

STATE-OF-HEALTH ESTIMATION OF LITHIUM-ION BATTERY THROUGH
AI-DRIVEN ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY MODELING

Chatcharan Yomjinda

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By	Chatcharan Yomjinda
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Thesis Advisor	Dr. Mahunnop Fakkao

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..... Vice President for Academic Affairs
(Assoc. Prof. Dr. Warakorn Srichavengsup)

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This thesis develops a hybrid State of Health (SOH) estimation framework for lithium-ion batteries by integrating Electrochemical Impedance Spectroscopy (EIS), Equivalent Circuit Models (ECM), and Long Short-Term Memory (LSTM) networks. To test the diagnostic reliability of AI models under interrupted real-world conditions, NMC pouch cells were cycled for 200 cycles, deliberately separated into Phase 1 (cycles 1-100) and Phase 2 (cycles 101-200) by a 40-day rest period. Four ECM-extracted resistance parameters were fed into the LSTM, and its internal feature-weighting logic was cross-checked against a Pearson correlation benchmark.

During continuous operation (Phase 1), the LSTM achieved high predictive accuracy (RMSE 0.99%) and correctly matched the physical benchmarks, identifying Warburg diffusion (R_w) as the primary degradation driver. However, following the 40-day rest (Phase 2), the battery's physical degradation regime fundamentally shifted. While the LSTM maintained high prediction accuracy (RMSE 0.75%), it entirely lost its diagnostic fidelity. Instead of adapting to the new physical hierarchy of resistance parameters, the model relied heavily on historical capacity trends to sustain its accuracy.

These results demonstrate that while EIS-trained LSTMs offer both high accuracy and physical interpretability under continuous cycling, these two virtues decouple when operational continuity is broken. Predictive accuracy survives the discontinuity, but mechanistic interpretability does not. This finding establishes a critical boundary for when data-driven SOH estimators can be trusted as diagnostic tools in Battery Management Systems.

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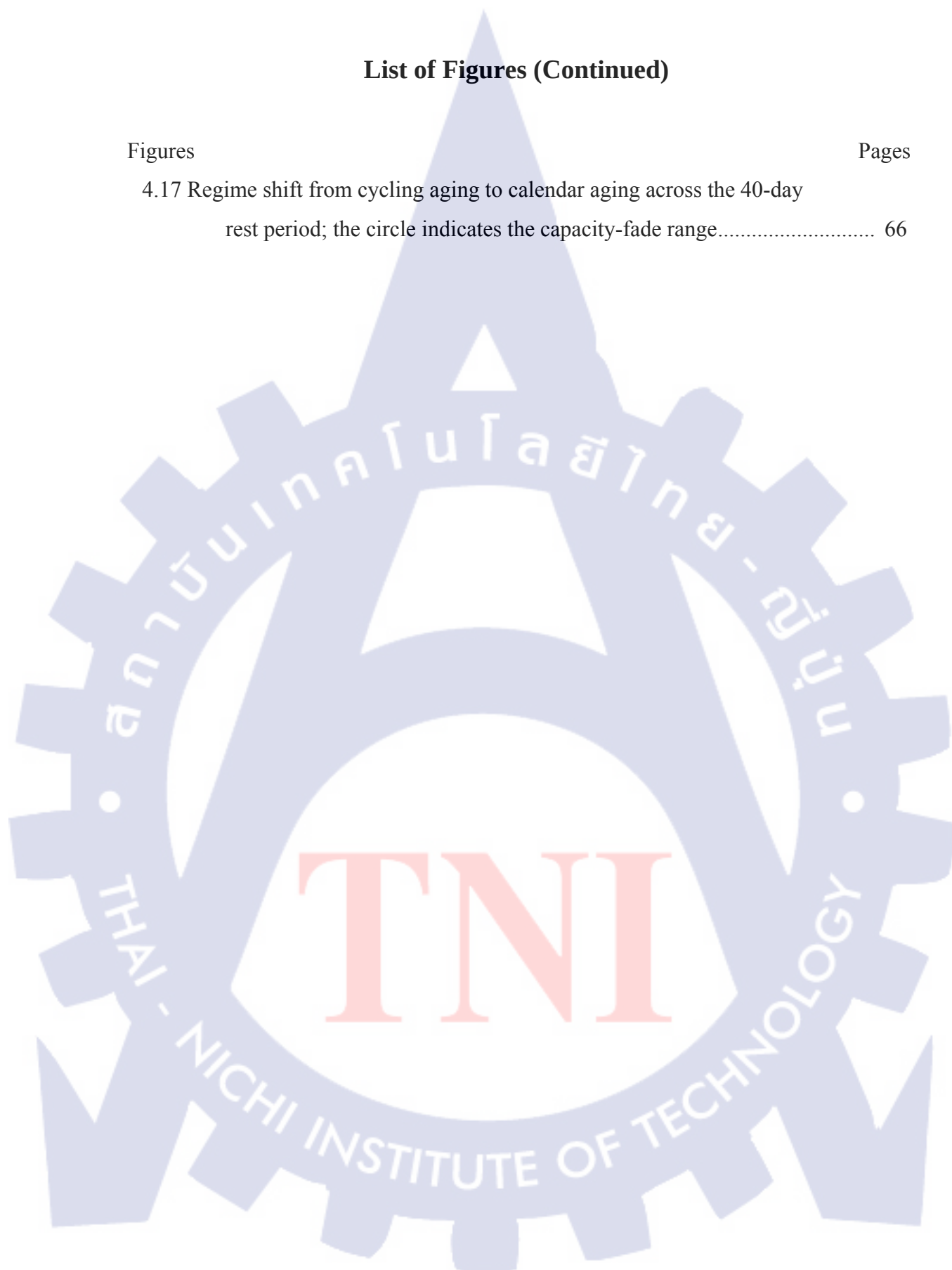
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Chapter 1

Introduction

1.1 Background and Motivation

Energy is a fundamental driver of human activity, supporting both daily life and the broader trajectory of technological and economic development. Most of this energy is still derived from finite fossil resources - oil, coal, and natural gas - and rising demand from economic growth places increasing pressure on supply. At the same time, fossil-fuel combustion is the leading source of greenhouse gases such as carbon dioxide and methane, which drive global warming and the broader climate crisis. Figure 1.1 illustrates the rising trend of annual mean maximum temperatures recorded in Thailand, reflecting the local manifestation of this global problem.

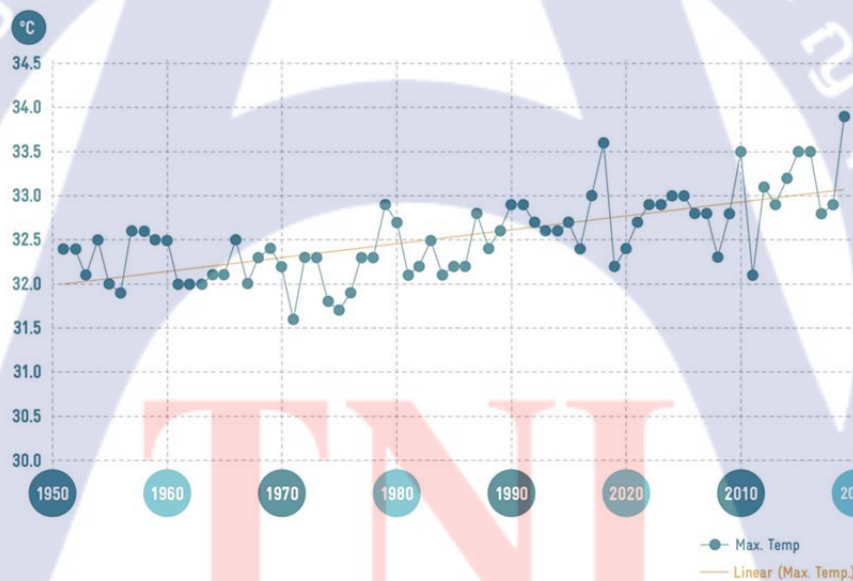


Figure 1.1 The annual mean of maximum temperatures in Thailand [1]

These pressures have prompted coordinated international action, most notably through the Conference of the Parties (COP). COP29, held in Baku, Azerbaijan, from 11-24 November 2024, focused on climate finance and secured an agreement to raise funding for developing countries from the previous target of US\$ 100 billion per

year to US\$ 300 billion per year by 2035 [2]. In line with this global agenda, Thailand has set three concrete national targets: (i) a Nationally Determined Contribution (NDC) goal of reducing greenhouse gas emissions by 43% by 2030, (ii) the enactment of Climate Change Legislation as a key tool for achieving net-zero emissions by 2065, and (iii) the submission of its first Biennial Transparency Report by December 2024 [3].

Within Thailand's emission profile, the transportation sector accounts for approximately 29.16% of total greenhouse gas emissions, primarily because the national vehicle fleet is still dominated by internal combustion engines [4]. Electric vehicles (EVs) are therefore a central decarbonisation strategy: they shift fuel demand from oil to electricity, eliminate tailpipe CO₂ emissions, and operate at higher overall energy efficiency than internal-combustion vehicles, as H. Dong et al. [5] have demonstrated quantitatively. Accordingly, promoting widespread EV adoption is central to reducing transport-sector emissions in Thailand and elsewhere.

An EV is built around several coupled subsystems: an electric motor that converts electrical energy into mechanical motion, a vehicle control unit that governs energy flow between the battery and the motor, an on-board charger, and - at the heart of the system - the traction battery. The battery determines the vehicle's range, performance, and lifetime, and advances in battery technology continue to be the main lever for EV improvement. Among the available chemistries, lithium-ion batteries currently represent the state of the art for EVs because of their combined energy and power density, as illustrated in the Ragone plot of Figure 1.2 [6]. Even so, lithium-ion cells in real applications consistently fall short of their theoretical performance limits [7], so understanding their internal behavior is essential for optimizing charge/ discharge protocols and extending service life.

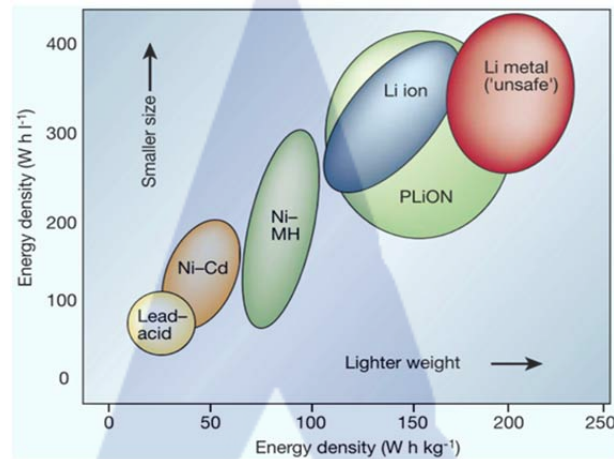


Figure 1.2 Ragone plot of different types of batteries [6].

