98 % energy efficiency of new batteries, the efficiency is good enough for BESS applications. The laboratory temperature is about 22 °C and the battery temperatures are around 27 °C–40 °C, indicating a battery

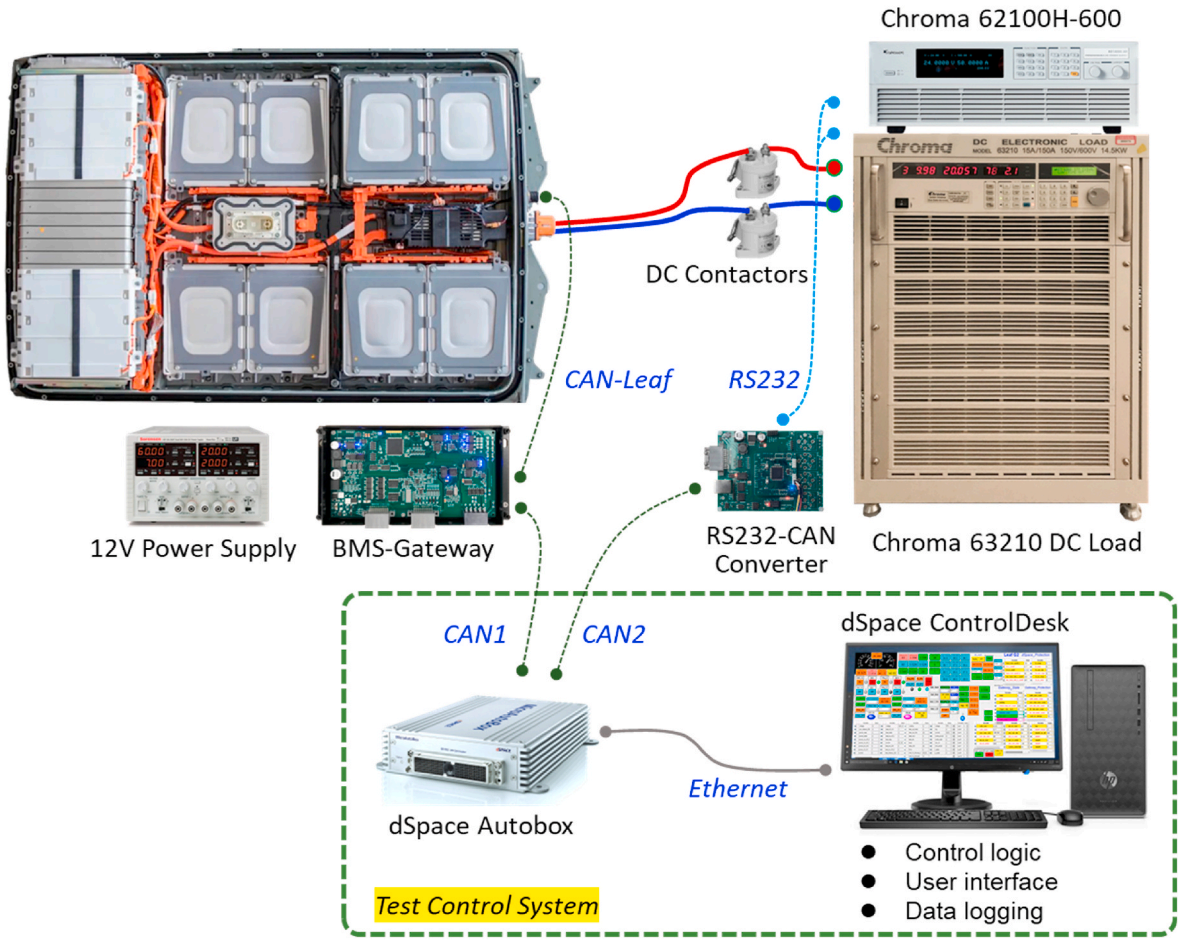

Fig. 3. The Nissan Leaf Gen 1 battery pack testing system.

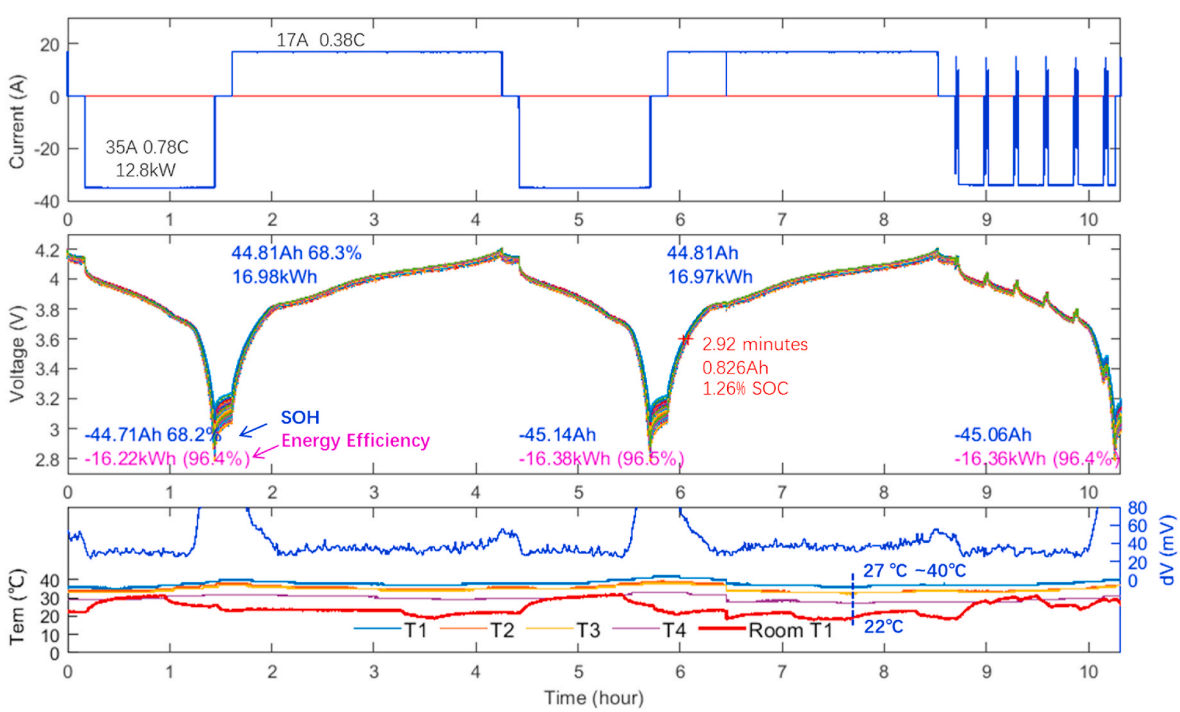

Fig. 4. Nissan Leaf Gen 1 Pack 01 test data.

temperature rise of about 18 °C in the cycling process, which is normal for a battery pack without a cooling system.

Fig. 4 shows that the voltage curves of the 96 cells are almost overlapped, suggesting a good battery consistency and balance state. Compared to an ideal balance state, the pack capacity can only be recovered by 0.826 A h (1.26 % SOH), which is negligible. The dV of the battery pack is 30–40 mV. Considering the good balance state, a battery pack with dV below 50 mV can be regarded as in a good balance state. Therefore, most battery packs in Fig. 2 are in good balance states.