The gap between theoretical and practical performance arises because, in real cells, sluggish reaction kinetics and mass-transport limitations lead to a nonuniform distribution of reactions across the porous electrode structure. Lithium ions cannot fully access the active material deep inside the electrodes, so the readily accessible surface regions are repeatedly overworked while inner regions are underutilized. Over many charge-discharge cycles, this asymmetry intensifies: surface regions degrade faster than normal, and the underutilized regions can lose their lithium-ion pathways entirely, becoming “dead zones” that no longer store energy. The result is a steady decline in the cell's usable capacity and a corresponding fall in its State of Health (SOH).

SOH is the central diagnostic parameter that a Battery Management System (BMS) uses to track aging, schedule maintenance, and ensure safe operation. In EVs, lithium-ion cells are typically retired from primary use once SOH falls below 80% and are then redirected to second-life applications such as stationary backup power [8]. The challenge is that the underlying degradation is driven by a coupled set of electrochemical mechanisms - SEI growth, lithium plating, active-material fracture, and others - that collectively raise internal resistance and reduce capacity [9, 10]. Diagnosing this degradation accurately and in real time is therefore critical, but no current method achieves all three of the necessary properties: accuracy, practicality, and physical interpretability.

Existing diagnostic methods fall into three broad categories, each with a characteristic limitation. Spectroscopic and imaging techniques resolve internal physical changes in detail but require specialized laboratory equipment and are impractical for in-vehicle real-time use [11, 12]. Model-based methods built on Equivalent Circuit Models (ECMs) preserve physical meaning [13, 14] but struggle to capture non-linear behavior without either high computational cost [15-17] or a sacrifice in accuracy [18]. Data-driven deep learning models - LSTMs in particular - excel at learning complex non-linear patterns but suffer from the well-known black “box” problem: they cannot explain the physical causes of their predictions, which limits their use in safety-critical applications [19-21].

To resolve the conflict between physical interpretability and prediction accuracy, this thesis proposes a hybrid ECM-integrated LSTM framework. The approach uses EIS-derived ECM parameters and changes in internal-resistance components as physically meaningful inputs to an LSTM that tracks long-term trends over time [22-24]. Earlier hybrid studies have largely focused on improving computational efficiency [25-27]. The present study extends this line of work in a different direction: it deliberately tests the LSTM's robustness when the temporal continuity of the operating history is disrupted. The experiment is therefore split into two phases separated by a 40-day rest period, and the model's prediction accuracy and diagnostic logic are evaluated separately for each phase. The central question is whether an accurate LSTM forecaster also remains a reliable diagnostic tool when the underlying degradation mechanism shifts.

1.2 Research Objectives

1.2.1 To develop a State-of-Health (SOH) prediction model for NMC lithium-ion pouch cells based on a Long Short-Term Memory (LSTM) network, using EIS-derived internal-resistance parameters extracted via an Equivalent Circuit Model.

1.2.2 To evaluate whether the LSTM's diagnostic logic remains physically consistent by comparing with the statistical analysis

1.3 Scope of Research

1.3.1 Cell type and quantity: five commercial lithium nickel manganese cobalt oxide (NMC) pouch cells from an e-commerce platform, each with a nominal capacity of 2000 mAh.

1.3.2 Cycling protocol: constant-current/constant-voltage (CC-CV) charge–discharge at 5 A (2.5 C rate), with cut-off voltages between 3.0– 4.2 V

1.3.3 Two-phase test design: Phase 1 covers cycles 1–100 of continuous cycling; Phase 2 covers cycles 101–200; the two phases are separated by a single 40-day open-circuit rest period that constitutes the controlled discontinuity studied in this thesis.

1.3.4 Impedance measurement: galvanostatic EIS performed at every cycle over the frequency range 10 kHz to 10 mHz, with five points per decade and a 50 mA AC perturbation.

1.3.5 ECM choice: a Randles-type ECM with one ohmic resistance (R_0), two RC branches representing surface-film (R_s/CPE_s) and charge-transfer (R_{ct}/CPE_{dl}) processes, and a Warburg element (R_w) for diffusion. Fitted parameters are validated by linear Kramers–Kronig testing.

1.3.6 LSTM architecture: a many-to-one network with a 30-cycle look-back window, taking the four ECM resistances and the historical capacity as inputs and predicting SOH as a continuous output.

1.3.7 Diagnostic benchmark: Pearson correlation coefficients computed phase by phase between each resistance parameter and the measured SOH, used as the independent physical reference against which the LSTM's Feature Importance ranking is compared.

1.3.8 Operating temperature: ambient 25°C, controlled throughout cycling and EIS measurement.

1.3.9 Out of scope: cell-level post-mortem analysis, temperature sweeps, calendar aging beyond the single 40-day rest, and testing into deep degradation (SOH < 80%). These define the boundaries within which the conclusions of this thesis hold.

Chapter 2

Literature Review

This chapter establishes the technical foundation for the proposed hybrid framework. It begins with the operating principles of lithium-ion batteries and the physical mechanisms responsible for their degradation, before defining the State of Health metric that this thesis aims to estimate. It then introduces Electrochemical Impedance Spectroscopy and the Equivalent Circuit Model framework, which produces physically meaningful input features for the subsequent LSTM. Finally, it reviews the machine-learning approach adopted in this study, the LSTM architecture, and the statistical metrics used to evaluate both prediction accuracy and feature relevance.

2.1 Batteries

Batteries generate electricity through electrochemical redox reactions occurring at two physically separated electrodes. Each cell consists of a negative electrode (anode), where oxidation releases electrons, and a positive electrode (cathode), where reduction consumes them. The two electrodes are immersed in an electrolyte - an ionic medium that allows ions to move between them but blocks electrons. When the cell is connected to an external circuit, electrons flow from anode to cathode through that circuit and deliver current to the load, while ions move internally through the electrolyte to maintain charge balance. This coordinated motion of electrons and ions is what enables a continuous current.

During discharge, this electrochemical process converts chemical potential energy into electrical energy. In a rechargeable cell the process can be reversed by an external charging current, so chemical energy is stored and later released on demand. The battery's function therefore relies on three fundamental electrochemical principles operating in concert: separation of charge carriers, redox reactions at the electrodes, and ion conduction through the electrolyte.

2.1.1 Types of Batteries

Primary batteries are designed for single use. Their electrochemistry is essentially irreversible: once the active chemicals are exhausted, the cell must be discarded. The advantages of primary cells are convenience and long shelf life, since they retain their charge during extended storage. Common examples include lead–acid and alkaline cells.

Secondary (rechargeable) batteries, by contrast, are designed for many use–recharge cycles. An external charging current drives electrons back from the positive to the negative electrode and regenerates the original chemical state. Because they amortise their cost over many cycles, secondary batteries are now essential to consumer electronics, electric vehicles, and stationary energy storage. Common examples include nickel–metal hydride (NiMH) and lithium-ion (Li-ion) cells. The structural differences between primary and secondary cells are illustrated in Figures 2.1 and 2.2.

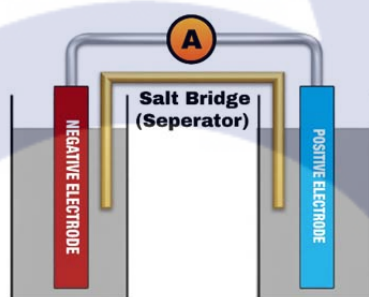


Figure 2.1 Model of the basic components of a primary cell battery

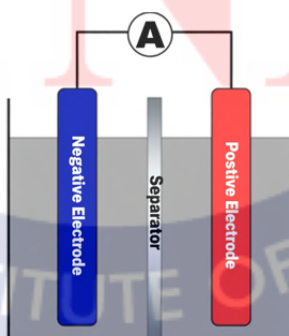


Figure 2.2 Model of the basic components of a secondary cell battery

Among secondary chemistries, lithium-ion batteries offer the highest power density [28] and have become the dominant choice for electric-vehicle applications. This thesis, therefore, focuses on lithium-ion cells, described in detail in the next section.

2.1.2 Lithium-Ion Batteries

A lithium-ion battery is a secondary cell in which energy storage and release are mediated by the movement of lithium ions between the cathode and the anode. Unlike lithium primary batteries, Li-ion cells can be recharged and reused many times. Lithium-ion chemistries are typically classified by the crystal structure of the cathode active material: layered oxides such as LiCoO_2 (LCO) and $\text{Li}(\text{Ni},\text{Mn},\text{Co})\text{O}_2$ (NMC), spinel structures such as LiMn_2O_4 (LMO), and olivine structures such as LiFePO_4 (LFP). These structures are illustrated in Figure 2.3(a)–(c).

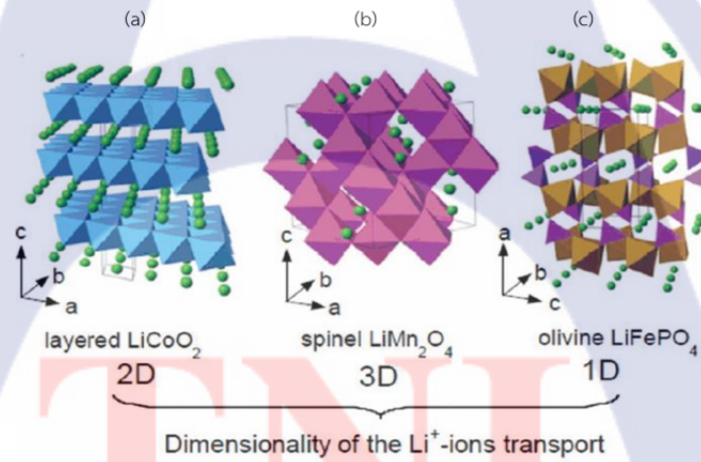
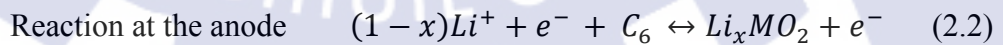
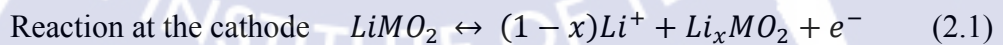


Figure 2.3 Diagram showing the structure of various types of lithium-ion batteries [29]

The general electrochemical reactions can be expressed as follows:



Because this study targets electric-vehicle applications, NMC was selected as the cathode chemistry. NMC currently offers one of the highest practically achievable energy densities and is one of the most widely used cathode materials in commercial EV batteries. Its maximum operating voltage (~ 3.7 V) is significantly higher than that of LFP (~ 3.2 V); since total energy is the product of capacity and voltage, this higher operating potential maximizes specific energy (Wh kg^{-1}) and is particularly well suited to long-range EVs.

2.2 Mechanisms of Battery Degradation

Battery degradation refers to the physical and chemical changes that occur inside the cell during operation and storage, and which collectively reduce its usable capacity (capacity fade) and deliverable power (power fade). Degradation mechanisms operate at the most detailed level of description but are also the hardest to observe directly during operation. Following the comprehensive review of J. S. Edge et al. [9], four principal mechanisms can be identified, each producing a distinct signature in the battery's internal resistance components. These are summarised schematically in Figure 2.4.

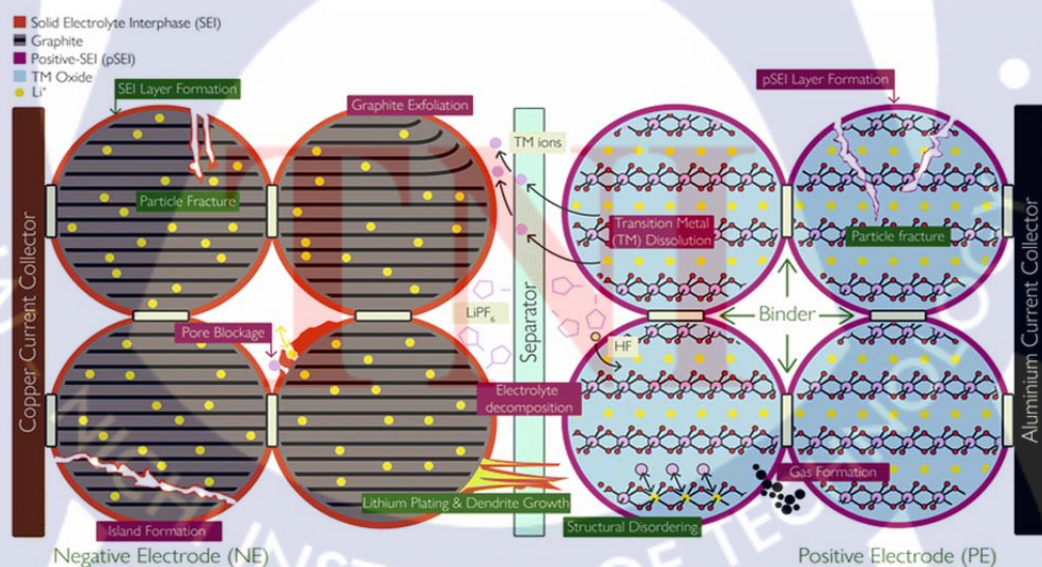


Figure 2.4 Schematic of the four principal degradation mechanisms [9]

2.2.1 Solid Electrolyte Interphase (SEI) Growth

The first mechanism arises from the limited stability window of the electrolyte. A typical organic-carbonate electrolyte (e.g. ethylene carbonate, EC) is stable between roughly 1.5 V and 4.5 V, but the operating potential at the graphite anode is only 0.01–0.25 V [9]. The electrolyte therefore undergoes a continuous reduction reaction at the anode and forms a thin solid electrolyte interphase (SEI) layer on its surface. This layer creates an interfacial resistance and a charge-accumulation region that appears as a semicircle on a Nyquist plot in the approximately 1 kHz–32 Hz frequency range. Because the present study uses a full-cell measurement, the observed semicircle reflects the combined effect of SEI resistance and charge-transfer resistance, not the SEI alone.

2.2.2 Lithium Plating

Lithium plating is the deposition of metallic lithium, typically on the anode. It occurs because the potential for lithium intercalation into graphite is only about 80 mV above the lithium-metal plating potential [30–32]; even small deviations from ideal cell design or charging conditions can therefore push the anode below 0 V, causing lithium to plate on the graphite surface. Charging at 1 C or higher in particular can drive the anode below 0 V and create favorable conditions for plating [31].

Some plated lithium can re-dissolve into Li^+ and re-enter the anode if given sufficient time. Reference [31] reported that after one year of storage, the anode's structure and accessible storage area had almost fully recovered, because the plated deposits had time to dissolve and disperse. However, the cell's overall capacity did not recover because the cyclable Li^+ had already reacted irreversibly with the electrolyte. Temperature is an additional accelerating factor: below approximately $-10\text{ }^{\circ}\text{C}$, plating becomes the dominant mechanism and can lead to dendrite formation [30]. Although the present experiments are conducted at a normal ambient temperature of $25\text{ }^{\circ}\text{C}$, the relatively high 2.5 C rate is sufficient to make plating a contributing mechanism. Figure 2.5 shows a graphite electrode after extensive lithium plating caused by overcharging.

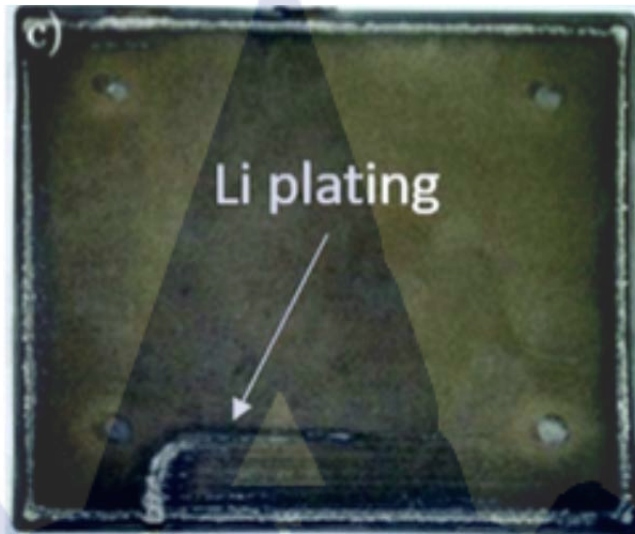


Figure 2.5 Graphite electrode after extensive Li plating [9]

2.2.3 Positive Electrode Decomposition

Cathode degradation and the deposition of secondary compounds is a continuous chain reaction triggered by structural changes in the cathode active material. It can be described as four sequential steps.

(1) Phase transition and oxygen release. Repeated cycling drives lithium ions in and out of the cathode lattice, producing mechanical stress that destabilizes the original layered structure (NCA or NMC). The lattice first transitions to a spinel phase and then collapses to a rock-salt structure, in which the metal-to-oxygen ratio shifts from 1:2 $\rightarrow$ 3:4 $\rightarrow$ 1:1. Each step releases oxygen as expressed in equations (2.4) - (2.5).



Under normal operation, this transition affects only the outermost few nanometres of the particle surface, but it still raises the diffusion (Warburg) impedance and releases oxygen.

(2) Electrolyte decomposition. The released oxygen is highly reactive and oxidizes the organic carbonate solvents (such as EC). The combustion and decomposition products include CO_2 , CO, and - most critically - H_2O . The water then

hydrolyses the lithium salt (e.g., LiPF_6), producing hydrofluoric acid (HF), which is highly corrosive. The salt decomposition and solvent loss together cause a sharp drop in ionic conductivity and a corresponding rise in ohmic resistance.

(3) Permeable solid interface (pSEI) formation. HF acid corrodes the cathode surface and dissolves transition-metal ions (Mn, Ni, Co). The solid by-products of corrosion and decomposition - lithium and transition-metal fluorides plus various organic compounds — precipitate back onto the cathode as a film known as the pSEI (or cathode electrolyte interphase, CEI). As this film thickens, it obstructs Li-ion intercalation, raising both the surface-film resistance R_s and the charge-transfer resistance R_{ct} .

(4) Transition-metal deposition and SEI degradation. The dissolved transition-metal ions diffuse through the separator to the anode, where the much lower electrical potential reduces them back to metallic form. The deposited metals act as catalysts that destabilize the anode SEI, forcing the cell to consume additional cyclable lithium to rebuild it. The result is a further increase in R_s and a rapid, permanent loss of cyclable lithium - *i.e.*, capacity fade.

2.2.4 Practical Factors: Electrode and Contact Loss

Following J. S. Edge et al. [9], two further practical mechanisms can be distinguished: loss of active material at the electrodes and current collectors, and loss of contact at internal interfaces.

(1) Electrode and current-collector loss. This mechanism describes the degradation of the electrode active material together with the current collectors (aluminum for the cathode, copper for the anode). On the cathode side, aluminum is normally protected by a passivation film that forms in contact with the electrolyte, but HF acid (produced as in 2.2.3) corrodes through this film and raises the contact resistance [33]. On the anode side, R. Guo et al. [34] showed that an anode driven beyond -120% depth-of-discharge experiences a potential above 4 V, sufficient to corrode the copper current collector and cause both current-collector loss and contact loss. Because the present experiments are limited to 100% DOD (cut-off at 3 V), this specific mechanism does not occur here.

(2) Contact loss. Contact loss describes abnormalities at the interface between active material and current collector, or between adjacent active-material particles. The dominant cause is the volumetric expansion and contraction (mechanical stress) that accompanies lithium intercalation and de-intercalation. Repeated cycling weakens the contact points between particles, generates microcracks, and can detach particles from the conductive network or the current-collector foil. Operating at wide SOC ranges accelerates this mechanism [30-32]. A separate contribution comes from insufficient compression pressure between the electrode and the current collector during manufacturing, which permanently raises the ohmic resistance [35]. Finally, contact loss can also originate from the measurement equipment itself: imperfect surface contact during reinstallation can produce a sudden spike in the measured ohmic resistance, which must be distinguished from genuine intrinsic degradation.

Although these degradation mechanisms appear individually distinct, they are in practice strongly coupled. Several review groups have mapped these interrelationships into integrated diagrams; the version reproduced here in Figure 2.6 provides a useful overview of how each mechanism links to a specific resistance component.