Pack 02 has a consistent test result as Pack 01. Therefore, it is not duplicated here. The tested capacity of pack 02 is 42.31 A h and 64.50 % SOH, which is only 0.38 % higher than the Leaf BMS data 64.12 %. This proves that the capacity and SOH estimation from the Leaf BMS are trustworthy. The dV is 39 mV, which also shows a good balance state.

The impedance of the 96 battery cells in each battery pack is calculated according to the current pulses and voltage response shown in Fig. 4. The 1-RC equivalent circuit model is used to simulate the battery dynamics [23]. Therefore, the ohmic resistance R_0 and diffusion resistance R_1 are used to depict the battery impedance. The particle swarm optimization (PSO) algorithm is used to calculate R_0 and R_1 based on the test data [23,24]. The calculation will be introduced in Section 3. Fig. 5 shows the value of R_0 and R_1 at 70 % SOC of all battery cells in Pack 01 and 02. The R_0 value is between 1.7 mΩ and 2.06 mΩ, with a difference of 0.36 mΩ (21.2 %). The value of R_1 is between 1.32 mΩ and 1.37 mΩ, with a 3.8 % difference. Both R_0 and R_1 show good consistency in the two battery packs. Usually, an impedance variance higher than 50 % is considered as poor consistency.

The battery specification from Nissan in Table 1 shows that the internal resistance of a new battery (two parallel) is 1 mΩ. However, it is not clear whether it is DC ($R_0 + R_1$) or AC (R_0) resistance. Referring to the Nissan Leaf Gen 3 battery cells we tested, the value of R_0 and R_1 of a new 56.3 A h cell are both 1 mΩ. Considering that the impedance of Gen 1 battery cell should not be lower than that of Gen 3 battery cell, a reasonable assumption is that the 1 mΩ is AC resistance, and the value of R_0 and R_1 are both 1 mΩ for a new 65.6 A h Gen 1 battery cell. Therefore, R_0 of the retired Nissan Leaf Gen 1 battery cells increased by about 100 %, while R_1 increased by about 35 % compared to those of new battery cells. This data matches the battery conductivity Hx = 44.24 % read from the Leaf BMS.

2.4. Battery cell aging test

To understand the second life potential and aging trajectory of these retired EV batteries, Pack 02 was disassembled into battery modules, two of which were used for the aging test. One battery cell (two in parallel) from each module was tested using a laboratory setup shown in Fig. 6. An Arbin BT2000 battery tester with eight channels was used for the battery aging test. The test voltage of each channel of BT2000 is 0 V–5 V, and the maximum current is 100A. The batteries are tested at room temperature, which is well controlled between 22 °C and 25 °C.

Each aging test procedure consists of 56 aging cycles followed by four characteristic test cycles, as shown in Fig. 7, lasting about 10 days. The 56 aging cycles are used to simulate the battery daily operation. The cycling conditions, including voltage range and current, are changed from time to time accordingly to mimic different real-world scenarios in BESS. For example, the cycling current is reduced after the batteries are severely aged. The current, voltage, and temperatures are recorded at a 5 S time step, and two of the 56 aging cycles are plotted in Fig. 7.

The four characteristics test cycles are used to evaluate the battery capacity and impedance after every 56 aging cycles, which include a 0.2C capacity test, two 0.5C capacity tests, and a Hybrid Pulse Power Characterization (HPPC) cycle to calculate the battery impedance. The voltage range is 2.8 V–4.2 V. The test conditions are rarely changed for consistent battery parameter evaluation. The HPPC test data is recorded at a 1 S time step for battery parameter calculation.

The battery aging test lasted 2.5 years, and Cell 01 and 02 finished 7380 and 6480 aging cycles, respectively. The battery aging trajectories are illustrated in Fig. 9. The aging test consists of three stages, as described below.

2.4.1. Stage 1: normal test conditions: 70%–80 % DoD and 1C

Considering the capacity of Cell 01 and 02 had already degraded to 64 % before the aging testing, a conservative cycling condition was deployed at the beginning of the aging test. The batteries were charged to 4.15 V (92 % SOC) with a constant current-constant voltage (CCCV) process at 40A (1C) charging current and 20A (0.5C) cutoff current. The cells were then discharged to 3.6 V (20 % SOC) with a 40A (1C) current. Fig. 7 (a) shows that the cyclable capacity is 29.90 A h, which is 71.45 % of the battery capacity. Here, the percentage of cyclable capacity is regarded as depth of discharge (DoD). After 660 aging cycles, the discharge cutoff voltage was extended to 3.3 V (10 % SOC), and the cyclable capacity increased to about 80 % of the present battery capacity.

2.4.2. Stage 2: abuse test conditions: 100 % DoD and 1C

After 3000 aging cycles, it was found that the two batteries degrade very slowly and linearly. To accelerate the battery aging, the cycling voltage range of cell 01 was increased to 2.8V–4.2 V as shown in Fig. 7 (b). The CCCV charging process was changed to a two-step const current (CC) charging mode. The charging current was still 40A (1C), and it would be reduced to 20A once the cell voltage reaches 4.15 V. With the increasing of battery impedance, although Cell 01 was cycled at the full voltage range, the cyclable capacity is only 87.26 % of the battery capacity tested at 0.2C. For comparison, the test condition of Cell 02 remained the same as Stage 1 (3.3V–4.15 V).

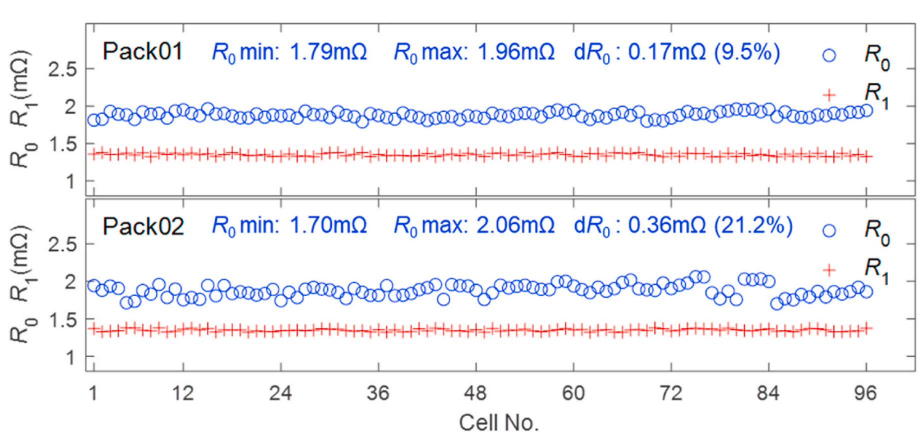

Fig. 5. The ohmic resistance R_0 and diffusion resistance R_1 of all battery cells of Pack 01 and 02.