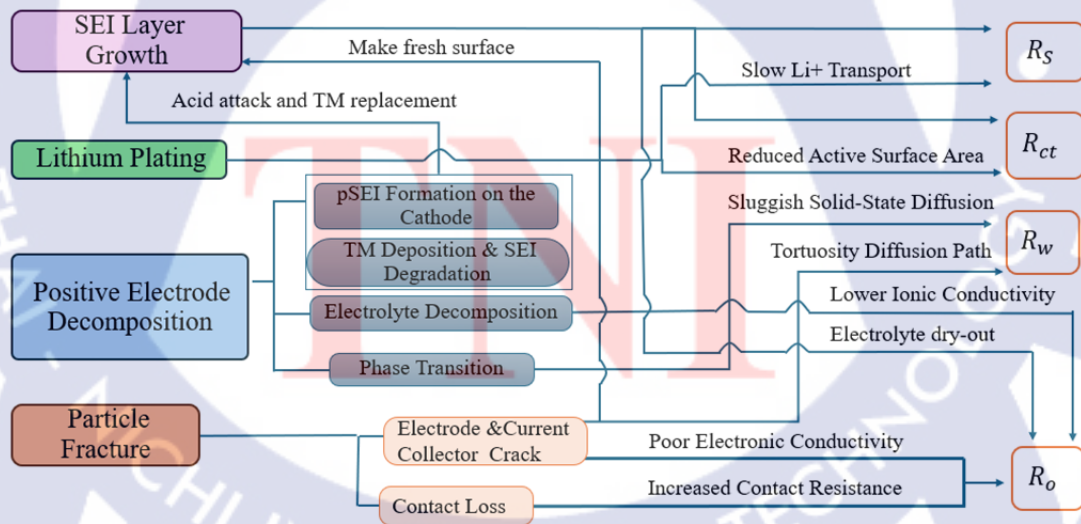


Figure 2.6 The degradation mechanisms and their effects on internal resistance

2.3 Classification of Degradation Mechanisms

Degradation does not occur only during operation: it continues during storage. Because the dominant mechanisms differ between the two regimes, the literature [30, 31] divides battery aging into cycling aging and calendar aging.

2.3.1 Cycling Aging

Cycling aging encompasses the irreversible capacity and structural degradation that accumulates during active charge–discharge operation. It is more complex than calendar aging because it combines chemical degradation with severe mechanical stress. As lithium ions repeatedly intercalate and de-intercalate, the electrode materials expand and contract; over many cycles, this produces graphite exfoliation, active-material cracking, and fractures in the SEI layer that must then be repaired at the cost of further cyclable lithium. Under fast charging or low temperatures, lithium plating becomes an additional contribution, as already discussed in Section 2.2.2.

A further mechanism specific to high-rate cycling is inhomogeneous reaction distribution. Local variations in electrolyte salt concentration cause regions of the composite electrode to be repeatedly under-utilised. T. Nakamura et al. [36] used X-ray imaging to show that even after a 20-hour rest, these unreacted regions persist and do not equalise - direct evidence that the inhomogeneity becomes locked in. The result is significant capacity fade, illustrated in Figure 2.7. The dominant stress factors of cycling aging are therefore not only temperature and SOC but also the dynamic parameters of operation: C-rate, depth of discharge (DOD), and total charge throughput.

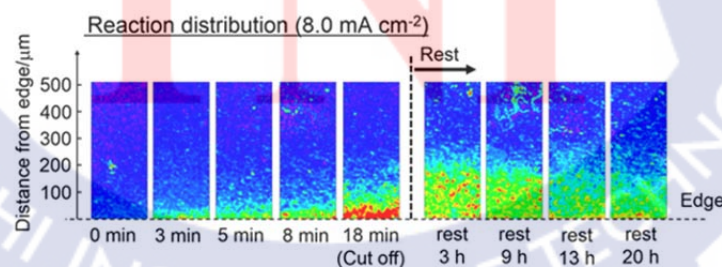


Figure 2.7 Inhomogeneous reaction distribution at high C-rate [36]

2.3.2 Calendar Aging

Calendar aging refers to degradation that occurs while the battery is at rest, with no charge or discharge in progress. It is driven primarily by parasitic side reactions at the electrode–electrolyte interfaces: continuous reduction and oxidation of the electrolyte, growth of the SEI on the negative electrode, and formation of a CEI on the positive electrode. These reactions trap active lithium in inactive forms the so-called "loss of lithium inventory" which is the predominant cause of capacity fade during rest periods.

Calendar aging depends heavily on three factors: time, temperature, and SOC. Storage at elevated temperatures (typically above 30°C) and at high SOC accelerates parasitic reactions and SEI growth, as illustrated in Figure 2.8.

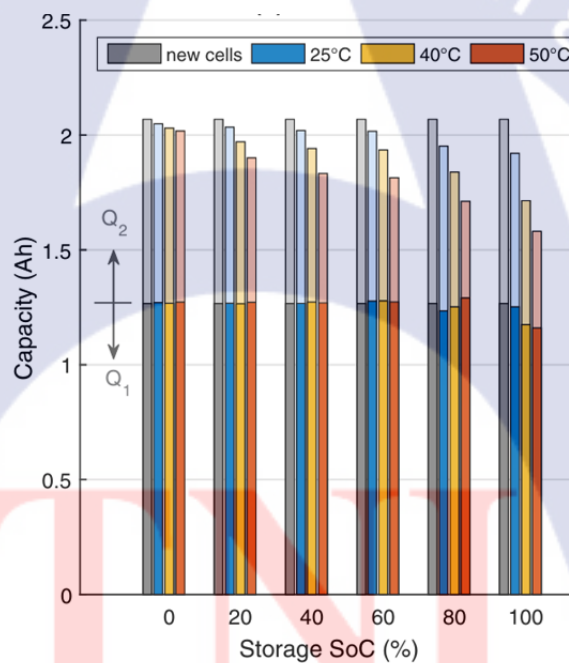


Figure 2.8 Capacity fade after 9-10 months of calendar aging at different temperatures and SOC for an NMC battery [37]

Together, cycling aging and calendar aging account for the loss of usable capacity that the State-of-Health metric is designed to quantify. The next section formally defines that metric.

2.4 State of Health (SOH)

The State of Health (SOH) is a metric that expresses the overall condition of a battery relative to its as-new state. It is most commonly defined as the ratio of the present measured capacity to the initial capacity, expressed as a percentage:

$$SoH(\%) = \frac{C_k}{C_0} \times 100 \quad (2.6)$$

where C_0 is the initial capacity, and C_k is the measured capacity at cycle k . Even cells from the same production batch start from slightly different initial capacities and degrade at different rates; the typical capacity-fade trajectory across cycles is illustrated in Figure 2.9.

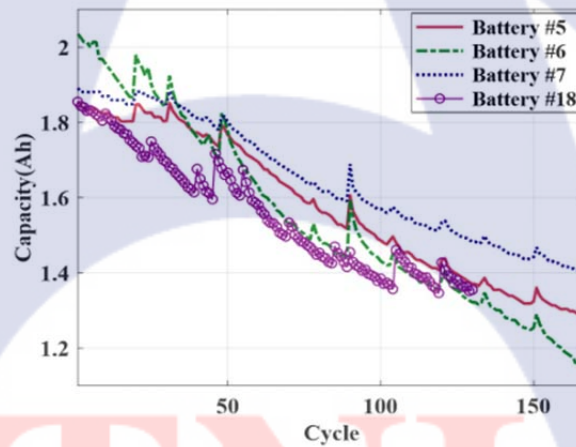


Figure 2.9 Capacity degradation over charge-discharge cycles [24]

Capacity fade can also be tracked indirectly through the shape of the CC-CV charging profile, as proposed by Park et al. [24] and shown in Figures 2.10 and 2.11.

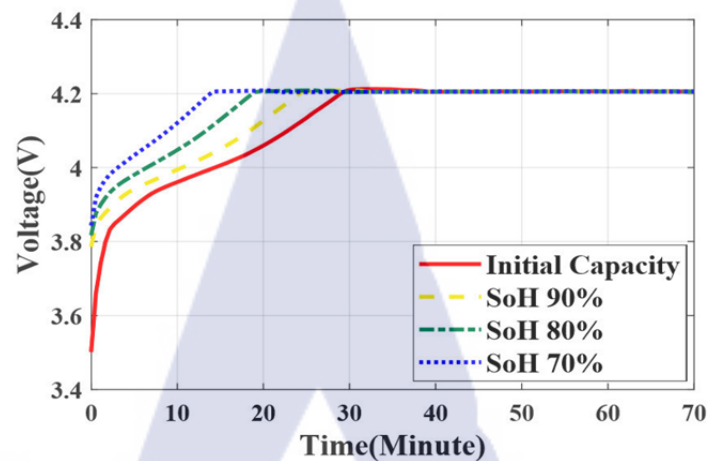


Figure 2.10 CV-charging response over time at different SOH levels [24]

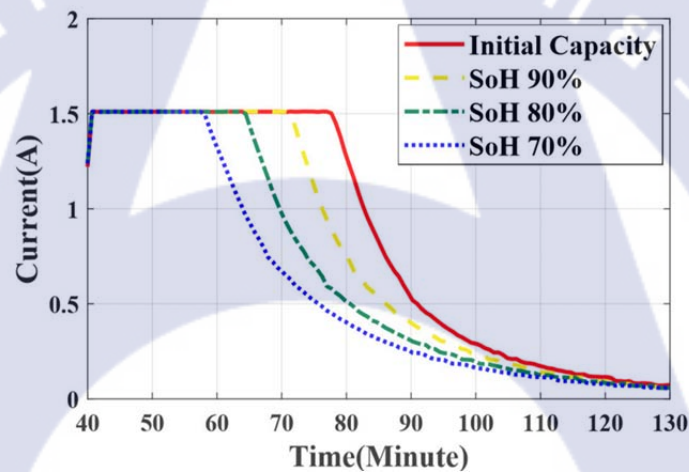


Figure 2.11 CC-charging response over time at different SOH levels [24]

On the constant-voltage curve (Figure 2.10), degraded cells (SOH below 90%) reach the upper voltage limit of 4.2 V earlier than fresh cells, both because internal resistance most notably the SEI layer requires a higher applied voltage to drive Li^+ diffusion, and because the cell's reduced capacity is filled more quickly. On the constant-current curve (Figure 2.11), the duration of the CC phase shortens with degradation because the electrodes can store less charge.

While CC-CV profiles, together with the qualitative degradation framework in Section 2.2, provide a useful first-pass diagnostic, they cannot determine which specific resistance component is responsible for the observed capacity fade. To gain that level of insight, a measurement that probes the cell's internal behavior as a function of frequency is needed. The next section introduces Electrochemical Impedance Spectroscopy.

2.5 Electrochemical Impedance Spectroscopy

Electrochemical Impedance Spectroscopy (EIS) probes the cell by applying a small-amplitude alternating current (AC) signal across a range of frequencies and measuring the resulting voltage response. Its principal advantage is that it is non-destructive: a small excitation signal (typically 5–10 mV) keeps the system in a pseudo-linear regime, so the cell's internal structure is not altered, and no measurement-induced degradation occurs. Although the result requires interpretation via equivalent-circuit fitting and does not provide a direct internal image as X-ray techniques do, EIS is far less resource-intensive and much faster than imaging methods [13], [14], [38].