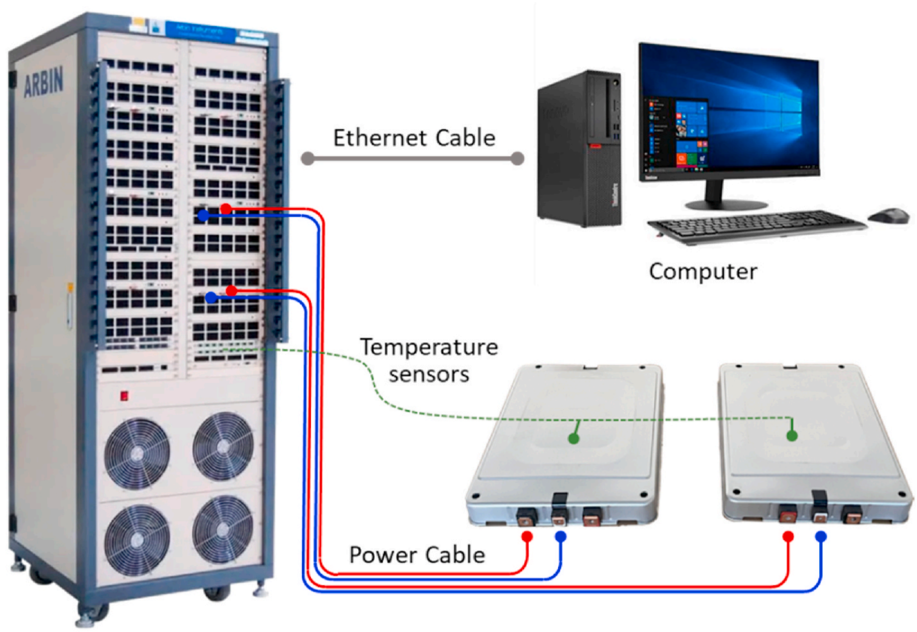

Fig. 6. Nissan Leaf Gen 1 battery cell aging test.

2.4.3. Stage 3: after severely aged: 100 % DoD and 0.5C

After 4200 aging cycles, the capacity of the two battery cells degraded to 31.8 A h (48 % SOH) and 29.9 A h (46 % SOH), respectively. R_0 increased to 3.26 mΩ and 4.26 mΩ, which increased by 63 % and 113 % compared to the initial value of 2 mΩ, as shown in Fig. 9. The cyclable capacity decreased fast due to the increased impedance. To maintain a reasonable cycling capacity, the cycling current of both batteries was reduced from 40A (1.3C) to 20A (0.7C) after 4200 cycles, and then further reduced to 11.2A (0.5C) after 6300 cycles for Cell 01 and 5600 cycles for Cell 02 to accommodate the further increased battery impedance.

For consistent battery capacity tracking, the 0.2C capacity test current was set to 8A (40 A h × 0.2C) in the first 4200 aging cycles. However, the battery capacity degraded to about 30 A h after 4200 cycles, and 8A is 0.25C now. Considering the increased impedance would further reduce the tested capacity at higher current, it is necessary to reduce the 8A test current to achieve a more accurate 0.2C battery capacity. Therefore, the test current was reduced from 8A to 5.6A after 4200 cycles. This is why the battery capacity increased slightly at 4200 cycles in Fig. 9. The current of the HPPC test was also reduced to adapt to the increased battery impedance, as shown in Fig. 7(c).

3. Battery parameter identification

The battery capacity and impedance were tracked during the aging process. The discharging capacity at 0.2C is regarded as the battery capacity, and the HPPC dynamic cycle is used to calculate the battery impedance. The 1-RC equivalent circuit model is used to simulate the battery dynamics [23,25]. The model consists of a voltage source, which is depicted by an open circuit voltage (OCV)-Ah curve, an ohmic resistance R_0, and a RC (diffusion resistance R_1 and capacitor C_1) network. Therefore, the battery impedance can be described with R_0 and R_1. The 1-RC model equation is:

$$\begin{cases} \dot{U}_1 = -\frac{1}{R_1 C_1} U_1 + \frac{1}{C_1} I_L \\ U_t = U_{OC} - U_1 - I_L R_0 \end{cases} \tag{1}$$

where U_1 is the voltage across the RC network, I_L is the current of the battery, U_{OC} is the OCV, and U_t is the terminal voltage. Its discrete-time format can be written as:

$$\begin{cases} U_{1,k+1} = \exp(-\Delta t / R_1 C_1) \times U_{1,k} + [1 - \exp(-\Delta t / R_1 C_1)] \times I_{L,k} R_1 \\ U_t = U_{OC} - U_1 - I_L R_0 \\ D_1 = \exp(-\Delta t / R_1 C_1) \end{cases} \tag{2}$$

where k is the step, Δt is the time interval, which is fixed at 1 S in this study, $U_{1,k+1}$ is the value of U_1 at time step k+1, $I_{L,k}$ is the value of I_L at time step k, and D_1 is the time constant.

In this model, I is the input and U_t is the output. Both the voltage and current can be measured in the physical system. U_{OC}, R_0, R_1, and D_1 are the unknown model parameters. The calculation process uses the recorded battery current and voltage data to find the optimal battery parameters so that the simulated battery voltage curve is as close as possible to the measured voltage curve under the same current load.

The particle swarm optimization (PSO) algorithm is used to search the optimal parameters [23,24]. Due to the nonlinear nature of the battery parameter curves in the whole SOC range, the recorded HPPC test cycle is cut into 15 small pieces, as shown in Fig. 7 (a), with each data piece lasting about 10–15 min. The 15 data pieces consist of two layers: pieces 1–8 cover the whole HPPC test cycle, while pieces 9–15 have a position bias to pieces 1–8 for calculation redundancy. The parameter calculation is conducted on each data piece. Fig. 8 (a) and (b) show section 04 and 14 of the 15 data pieces. The parameter vector under estimation for each data piece is:

$$X = [U_{OC1}, U_{OC2}, R_0, R_1, D_1, U_{1,init}] \tag{3}$$

where U_{OC1} and U_{OC2} are the OCV on the two side of each data piece, $U_{1,init}$ is the initial voltage of the RC network. The optimization target is to minimize the root mean square error (RMSE) between the measured and simulated voltage curves. The PSO algorithm searches for the optimal parameters using 64 particles randomly chosen in the search space. After hundreds or thousands of iterations, all the particles converge to the optimal position. The details of the algorithm are elaborated in Refs. [23,24].

Fig. 8 (a) and (b) compare the measured and simulated battery voltage curves of section 04 and 14. The RMSE of the two sections is only 1.49 mV and 5.73 mV, respectively. It proves that the 1-RC model can accurately simulate the battery dynamics.