2.5.1 AC Response and Mathematical Form of Impedance

EIS begins by applying a sinusoidal voltage and measuring the sinusoidal current response, which has the same frequency but a phase shift, as illustrated in Figure

- 2.12. The two signals can be written as:

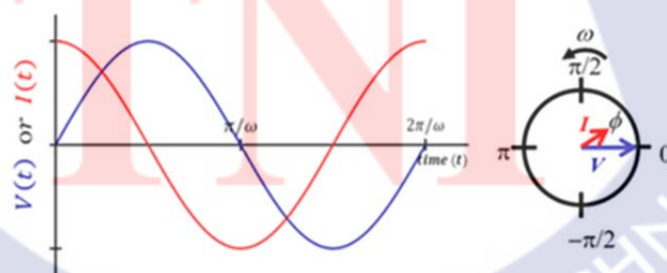


Figure 2.12 Voltage and current under an applied AC voltage at angular frequency ω [38]

$$V(t) = V_m \sin(\omega t) \quad (2.7)$$

$$I(t) = I_m \sin(\omega t - \phi) \quad (2.8)$$

where V_m and I_m are the peak voltage and current, ω is the angular frequency, and ϕ is the phase shift. The phase shift depends on the type of circuit element: for a pure resistor, $\phi = 0$, for a capacitor, the current leads the voltage ($+\phi$), and for an inductor, the voltage leads the current ($-\phi$). These three cases are illustrated in Figure 2.13.

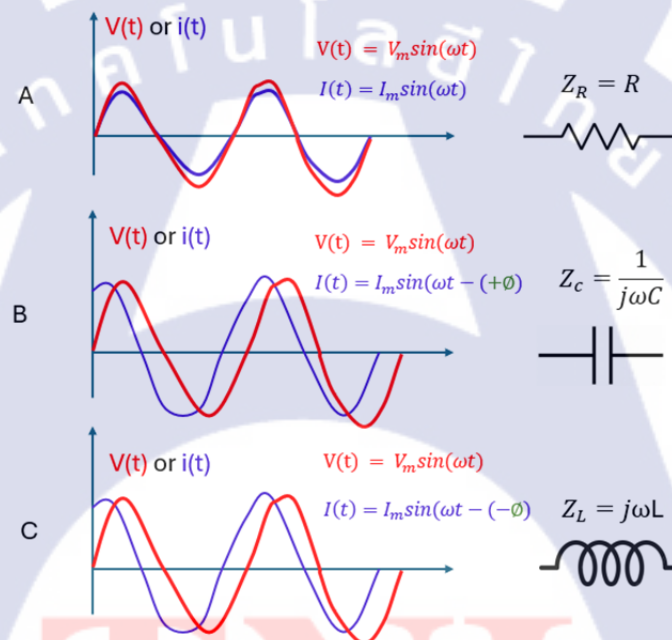


Figure 2.13 AC response and phase shift for (A) resistance, (B) capacitance, (C) inductance

By Ohm's law, the impedance $Z(\omega)$ is the ratio of voltage to current:

$$Z(\omega) = \frac{V(t) = V_m \sin(\omega t)}{I(t) = I_m \sin(\omega t - \phi)} \quad (2.9)$$

Working with this ratio in the time domain becomes mathematically awkward when the system contains capacitive or inductive elements. The standard

remedy is to apply Euler's formula and rewrite the signals in the complex frequency domain:

$$e^{j\theta} = \cos(\theta) + j\sin(\theta) \quad (2.10)$$

where $j = \sqrt{-1}$. The voltage and current then become:

$$V(t) = V_m(e^{j\omega t}) \quad (2.11)$$

$$I(t) = I_m(e^{j(\omega t - \phi)}) \quad (2.12)$$

and the impedance simplifies to:

$$Z(\omega) = \frac{V(t)}{I(t)} = \frac{V_m(e^{j\omega t})}{I_m(e^{j(\omega t - \phi)})} \quad (2.13)$$

The $e^{j\omega t}$ terms cancel. Defining $Z = \frac{V(t)}{I(t)}$ as the magnitude of the total impedance, the result depends only on the phase angle:

$$Z(\omega) = Z_0(e^{j\phi}) \quad (2.14)$$

Returning to trigonometric form gives the standard expression:

$$Z(\omega) = Z_0 \cos(\phi) + Z_0 \sin(\phi) \quad (2.15)$$

which decomposes the impedance into two physically meaningful parts: a real part ($Z_0 \cos \phi$) that represents the actual electrical resistance of the system, and an imaginary part ($Z_0 \sin \phi$) that represents the capacitive or inductive properties associated with chemical reactions and charge accumulation at the electrode surface.

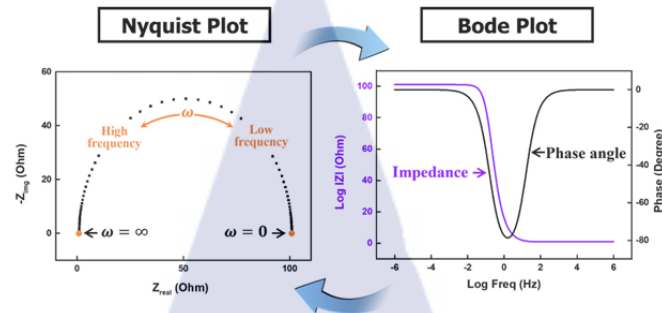


Figure 2.14 Nyquist plot and Bode plot [38]

Equation (2.15) can be visualized in two complementary ways, both of which are shown in Figure 2.14. The Bode plot displays impedance magnitude and phase angle as functions of frequency and is the natural choice for analyzing control systems or signal filters. The Nyquist plot, by contrast, plots imaginary impedance against real impedance, producing curves and semicircles that distinguish individual electrochemical processes. Because this study focuses on the internal-resistance components of lithium-ion batteries, the Nyquist plot is used throughout. However, Equation (2.15) is only the mathematical form of the plot; on its own, it cannot reveal which physical resistance corresponds to which feature on the spectrum. To extract that information, an Equivalent Circuit Model is needed.

2.6 Equivalent Circuit Model

An Equivalent Circuit Model (ECM) represents the internal behavior of a battery as a network of standard electrical elements — resistors (R), capacitors (C), and inductors (L) chosen so that each element corresponds to a real physical process inside the cell. The mapping from physical process to circuit element, as developed by P. Keil [31] and A. Lazanas and M. I. Prodromidis [39], proceeds as follows.

In the high-frequency region (~ 10 kHz–1 kHz), the response is dominated by external circuit elements (cables, connectors, current collectors) and is generally treated as inductive. It is usually considered uninformative for internal-process analysis. The corresponding inductor response on the Nyquist plot is shown in Figure 2.15.

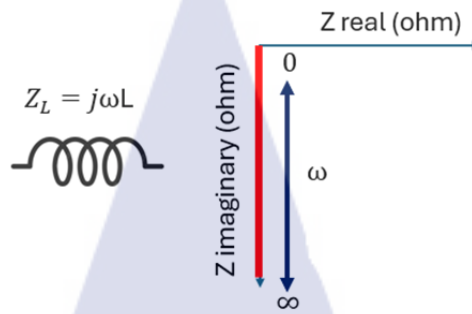


Figure 2.15 Inductor response on a Nyquist plot

The first physically meaningful contribution is the ohmic resistance R_0 , associated with the migration of Li^+ through the bulk electrolyte toward the anode. R_0 is frequency-independent and appears as a single point on the real axis of the Nyquist plot, as shown in Figure 2.16.

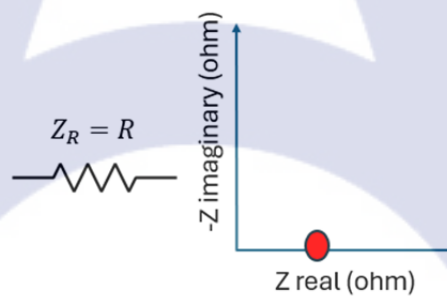


Figure 2.16 Ohmic resistance on a Nyquist plot

When solvated Li^+ ions reach the electrode surface, they encounter the SEI (or the CEI on the cathode side), a thin film that separates the liquid electrolyte from the solid electrode. The SEI pores are small enough that ions cannot pass through instantaneously; instead, they accumulate at the SEI interface and behave like a capacitor the so-called double-layer capacitance. This appears in the mid-to-low-frequency region of the Nyquist plot, as illustrated in Figure 2.17.

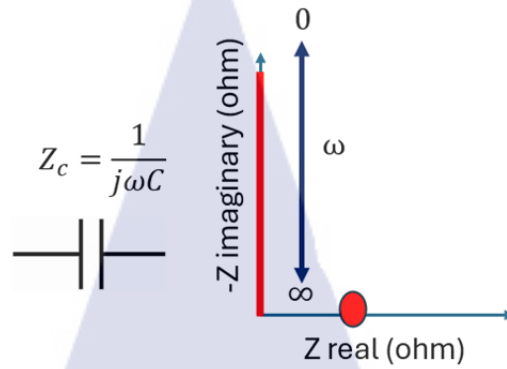


Figure 2.17 Capacitor response on a Nyquist plot

Li^+ ions eventually acquire enough energy to shed their solvent shells and pass through the SEI into the active material. This passage incurs an additional voltage drop that obeys Ohm's law and is denoted the SEI (or surface-film) resistance R_s . Because Li^+ ions can either accumulate at the SEI surface or pass through it, the two pathways are best represented as a parallel $R_s||C_s$ combination, whose impedance is given by Equation (2.16) and whose Nyquist response is shown in Figure 2.18. This phenomenon is observed in the approximately 1 kHz–32 kHz frequency range.

$$Z_{R_s||C_s} = \frac{R_s}{1 + j\omega R_s C_s} \quad (2.16)$$

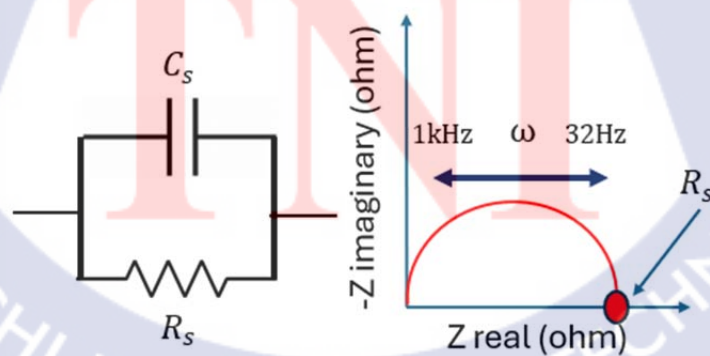


Figure 2.18 Parallel $R_s||C_s$ circuit and its Nyquist response (1-32 kHz)

Once Li^+ has crossed the SEI and reached the active material (NMC or graphite), the same physical pattern repeats at a finer scale. The Li^+ that gathers at the active-material surface attracts an opposing charge in the electrolyte, separated by a microscopic gap of solvent molecules. This arrangement of opposing charges behaves exactly like a physical capacitor and is known as the double-layer capacitance C_{dl} . A subset of these Li^+ ions then breaks their bonds with solvent molecules and intercalates into the electrode; the resistance to this chemical step is the charge-transfer resistance R_{ct} . Because the two pathways—accumulation versus chemical reaction—are available at the same physical boundary, they are modelled as a parallel $R_{ct}||C_{dl}$ combination, whose impedance is given by Equation (2.17) and shown in Figure 2.19. This response appears in the approximately 32 kHz–350 mHz frequency range.

$$Z_{R_{ct}||C_{dl}} = \frac{R_{ct}}{1 + j\omega R_{ct}C_{dl}} \quad (2.17)$$

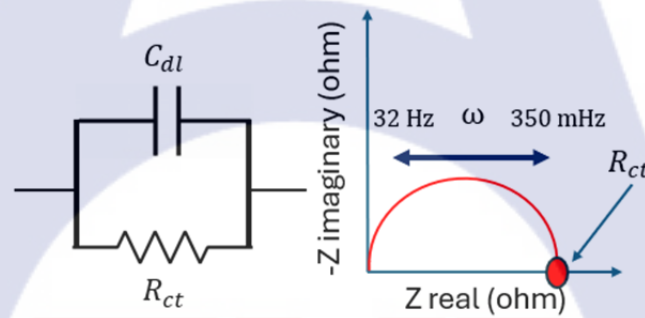


Figure 2.19 Parallel $R_{ct}||C_{dl}$ circuit and its Nyquist response (32 kHz–350 mHz)

Finally, once Li^+ has crossed the interface, it must diffuse into the electrode bulk. The Warburg impedance models this diffusion. Because the electrode thickness is much greater than the penetration depth of the AC signal, lithium diffuses as if into a semi-infinite tunnel: ion motion is impeded along the real axis while ion accumulation along the imaginary axis follows at the same rate, consistent with the diffusion equation. As a result, the Nyquist plot in the low-frequency region ($\sim 350 \text{ mHz}$ – 10 mHz) shows a 45-degree straight line. The Warburg frequency dependence is given by Equation (2.18) and the response is shown in Figure 2.20.

$$Z_W = \frac{\coth\sqrt{j\omega\sigma}}{\sqrt{j\omega\sigma}} \quad (2.18)$$

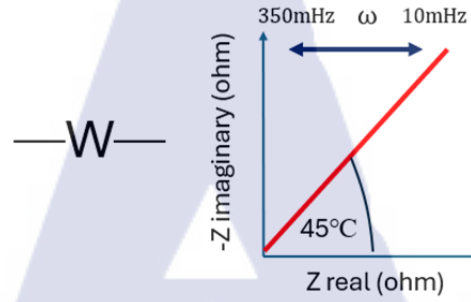


Figure 2.20 Warburg element and its Nyquist response (350 mHz–10 mHz)

Combining all the above contributions yields the Randles cell, named after J. E. B. Randles [40]. Its impedance is given by Equation (2.19) and its circuit topology together with the corresponding Nyquist plot subdivided by frequency and the physical locations where each resistance arises is shown in Figure 2.21.

$$Z_{LIB(\omega)} = R_0 + \frac{R_s}{1 + j\omega R_s C_s} + \frac{1}{j\omega C_{dl} + \frac{1}{R_{ct} + \frac{\coth(\sqrt{j\omega\sigma})}{\sqrt{j\omega\sigma}}}} \quad (2.19)$$

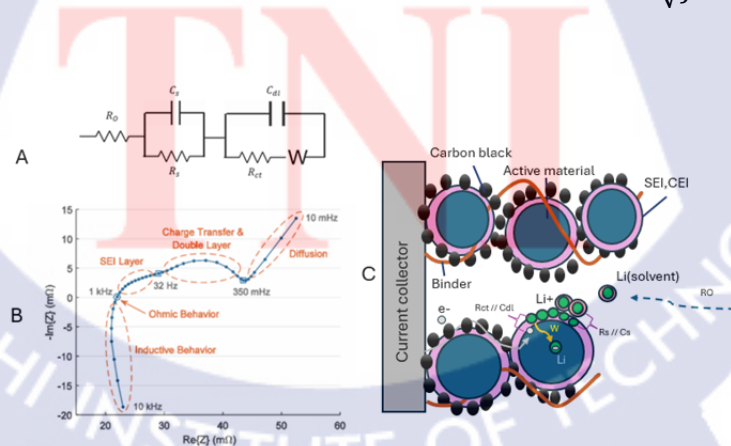


Figure 2.21 (A) Randles full-cell ECM, (B) Nyquist plot decomposed by frequency, (C) physical locations of each resistance

Real capacitors, however, do not behave ideally: surface roughness, leakage capacitance, and non-uniform charge distribution all introduce deviations from the ideal capacitive response. The standard remedy is to replace each ideal capacitor with a Constant Phase Element (CPE) [41], [42]. The CPE-modified responses for $R_s||C_s$ and $R_{ct}||C_{dl}$ are shown in Figure 2.22, and the impedance of a parallel $R||CPE$ block is given by Equation (2.20):

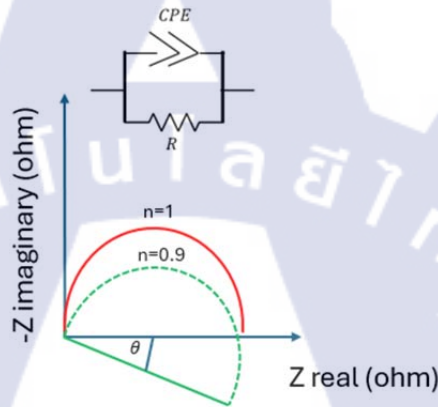


Figure 2.22 Nyquist response of CPE and of the parallel $R//CPE$

$$Z_{R//CPE} = \frac{R}{1 + R(j\omega)^\alpha Q} \quad (2.20)$$

where Q is the pseudo-capacitance and α ($0 \leq \alpha \leq 1$) measures the degree of non-ideality: $\alpha = 1$ corresponds to an ideal capacitor. The CPE depression angle θ (measured from the real Z -axis) is related to α by:

$$\theta = 90^\circ(1 - \alpha) \quad (2.21)$$

Substituting CPEs for ideal capacitors in the Randles cell yields the more general impedance expression:

$$Z_{LIB(\omega)} = R_0 + \frac{R_s}{1 + R_s(j\omega)^{\alpha_s} Q_s} + \frac{1}{(j\omega)^{\alpha_{dl}} Q_{dl} + \frac{1}{R_{ct} + \frac{\coth(\sqrt{j\omega\sigma})}{\sqrt{j\omega\sigma}}}} \quad (2.22)$$

Although Equation (2.22) captures the main internal behaviors, the actual physical structure of a battery is far more detailed than any analytic ECM, as the schematic in Figure 2.23 illustrates. Using a more elaborate ECM in practice tends to introduce over-parameterization, which produces curve-fitting instabilities. For practical analysis, several simplifications are therefore standard: series resistances from the current collectors, electrolyte, and separator are all combined into a single ohmic resistance R_0 without losing physical meaning, and components with negligible electrical effect such as the small capacitance of the separator are omitted entirely.

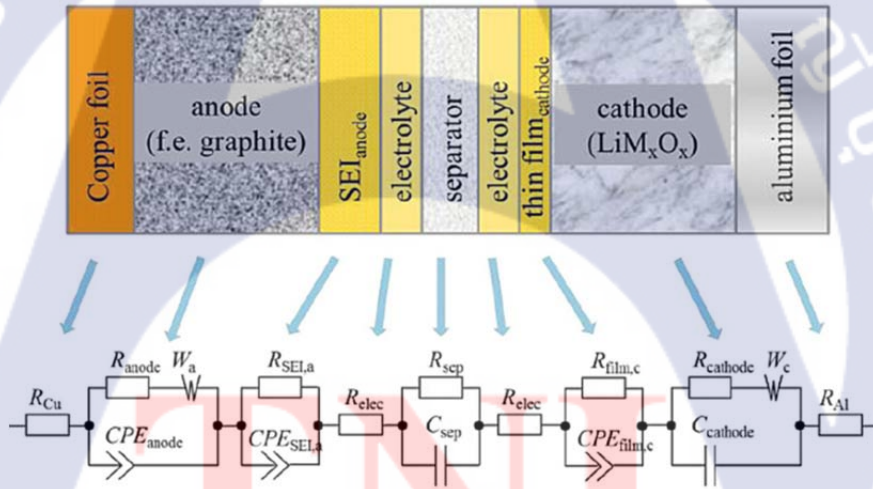


Figure 2.23 Detailed ECM for the components of a lithium-ion battery [43].

The choice of ECM topology in this study is guided by an explicit trade-off between physical rigor and computational tractability. Recent fundamental work by M. E. Orazem and B. Ulgut [44] argues that the traditional Randles ECM offers a more rigorous physical representation of lithium-ion interfaces, but its highly coupled equations introduce significant mathematical complexity. In the practical context of a Battery Management System, computational efficiency and feature stability take precedence. A.

Kulkarni et al. [45] showed that simplified topologies such as a multiple-RC branch model for example, the 3RC model in Figure 2.24 capture the impedance characteristics needed for accurate state estimation.

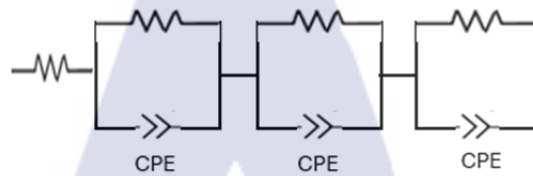


Figure 2.24 3RC-branch ECM [45]

Because the low-frequency impedance response is dominated by mass-transfer diffusion, this region can be modeled by a single Warburg element placed in series, as proposed by T. R. Penki et al. [46] and shown in Figure 2.25. This decoupled series arrangement reduces computational overhead and stabilizes the parameter-extraction process, making it particularly suitable for generating inputs for machine-learning algorithms. The standard Randles ECM remains the better choice for research that requires rigorous first-principles electrochemical interpretation; however, the series-based and multiple-RC ECMs are more suitable for data-driven predictive modeling.