After the calculation of all 15 data pieces, the battery parameters of

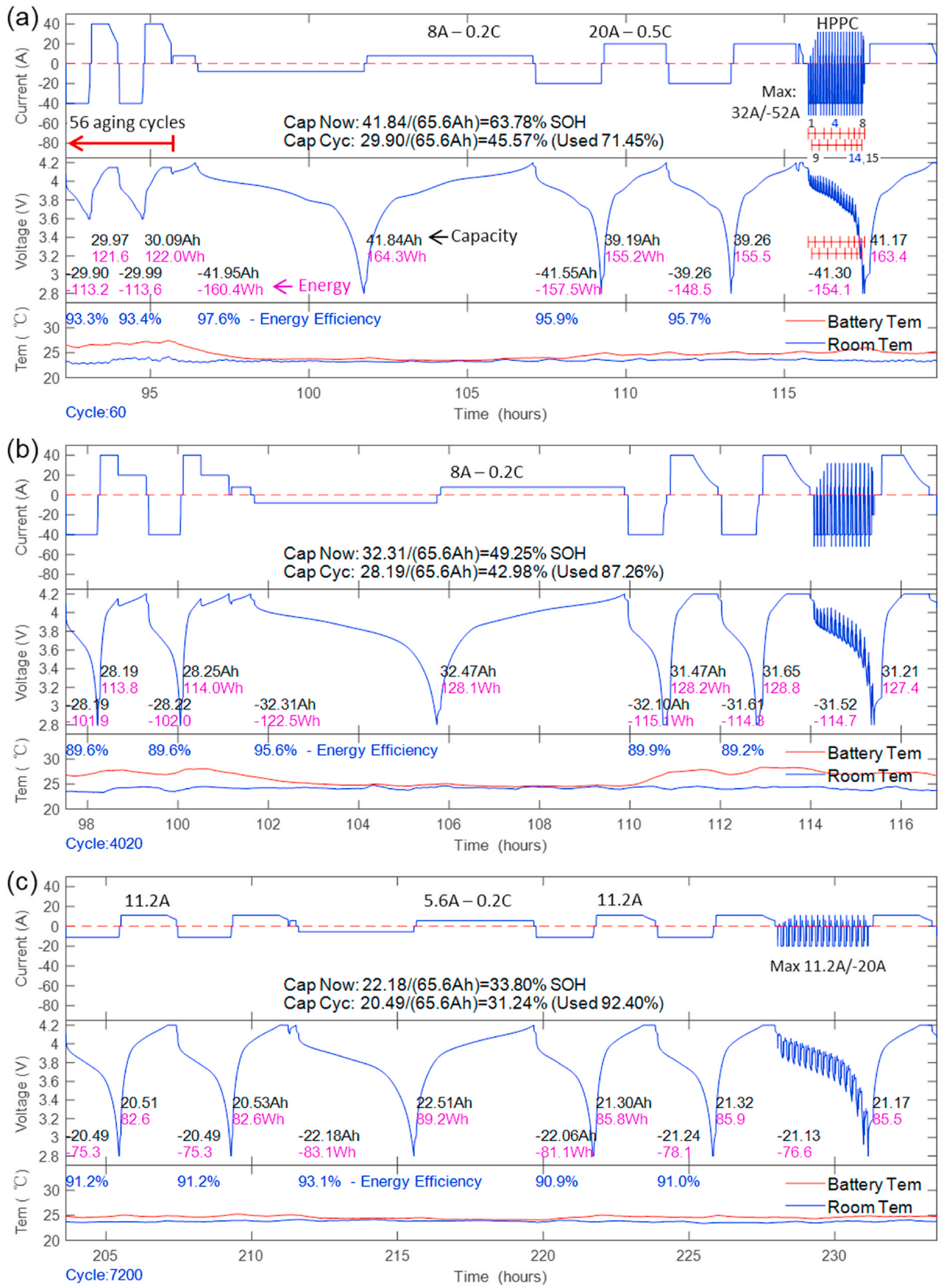

Fig. 7. Nissan Leaf Gen 1 battery Cell 01 aging test. (a) After 60 cycles; (b) After 4020 cycles; (c) After 7200 cycles.

the 15 data pieces are connected into parameter-Ah curves. Fig. 8 (c) shows the connected OCV-Ah curves and Fig. 8 (d) shows the R_0-Ah, R_1-Ah, and D_1-Ah curves. The blue lines are the parameters of data pieces 1–8 of the first layer, the green lines are the parameters of data pieces 9–15 of the second layer, and the red curves are the connected parameter-Ah curves. The values of R_0 and R_1 at 70 % SOC are used for the battery aging analysis in Fig. 9.

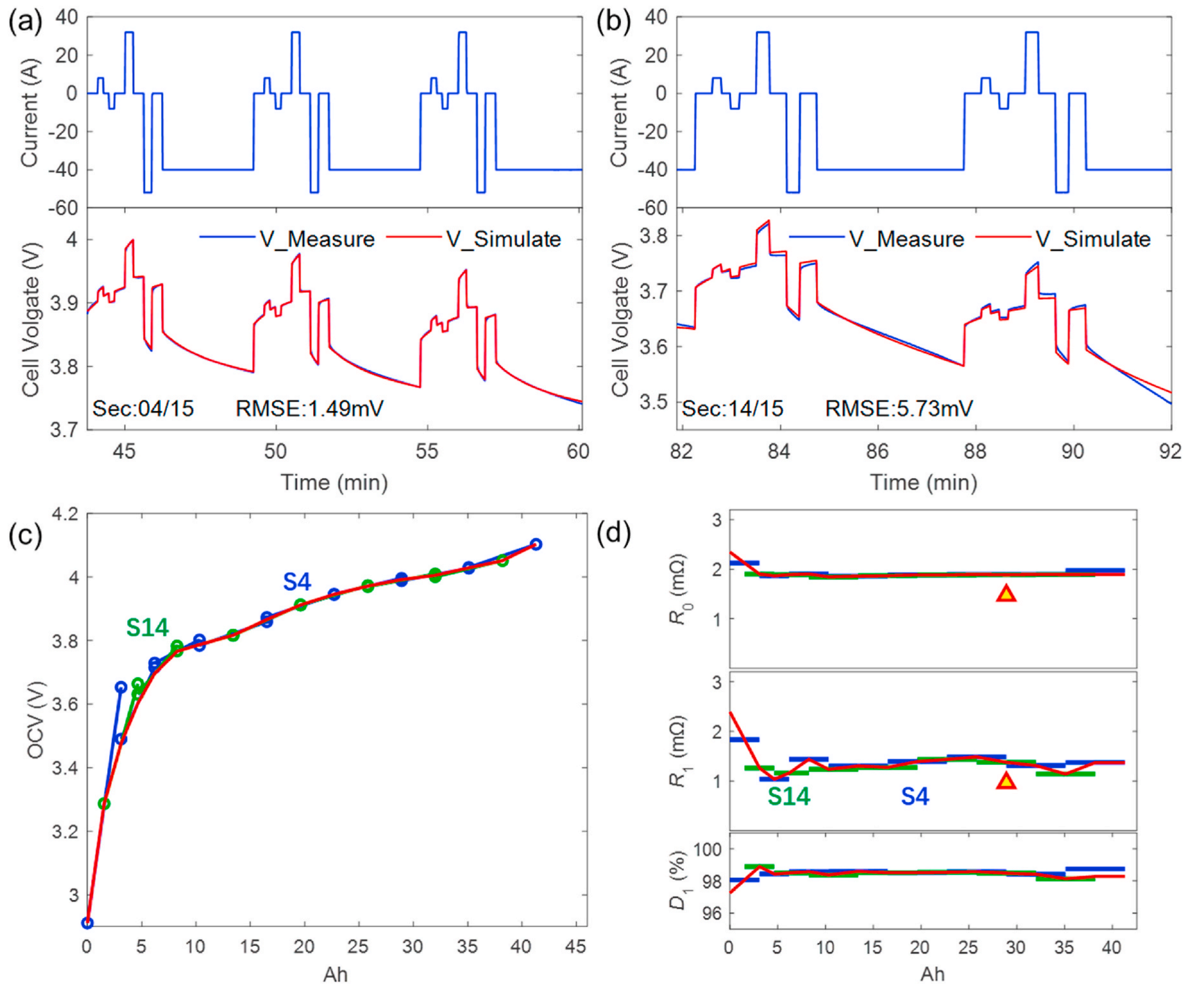

Fig. 8. The battery parameter calculation using PSO. (a) Validation of section 4; (b) Validation of section 14; (c) The OCV-Ah curve; (d) The battery impedance-Ah curves.