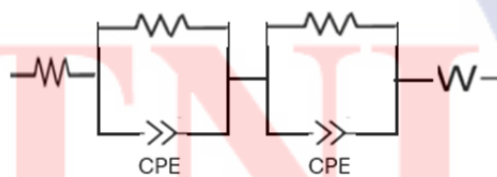


Figure 2.25 2RC + Warburg-in-series ECM [46]

One further caveat applies to the use of ECM with full-cell measurements. Following M. Gaberšček, [47], the situation is illustrated in Figure 2.26. In an ideal case where each component responds at a clearly distinct frequency, the Nyquist plot shows well-separated semicircles (Figure 2.26A) and each process can be identified unambiguously. In practice, however, cathode and anode reactions often overlap in frequency, and some

processes have such low resistance that they fail to form a clear semicircle (Figure 2.26B); the responses merge into a single broad arc. Distinguishing which electrode is responsible for an observed resistance increase therefore becomes difficult.

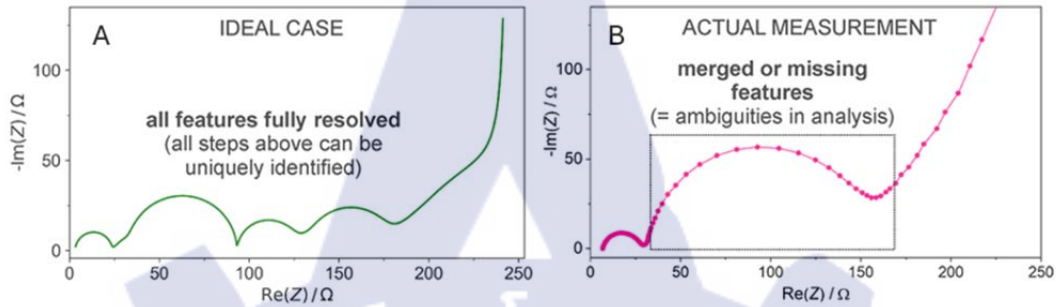


Figure 2.26 Comparison of (A) ideal and (B) actual Nyquist plots

Reference [47] recommends half-cell or three-electrode configurations to resolve this ambiguity at the material level. The aim of the present study, however, is to characterize the overall resistance behavior of real commercial batteries and to use these data to train an AI model for full-cell health estimation, rather than to isolate the individual contributions of each electrode. A full-cell measurement, combined with a simplified ECM, is therefore both appropriate and sufficient for extracting the global resistance characteristics required for this work.

2.7 Linear Kramers–Kronig Testing

Extracting meaningful physical information from an EIS spectrum requires that the underlying system be linear, time-invariant, and causal. If any of these three conditions is violated during the measurement, the resulting spectrum is invalid and any subsequent ECM fitting will produce erroneous parameters. These conditions can, in principle, be checked experimentally for example, by detecting harmonics in the response or applying broadband excitation but most commercial frequency-response analyzers (FRAs) do not expose the raw excitation and response signals needed. Researchers therefore rely on analyzing the obtained spectrum itself using the Kramers–Kronig (KK) relations [48], [49].

2.7.1 The Kramers–Kronig Relations

The KK relations are mathematical identities that link the real and imaginary parts of an impedance spectrum for any system that satisfies the three conditions above. They are defined by:

$$Z_{Re}(\omega) = \frac{2}{\pi} \int_0^{\infty} \frac{\omega' \cdot Z_{Im}(\omega')}{\omega^2 - (\omega')^2} d\omega' \quad (2.23)$$

$$Z_{Im}(\omega) = \frac{-2}{\pi} \int_0^{\infty} \frac{\omega \cdot Z_{Re}(\omega')}{\omega^2 - (\omega')^2} d\omega' \quad (2.24)$$

where $Z_{Re(\omega)}$ and $Z_{Im(\omega)}$ are the real and imaginary parts of the impedance at angular frequency ω , and ω' is the integration variable. Direct numerical integration is impractical because it requires data over an infinite frequency range. The Lin-KK approach, therefore, tests compliance indirectly: it fits the measured spectrum to a generic ECM that is known to be KK-compliant by construction, and judges its validity from the residuals between the measured impedance Z and the KK-compliant fit $\hat{Z}$:

$$\Delta_{Re}(\omega) = \frac{Z_{Re}(\omega) - \widehat{Z}_{Re}(\omega)}{|Z(\omega)|} \quad (2.25)$$

$$\Delta_{Im}(\omega) = \frac{Z_{Im}(\omega) - \widehat{Z}_{Im}(\omega)}{|Z(\omega)|} \quad (2.26)$$

2.7.2 Interpretation of the Residuals

1. Valid spectra. Small residuals typically less than 0.5% distributed randomly (noise-like) across the frequency range indicate a high-quality, time-invariant spectrum.

2. Invalid spectra (time-variance). Strongly biased residuals, particularly in the low-frequency region, indicate that the cell's state changed during the measurement and that the spectrum is unusable for ECM fitting.

2.8 Machine Learning Approach

The internal behavior of a battery is intrinsically nonlinear, and the traditional combination of chemical and physical models that aims to capture it is computationally expensive and often inaccurate. For this reason, modern battery research increasingly adopts data-driven methods, which construct a flexible mapping between measured inputs and target outputs without requiring an explicit physical model. Data-driven methods are particularly well-suited to non-linear phenomena, which makes them a natural choice for SOH prediction [19]-[21]. This study, therefore, adopts a data-driven approach. Machine-learning algorithms are conventionally divided into four families [50], summarized below.

2.8.1 Supervised Learning

Supervised algorithms are trained on labelled data and are typically used either to classify new examples or to predict continuous outcomes. The model learns the relationship between inputs and outputs from the training set, and once deployed it can apply this relationship to new data either to assign a category or to estimate a numerical value.

2.8.2 Unsupervised Learning

Unsupervised algorithms operate on unlabelled data, which is the most common form of data in industry. Their goal is to discover structure clusters, patterns, or trends without an external label. Common applications include audience segmentation in marketing platforms and trend analysis driven entirely by the data itself.

2.8.3 Semi-supervised Learning

Semi-supervised algorithms operate on partially labelled data. They are useful for large or complex datasets in which exhaustive labelling would be prohibitively expensive for example, large image collections or rich text corpora. The model is trained on a labelled subset and then extends what it has learned to the unlabelled remainder.

2.8.4 Reinforcement Learning

Reinforcement learning improves a system's performance through trial and error in interaction with an environment. It is well suited to scenarios where the environment is random or hard to predict and where a static, hand-coded algorithm would not cover all possible cases.

Each family suits a different problem, and choosing the right family is critical to achieving accurate predictions. In this study the goal is to predict SOH on degrading batteries, with SOH itself serving as the labelled output, so supervised learning is the natural choice. Within supervised learning several algorithms are available, including artificial neural networks (ANN), deep learning (DL), support vector machines (SVM), and Long Short-Term Memory (LSTM). Battery degradation is governed by chemical and physical processes that evolve over time, so a model that is explicitly designed for time-series data is preferable. As Haraz et al. and several subsequent studies have shown, LSTMs are highly effective for time-series prediction because they track sequential dependencies. LSTM is therefore selected for this study and described in detail in the next section.

2.9 Long Short-Term Memory (LSTM)

Long Short-Term Memory (LSTM) is a specialized Recurrent Neural Network (RNN) designed to handle sequential data and capture long-term dependencies. Standard RNNs struggle to retain information across long sequences because of the vanishing-gradient problem, in which information from earlier time steps is progressively lost as it propagates through the network. LSTM overcomes this limitation through a gating mechanism that selectively retains or discards information at each time step, making it particularly well-suited to time-series forecasting tasks such as predicting the Remaining Useful Life (RUL) of lithium-ion batteries [22]-[24]. The LSTM cell architecture is illustrated in Figure 2.27.

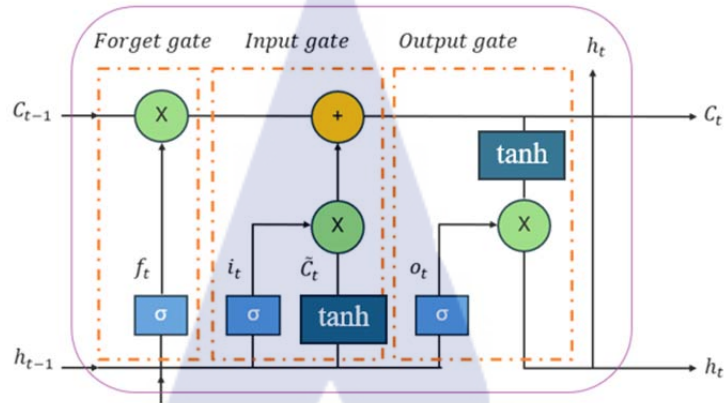


Figure 2.27 LSTM cell architecture

Each LSTM cell contains three gates that regulate the flow of information: a forget gate that decides which information from the previous state should be discarded; an input gate that decides which new information should be added to the cell state; and an output gate that regulates which part of the current cell state is sent forward to the next time step. Each gate uses an activation function (typically sigmoid or ReLU) to scale its output to the range $[0, 1]$, allowing fine-grained control over what is retained and what is filtered out. The mathematical form of each gate is given below.

Forget gate:

$$f_t = \sigma(W_f * [h_{t-1}, x_t] + b_f) \quad (2.27)$$

Here, f_t controls how much of the past information is retained: σ is the sigmoid function, which compresses values into $[0, 1]$; values close to 1 retain most of the past information, values close to 0 discard most of it. W_f is the forget-gate weight matrix, h_{t-1} is the hidden state from the previous time step, x_t is the input at the current step, and b_f is the bias term.

Input gate and candidate cell state:

$$i_t = \sigma(W_i * [h_{t-1}, x_t] + b_i) \quad (2.28)$$

$$\tilde{C}_t = \tanh(W_c * [h_{t-1}, x_t] + b_c) \quad (2.29)$$

I_t controls how much new information is admitted, and $\tilde{C}_t$ is the candidate cell state the new information generated from the current input. W_i and b_i are the weight matrix and bias for the input gate; W_c and b_c are the weight matrix and bias for the candidate cell state.

Cell-state update:

$$C_t = f_t * C_{t-1} + i_t * \tilde{C}_t \quad (2.30)$$

where C_{t-1} is the previous cell state, carrying the long-term memory from earlier time steps. The update has three components: (i) retained past information, given by $f_t * C_{t-1}$ when $f_t \approx 1$ most of the old information is kept, when $f_t \approx 0$, most of it is discarded; (ii) new information, given by $i_t * \tilde{C}_t$ when $i_t \approx 1$, new information is admitted strongly, when $i_t \approx 0$, little is admitted; (iii) the final updated cell state, which is the sum of the two and becomes the long-term memory available to the next time step.