4. Results and discussion

4.1. The battery packs' health condition at the time of retirement

The battery capacity, impedance, balance state, battery consistency, power performance, and energy efficiency are the key metrics to evaluate a battery pack's health condition.

4.1.1. Capacity

Fig. 2 shows that the remaining capacity of most of the 100 battery packs is between 60 % and 67 % of nominal capacity, which is close to or below the 66.25 % warranty line. The battery pack capacity loss is mainly caused by battery cell capacity degradation. There are generally no balance issues.

4.1.2. Impedance

The battery impedance nearly doubled compared to new batteries. Fig. 5 shows that the ohmic resistance R_0 increased from 1 mΩ to about 2 mΩ, which increased by 100 %. While the diffusion resistance R_1 increased from 1 mΩ to about 1.35 mΩ, or 35 %. The tested battery impedance matches the battery conductivity data Hx = 44.24 % read from the Leaf BMS.

4.1.3. Balance state and battery consistency

The pack test data in Fig. 4 shows that all the 96 battery voltage curves are almost overlapped, proving the good balance state and cell capacity consistency. Fig. 5 shows good battery impedance consistency. The difference of R_0 is 21.2 % and that of R_1 is only 3.8 %. Considering that most of the 100 battery packs in Fig. 2 have similar capacity as the two tested packs, and most of their dV is below 50 mV, we can draw a conclusion that most retired Nissan Leaf Gen1 battery packs have good balance state and cell consistency, which makes them ideal for second life applications.

4.1.4. Power performance, coulombic efficiency, and energy efficiency

The peak discharge power of the new battery packs is 90 kW (3.75C), and the quick charging power is 50 kW (2C). The internal resistance of the batteries nearly doubled at the time of retirement, which significantly reduces the power performance. Fig. 7(a) shows that the battery can be charged and discharged at 40A (1C), which is much lower than those of the new battery, but sufficient for the BESS applications.

Fig. 7(a) shows that the energy efficiency at 1C, 0.5C, and 0.2C current is 93.3 %, 95.7 %, and 97.6 %, respectively. Therefore, the recommended second-life working current is 0.2C to maintain a high energy efficiency and long battery life. The maximum current should not exceed 0.5C,

The battery coulombic efficiency during the whole aging test is always close to 100 %. Fig. 7(c) shows that the coulombic efficiency of the 11.2A (0.5C) cycling process after 7200 aging cycles is 20.49 A h/20.51 A h = 99.90 %, which is still at a nearly perfect level, proving the usability of the severely aged batteries.

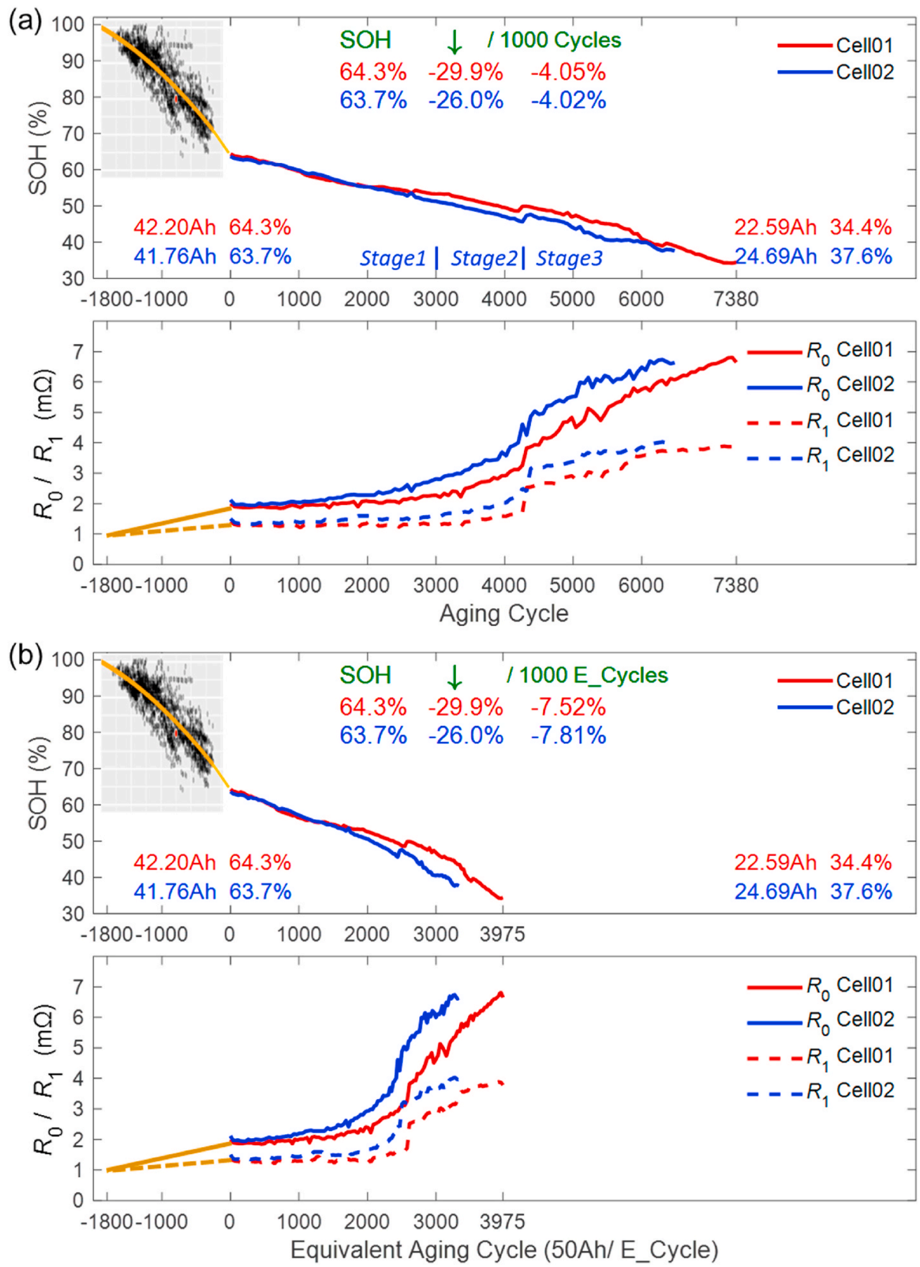

Fig. 9. Nissan Leaf Gen 1 battery aging process of first life and second life.

4.2. Whole-pack utilization of second-life battery packs

Whole-pack utilization can minimize the labor, cost, and time of EV battery pack repurposing, making it commercially viable. The deployment at the pack level consists of only three steps: First, ship the battery pack to the test center; Second, connect the power cable and signal cable and test the battery pack to achieve the capacity, impedance, and balance state, which only cost 2–4 h. Third, lay the battery pack in the BESS with a BMS-Gateway for battery system energy management.

The cost of the retired Nissan Leaf Gen1 battery pack is $1000/(24 kW h × 66 % SOH) = $63.1/kWh. If the battery packs need to be disassembled, tested, and reassembled, the processing cost could be $40/kWh [26], with a total cost of $103.1/kWh. Whole-pack utilization can reduce the processing cost to $10/kWh. Therefore, the total cost can be reduced to $73.1/kWh, saving 30 %.

4.2.1. The battery packs suitable for whole-pack utilization

However, some battery packs are suitable for whole-pack utilization, while others have to be disassembled and reassembled. Battery packs with good battery consistency and balance state are ideal for whole-pack utilization. This study shows that most retired Nissan Leaf Gen 1 battery packs meet this requirement. It proves that the high-efficiency, less laborious, large-scale whole-pack utilization of second-life EV battery packs is possible and economically feasible.

For battery packs with good battery consistency but poor balance state, a balance process has to be conducted before they can be used for whole-pack utilization.

4.2.2. The battery packs that have to be disassembled and reassembled

If some battery cells in a battery pack are already dead or swelled, or if a battery pack shows significant cell capacity or impedance variance, e.g., the LFP battery packs in Refs. [8,16,19], the battery pack has to be disassembled and then regrouped according to the capacity and impedance.

4.3. Battery aging speed analysis of first and second life

4.3.1. First life aging speed

Myall et al. recorded the battery SOH change of 283 Nissan Leaf during the first eight years of operation [27,28], as plotted in Figs. 9 (−1800 to 0 cycles are the 1800 first life aging cycles). The general trend is that the SOH will drop to about 66 % after eight years, which matches our study. The mileage was about 144,000 km (90,000 miles) by that time. The EPA mile range of a new car is 117 km (73 miles). Considering the battery degradation, the mean mile range per charge is assumed to be 80 km. Then, the battery experienced about 1800 charging cycles in eight years. The capacity degradation of the batteries in their first life is 34 % total, or 4.25 % yearly, and 18.9 % per 1000 cycles. Ref [27] also mentioned that the Leaf Gen 1 battery degrades slower in the United Kingdom than in Japan due to lower temperatures. The ohmic resistance R_0 increased from 1 mΩ to 2 mΩ, doubled in its first life, and R_1 increased from 1 mΩ to about 1.35 mΩ.

4.3.2. Second life aging speed

Fig. 9 (a) also shows the second life aging trajectory of the batteries (0–7380 aging cycle). The capacity of Cell 01 degraded from 42.2 A h (64.3 % SOH) to 22.59 A h (34.4 %) in 7380 cycles and the capacity of Cell 02 degraded from 41.76 A h (63.7 %) to 24.69 A h (37.6 %) in 6480 cycles. The capacity degradation rate is 4.05 % and 4.02 % per 1000 cycles, respectively, which is much lower than the aging speed in their first life. Despite the change of test conditions during the aging process, the battery capacity fading speed is stable, and the aging knee did not occur.

In Stage 2, the cycling voltage of Cell 01 was increased to 2.8V–4.2 V. However, the degradation speed of battery capacity and impedance were the same as Cell 02, which was cycled between 3.3 V and 4.15 V. This proves that high DoD, even 100 % DoD, does not cause fast capacity degradation, swelling, or aging knee for the Nissan Leaf Gen 1 batteries. It is noteworthy that for batteries with aging knee issues, e.g., the 62 kW h Nissan Leaf Gen 3 batteries, fully charging to 4.2 V and over 1C charging rate would induce fast degradation, swelling, and aging knee. This is why Tesla suggests their drivers to charge to 80 % or 90 % instead of 100 % to prolong the battery life [29]. Due to the Nissan Leaf Gen 1 battery is not sensitive to fully charging, Nissan does not give the driver the option to set the charging cutoff SOC [30].

4.3.3. Second life aging speed with equivalent aging cycles

To evaluate the battery aging speed with throughput ampere hour (Ah), Fig. 9 (b) plots the battery aging trajectory with Equivalent Aging Cycles (E_Cycle), where 50 A h throughput Ah is considered as one E_Cycle. For example, Fig. 7 (c) shows the cycling capacity of cell 01 was 20.49 A h. Therefore, 2.44 real aging cycles equals one E_Cycle. Each E_Cycle creates the same value due to the same throughput Ah or kWh. Fig. 9 (b) shows that the batteries can achieve 3300 to 4000 E_Cycles in their second life, which is about twice of their first life 1800 aging cycles. The aging speed is 7.52 % and 7.81 % per 1000 E_Cycles, respectively, which is also much lower than the aging speed in their first life.

4.3.4. Discussion of slower aging speed in the laboratory testing

First, the temperature condition in the EV is harsh. If the environment temperature is 35 °C in the summer, the battery temperature can reach 60 °C, especially because the Nissan Leaf battery packs do not have an air or liquid cooling system. The optimum temperature for LiBs is 15 °C–25 °C [14]. The elevated temperature will accelerate the battery aging in their first life. The battery aging test in the laboratory was conducted between 22 °C and 25 °C room temperature, which is ideal for battery life.

Secondly, the battery pack has to deliver 90 kW (3.75C) peak power in the EV operation. However, the C-rate in the laboratory aging test was less than 1C. Considering that the C-rate in the BESS operation is usually 0.2C–0.3C, it will reduce heat generation and further slowdown the battery degradation.

Thirdly, there is potential calendar aging in their eight years of first life operation. While the laboratory aging test is continuous, and there is only 10 min resting between each cycle. Therefore, the calendar aging is minimal. The vibration of the EV is another potential reason to accelerate battery aging. However, there is rarely any study on this topic to date.

The first life and second life working conditions and aging speed of Leaf Gen 1 battery packs are compared in Table 2.

4.4. Battery aging mechanism analysis

The battery aging mechanism can be summarized as: loss of lithium-ion inventory (LLI), loss of anode/cathode active materials (LAM), internal resistance increase, and electrolyte decomposition [2]. Usually, multiple aging mechanisms would happen simultaneously and affect each other. We believe the capacity degradation of the Nissan Leaf Gen1 batteries is caused by a combination of LLI and LAM, and the battery impedance increase is caused by solid electrolyte interface (SEI) film growth and electrolyte decomposition.

4.5. Second life evaluation

Considering the low SOH of the retired Nissan Leaf Gen 1 battery packs, they are only suited for low power-demanding BESS, such as peak shifting. For example, the BESS is charged between midnight and 5 a.m. during the super off-peak hours, and then discharged between 4 p.m. and 9 p.m. during the peak hours. In this way, the current rate is as low as 0.2C. It not only maintains high energy efficiency but also reduces temperature-rise and prolongs battery life.

4.5.1. The performance degradation during second life

The performance metrics of a BESS include energy capacity, energy density, power performance (C-rate), energy efficiency, and cycle life. The performance changes of Nissan Leaf Gen 1 battery pack at different aging states are compared in Table 3.

The remaining capacity of the battery packs was about 66 % when it was retired from EVs. The weight of the battery pack is 300 kg. Therefore, the specific energy at the pack level is 53.3 W h/kg, which is the same as lead-acid batteries. However, the cycle life of lead-acid battery is only about 500–800 cycles. The retired Leaf Gen 1 batteries can last 4000 cycles before their performance deteriorates. Therefore, the retired Leaf Gen 1 batteries are a good substitute for lead-acid batteries. Fig. 7 (a) shows that the round-trip energy efficiency is 97.6 % and 95.7 % at 8A (0.2C) and 20A (0.5C), respectively, which is an acceptable performance.

The capacity retention degrades to 50 % after 4200 aging cycles; R_0

Table 2
The 1st and 2nd life working condition comparison of Nissan Leaf Gen 1 battery.

	First Life - EV	Second Life - BESS
Aging Cycle	1800	7380
E_Cycle (50 A h/Cycle)	1800	3975
Service Time (Year)	8~10	12~20
Days/Charge	1.62	1
SOH	100 %–64.3 %	64.3 %–34.4 %
Aging Speed (%/1000 Cycles)	18.9 %	4.05 %
Aging Speed (%/1000 E_Cycles)	18.9 %	7.81 %
Aging Speed (%/year)	4.25 %	1.50 %
Temperature Range	−20 °C–50 °C	15 °C–25 °C
Current (A)	246A (3.75C)	20A–5.6A (0.25C)
Power (kW)	Up to 90 kW	8 kW–2 kW
Energy (kWh)	24 to 16 kW h	16 to 8 kW h
Energy Efficiency at 0.2C	98 %	97.6 %–93.1 %
R_0 (mΩ)	1 mΩ–2 mΩ	2 mΩ–3 mΩ - 6.8 mΩ

Table 3
Nissan Leaf Gen 1 battery pack performance at different aging states.

	New	Retired	4200 cycles	7380 cycles
Energy Capacity (kWh)/ SOH (%)	24/100 %	16/66 %	12/50 %	8/33 %
Energy Density (Wh/kg)	80.0	53.3	40.0	26.7
Power (kW)/C-rate	90kW/ 3.75C	8kW/ 0.5C	3kW/ 0.25C	2kW/ 0.25C
Energy Efficiency at 0.2C (%)	>98 %	97.60 %	95.60 %	93.10 %

increased from 2 mΩ to 4 mΩ; R_1 increased from 1.4 mΩ to about 2 mΩ; and the round-trip energy efficiency is 95.6 % at 8A (0.25C). Therefore, the current should be no more than 0.25C (8A, 3 kW) to maintain energy efficiency above 95 %.

The capacity degrades to 33 % after 7380 aging cycles; R_0 increased to 6.7 mΩ, and R_1 increased to 4 mΩ; which is significantly higher than a new battery. Fig. 7 (c) shows that the energy efficiency is only 93.1 % at 0.25C (5.6A). Theoretically, the battery can still be cycled at an extremely low power despite the low capacity and high impedance. However, the battery pack can only provide 6~8 kW h per cycle. Therefore, it is reasonable to suggest that this is the right time for the batteries to be finally recycled for raw materials.

4.5.2. The energy efficiency of second-life BESS

If the BESS is connected to the power grid through an AC/DC inverter, the system round-trip efficiency is:

$$\eta_{BESS} = \eta_{Inv} * \eta_{Batt} * \eta_{Inv} \tag{4}$$

where η_{Inv} is the inverter efficiency, which is usually 98 %, and η_{Batt} is the battery round-trip efficiency. For new batteries, $\eta_{Bess} = 98\,\% \times 98\,\% \times 98\,\% = 94.1\,\%$. When η_{Batt} drops to 95.6 % at 4200 aging cycles, $\eta_{Bess} = 91.8\,\%$. When η_{Batt} drops to 93.1 % at 7380 aging cycles, $\eta_{Bess} = 89.4\,\%$, which is still acceptable.

4.5.3. The second life at different working conditions

The battery aging speed changes with working conditions. If the BESS working conditions are better than the aging test, e.g., lower C-rate (0.2C), lower SOC range (10 %–90 %), and well-controlled temperatures, the batteries could last longer than 7380 aging cycles in their second life applications.

However, if the working conditions of the BESS are not well controlled, e.g., the batteries are exposed to elevated temperatures (>40 °C), or high current (>2C), the batteries could degrade faster. For example, if we extend the first life aging curve (the yellow line) in Fig. 9, the projected second life is only 1000 cycles.

4.5.4. Safety evaluation of the second-life batteries

Nissan Leaf has a good battery safety record. There is seldom a report about battery thermal runaway or fire accidents. The battery aging test also shows no safety concerns during the second life operation. Even though Cell 01 was abused during Stage 2, i.e., 2.8 V–4.2 V full voltage range and 1C current, the battery did not swell or encounter aging knee. The safety risk did not increase with battery aging.

In summary, the retired Nissan Leaf Gen 1 battery packs perform well in the first 4200 aging cycles, and then its power and efficiency gradually deteriorate. The second life of the battery packs can be stopped at 4200 cycles when the capacity degrades to 50 %, which is about 12 years in their second life if it is charged once a day. It is also reasonable to assume that the battery packs could work until 7380 aging cycles (20 years) until the capacity drops to 34 % in certain applications.

4.6. The proposed guidelines for the second-life applications of retired EV batteries

Retired EV batteries are like retired humans. The working load has to be reduced, and the working conditions have to be well controlled to extend their second life. Regular health condition checks, optimal working conditions, and proper maintenance are necessary to ensure the batteries' reliable operation.

4.6.1. Regular health condition checks

The health conditions of the batteries need to be updated every two years or 500 aging cycles, including capacity, impedance, balance state, battery consistency, etc. The working current should be adjusted according to the capacity and impedance degradation. The maintenance is also based on battery health analysis. There are technologies to analyze battery health conditions based on their operation data, without the need for special tests [24].

4.6.2. Temperature

The optimal temperature range for LiBs operation is 15 °C–25 °C [2,14]. The well-controlled temperature plays an important role in the slow degradation of the Nissan Leaf Gen1 batteries in this study. Elevated temperatures (>40 °C) not only accelerate battery aging during battery operation, but also accelerate battery calendar aging when the batteries are resting. Therefore, even if the batteries are not in operation, it is still preferable to keep the temperature below 25 °C to reduce calendar aging [20,31]. Liquid cooling and air conditioning are effective ways to control battery temperature.

4.6.3. Current

Due to the increased battery impedance, the suggested battery operation current is below 0.2C. Thus, the current load could be significantly reduced, the heat generation and temperature-rise could be suppressed, and the round-trip energy efficiency and useable capacity would increase. The maximum power of the Nissan Leaf Gen1 battery pack would be reduced from 90 kW to 3.2 kW (24 kW h × 66%SOH × 0.2C).

4.6.4. SOC range

The suggested SOC range is 10 %–90 %, and the corresponding voltage is 3.2 V–4.1 V. Although this study shows that full voltage range did not induce faster degradation or aging knee, the highest 10 % SOC should be reserved for safety concerns [32,33]. Theoretically, using 0 %–10 % SOC range is safe and would not accelerate battery aging. However, the battery resistance is higher in the low SOC range, as shown in Fig. 8(d), which reduces the energy efficiency. Fully discharge may cause anode copper current collector corrosion [2]. The low battery pack voltage could also induce the power converter system (PCS) to work in a low-efficiency range. Therefore, it is suggested not to use the 0 %~10 % SOC range.

Ref [15] used 20 %–80 % SOC range in their Leaf Gen1 SLBESS. According to our study, the SOC range can be extended to 10 %–90 % to create more value without reducing battery life.

4.6.5. Maintenance

Maintenance includes battery balancing and replacement of dead battery cells or modules. The Nissan Leaf Gen1 battery packs have good battery consistency and balance state. Therefore, maintenance is usually not needed in their second life.

4.7. Return on investment (ROI)

Table 4 shows the electricity bill of a home in San Diego, California, USA, for June 2023. The electricity cost consists of Electricity Delivery, a fixed rate at $0.25682/kWh, and Electricity Generation, which varies with time. The bill shows that the electricity price during peak hours is

Table 4
The electric bill of a home in San Diego.

		On-Peak	Off-Peak	Super Off-Peak	Total Amount ($)
	Time	4pm–9pm	6am-4pm; 9pm-Midnight	Midnight - 6am	
	kWh used	60	70	39	
Electricity Delivery	Rate/kWh	$0.25,682	$0.25,682	$0.25,682	
	Cost	$15.41	$17.98	$10.02	$43.40
Electricity Generation	Rate/kWh	$0.57,043	$0.25,697	$0.09233	
	Cost	$34.23	$17.99	$3.60	$55.81
Total cost					$99.22

much more expensive than that during the super off-peak hours. If a BESS is deployed, the 130 kW h on-peak and off-peak energy consumption can be shifted to the super off-peak hours. Assume the BESS efficiency is 90 %, then 130 kW h/0.9 = 144.4 kW h will be charged to the batteries after midnight. The electricity bill can be reduced to:

$(144.4 + 39)$ kWh * $(0.25682 + 0.09233)$ \$/kWh = \$64.03 (5).

The home can save $35.18 b y peak shifting of 130 kW h electricity. The BESS creates a $0.27 value for every 1 kW h shifted. On the other hand, photovoltaic power generation companies sell electricity at $0.25697/kWh from 6am to 4pm. With the help of a BESS, the price can be increased to $0.57043/kWh by shifting the electricity sales to the peak hours. The BESS also creates approximately $0.27 value for every 1 kW h shifted.

The retired Nissan Leaf Gen 1 battery packs have approximately 16 kW h energy capacity remaining at the time of retirement. Assume 80 % DoD is used, then one battery pack can shift 12.8 kW h electricity per day. With an average electricity shifting value of $0.27/kWh, this translates to $103.70 value per month (12.8 kW h × 30 days * $0.27 = $103.70) or $1244 a year. After 7380 aging cycles, the battery pack has 8 kW h energy capacity. It generates 8 kW h × 80%DoD* 30 days *$0.27 = $51.8 per month, or $622 every year

The initial investment for the BESS is approximately $2000 per pack, including $1000 for the battery pack and $1000 for the power converter and auxiliary systems. The investment can be paid back in two years. The return on investment (ROI) is 50 % per year. If the second life is 4200 cycles or 12 years, the total payback is about $12,000. If the second life is 7380 cycles or 20 years, the total payback is approximately $16,200.

The peak/valley electricity price difference is lower in other countries or states than in California. For example, in China, the BESS can only create about US$0.1 per kWh. One battery pack can generate $460 value per year. The $2000 investment can be paid back in 4.4 years, with a yearly ROI of 23 %, which is still profitable.

5. Conclusions

This paper presented a comprehensive study of the retired Nissan Leaf Gen 1 batteries to evaluate their SOH at the time of retirement and second life potential. The key findings include.

1. Most retired Nissan Leaf Gen 1 EV battery packs have an SOH of 60 %–67 %, which challenges the conventional wisdom that EV batteries will be retired at 80 % SOH. The battery pack capacity loss is mainly caused by battery cell capacity degradation but not balance issues.
2. The battery pack test shows good battery consistency on both capacity and impedance. Most battery packs' dV is below 50 mV, suggesting good balance states. Therefore, whole-pack utilization is the best choice for retired Nissan Leaf Gen1 battery packs, which minimizes the labor, cost, and time of repurposing. The battery system cost can be reduced from $103.1/kWh to $73.1/kWh.
3. The aging test shows a second life potential of 7380 aging cycles. The batteries have a superior performance in the first 4200 s-life cycles before the SOH drops to 50 %, which is equivalent to 12 years if the battery pack is charged once a day. Afterward, the battery impedance increases fast, and the energy efficiency reduces. Nevertheless, the battery is still useable with limited current until 7380 aging cycles (20 years) and 34 % SOH.
4. The optimal working conditions for the second-life batteries are: 15 °C–25 °C temperature, 10 %–90 % SOC range, and 0.2C current load. With well-controlled working conditions, the aging speed of the second life batteries is only 4.05 % per 1000 cycles, which is much lower than the 18.9 % per 1000 cycles in their first life.
5. The ROI analysis shows that the BESS can create approximately $0.27 value in California, USA per kWh charged and discharged. The $1000 ($62.5/kWh) retired Nissan Leaf Gen 1 battery pack can create a $1244 value in the first year and a $16,200 value in its whole second life. Even if the value per kWh is $0.10, the yearly ROI is 23 %, which is still profitable.

In summary, this study shows a positive prospect for the second life application of retired EV batteries. The high-efficiency, large-scale whole-pack utilization of retired EV battery packs is possible. Although the initial SOH is only 60 %–67 %, the expected second life is 12–20 years, which shows good commercial feasibility.

It should be noted that the health condition of the retired battery packs, the aging trajectory, second-life evaluation, and the optimal working conditions only apply to the Nissan Leaf Gen1 battery packs. The conclusions for other battery types may vary. More studies on different types of retired LiBs are necessary to draw a whole picture of the prospect of second-life LiBs.

CRediT authorship contribution statement

Wei Gao: Writing – original draft, Validation, Software, Methodology, Investigation, Data curation. **Zhi Cao:** Writing – review & editing, Software, Investigation. **Naser Vosoughi Kurdkandi:** Writing – review & editing, Validation, Data curation. **Yuhong Fu:** Software, Investigation, Data curation. **Chirs Mi:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Chris Mi reports financial support was provided by California Energy Commission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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