Output gate and hidden state:

$$o_t = \sigma(W_o * [h_{t-1}, x_t] + b_o) \quad (2.31)$$

$$h_t = o_t * \tanh(C_t) \quad (2.32)$$

o_t controls how much of the updated cell state is exposed as the next hidden state h_t . W_o and b_o are the weight matrix and bias for the output gate. Together, Equations (2.31) and (2.32) determine which part of the long-term memory is passed on to the next time step.

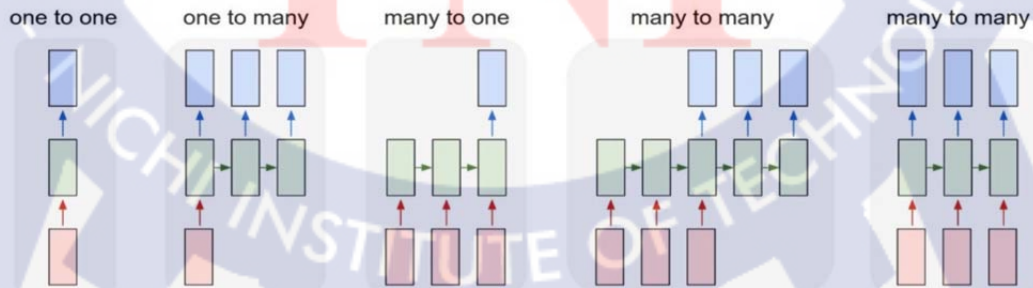


Figure 2.28 Several types of RNN architectures [24]

RNN architectures can be configured in several ways depending on whether the input and output are single values or sequences, as shown in Figure 2.28. Park et al. [24] used a many-to-one architecture, in which the model processes a sequence of consecutive cycles to predict the SOH at a single target cycle, and reported MAE = 0.07, $R^2 = 0.95$, and RMSE = 0.09 for capacity-remaining prediction. The many-to-one configuration is illustrated in Figure 2.29.

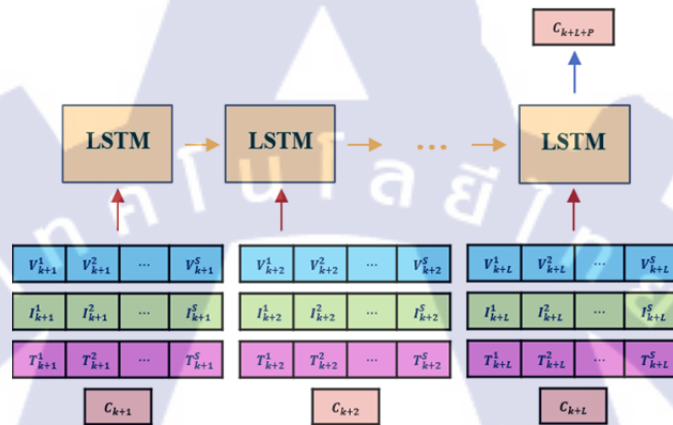


Figure 2.29 Many-to-one architecture for capacity prediction [24]

Because the present study estimates SOH from multiple time-varying inputs at each cycle (voltage, current, and the EIS-derived resistances R_0 , R_s , R_{ct} , R_w), the many-to-one architecture is adopted here as well.

2.10 Performance Evaluation Indicators

Model performance is judged by a small set of statistical metrics that capture complementary aspects of accuracy and explained variance. The three indicators used most commonly in the data-driven SOH literature [22]-[24] are described below.

2.10.1 Mean Absolute Error (MAE)

The Mean Absolute Error (MAE) measures the average absolute discrepancy between predicted and observed values, and so reflects how far, on average, the forecasts deviate from the actual outcomes. MAE provides a transparent measure of

accuracy but does not indicate whether the errors are systematically positive or negative i.e. whether the model tends to over- or under-predict. MAE is defined by:

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i| \quad (2.33)$$

where y_i and $\hat{y}_i$ are the actual and predicted values respectively. Lower MAE indicates better predictive performance.

2.10.2 R-squared (R^2)

R^2 is a statistical measure that expresses the proportion of variance in the dependent variable that is explained by the independent variables. It is defined in terms of the residual sum of squares (SS_{res}) and the total sum of squares (SS_{tot}):

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (2.34)$$

where $\bar{y}$ is the mean of the actual values. An R^2 close to 1 indicates that the model explains most of the variance in the data.

2.10.3 Root Mean Square Error (RMSE)

RMSE is closely related to MAE but takes the square root of the mean squared difference between observed and predicted values. The squaring step emphasizes larger residuals, so RMSE is more sensitive than MAE to occasional large errors:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (2.35)$$

Lower RMSE indicates a better fit. Together, RMSE and MAE describe the magnitude of the residuals while R^2 describes how well the model fits the data; all three are reported in this study.

2.11 Pearson Correlation Coefficient

Correlation analysis is a statistical technique that quantifies the relationship between two or more quantitative variables. The most widely used method, developed by B. Illowsky and S. Dean [51], is the Pearson correlation coefficient r , which measures both the direction and strength of the linear relationship between two continuous variables.

2.11.1 Mathematical Formulation

The Pearson correlation coefficient is the ratio of the covariance between the two variables to the product of their standard deviations:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (2.36)$$

where n is the number of paired observations, x_i and y_i are the values of the two variables at index i , and $\bar{x}$ and $\bar{y}$ are their respective arithmetic means.

2.11.2 Interpretation

The Pearson correlation coefficient always lies in the range $-1 \leq r \leq +1$ and is interpreted as follows.

Direction:

1. $r > 0$ (positive correlation): both variables move in the same direction; as x increases, y tends to increase.
2. $r < 0$ (negative correlation): the variables move in opposite directions; as x increases, y tends to decrease.

Strength:

1. $|r| = 1$: perfect linear correlation.
2. $0.7 \leq |r| < 1.0$: strong correlation.
3. $0.3 \leq |r| < 0.7$: moderate correlation.
4. $0 < |r| < 0.3$: weak correlation.
5. $r = 0$: no linear correlation.

2.11.3 Confidence Interval and Fisher's Z-Transformation

Evaluating a confidence interval (CI) is essential for judging the stability and reliability of a correlation. This study uses a 95% confidence interval (95% CI); if the interval includes zero, the linear relationship is not statistically significant at the 95% level. Standard CI calculations assume that the data are normally distributed, but the Pearson coefficient r cannot be used directly because its values are bounded between -1 and $+1$, which produces a skewed, non-normal distribution. Fisher's Z-transformation converts r to an approximately normally distributed quantity:

$$z = \frac{1}{2} \ln\left(\frac{1+r}{1-r}\right) \quad (2.37)$$

where z is the transformed value of r . The 95% CI is then:

$$CI\ 95\% = \bar{x} \pm (1.96 \times \frac{SD}{\sqrt{n}}) \quad (2.38)$$

$$z_{CI95\%} = z \pm (1.96 \times SE) \quad (2.39)$$

where $\bar{x}$ is the sample mean, SD is the standard deviation, n is the sample size, and SE is the standard error.

In the present study, the Pearson correlation coefficient is used as a statistical benchmark for validating the Feature Importance results produced by the LSTM. By comparing the correlations between each internal-resistance parameter (R_o, R_s, R_{ct}, R_w) and SOH with the corresponding Feature Importance ranking, it is possible to determine whether the model's predictive accuracy reflects genuine learning of the underlying electrochemical behavior or merely a mathematical optimization that happens to fit the data. This benchmark plays an important role in the analysis of Phase 2 in Chapter 4.

Chapter 3

Research Methodology

This chapter describes the experimental and computational procedure used to produce, fit, and analyze the data on which the LSTM model is trained and evaluated. The procedure has three logical stages: (i) the experimental cycling and EIS protocol, which generates the raw impedance and capacity data; (ii) the ECM fitting pipeline, which converts the raw impedance spectra into the four physically meaningful resistance parameters (R_o, R_s, R_{ct}, R_w), and (iii) the LSTM modelling and diagnostic framework itself, which uses these parameters as inputs to predict SOH and to produce Feature Importance rankings.

3.1 Experimental Procedure

The experiments use five commercial 2000 mAh NMC lithium-ion pouch cells from A123 Systems, shown in Figure 3.1. All charge–discharge cycling and EIS measurements were performed on a Biologic VSP-3e Potentiostat/Galvanostat connected to a VMP3B current booster, as shown in Figure 3.2. Each cell was cycled at a current of 5 A (equivalent to a 2.5 C rate) under a standard Constant Current/Constant Voltage (CC–CV) protocol. Before each impedance measurement, the cell was rested for 30 minutes to allow full electrochemical relaxation. EIS was then performed from 10 kHz to 10 mHz, sampling 41 logarithmically spaced points using a four-probe configuration.



Figure 3.1 NMC lithium-ion pouch cell, 2000 mAh



Figure 3.2 Biologic VSP-3e Potentiostat/Galvanostat connected to VMP3B current booster

The 200-cycle test was deliberately divided into two phases: Phase 1 (cycles 1-100) and Phase 2 (cycles 101-200). Between Phase 1 and Phase 2, the cells were left at rest for 40 days due to the 5-cell iteration. The full experimental sequence is summarised in Table 3.1, and the operational workflow is shown in Figure 3.3.

Note on the phase division. The 40-day rest period was a practical consequence of the experimental timeline rather than a contrived perturbation: the first 100 cycles were collected initially to build a prototype LSTM model, and because each cell required 10 days of continuous testing to complete 100 cycles, a natural 40-day gap arose before the second phase could begin. The gap is nevertheless retained in the analysis because as Chapter 4 shows it provides a uniquely informative test of the model's ability to handle a discontinuity in the operating history.

Table 3.1 Experimental condition settings

State	Experimental Condition Setting		
	Control	Limits	T (°)
1	Rest time	5 min	25°C
2	EIS 10 mV from 10kHz to 10mHz	15 min	
3	Rest time	5 min	
4	CC-CV charge(I= 5 A,EM=4.2V, Im=1 mA)	3V to 4.2V	

Table 3.1 Experimental condition settings (Continued)

State	Experimental Condition Setting		
	Control	Limits	T (°)
5	Rest time	30 min	
6	EIS 10 mV from 10kHz to 10mHz	15 min	
7	Rest time	30 min	
8	CC-CV discharge ($I=5\text{ A}$, $E_M=4.2\text{ V}$, $I_m=1\text{ mA}$)	4.2V to 3V	

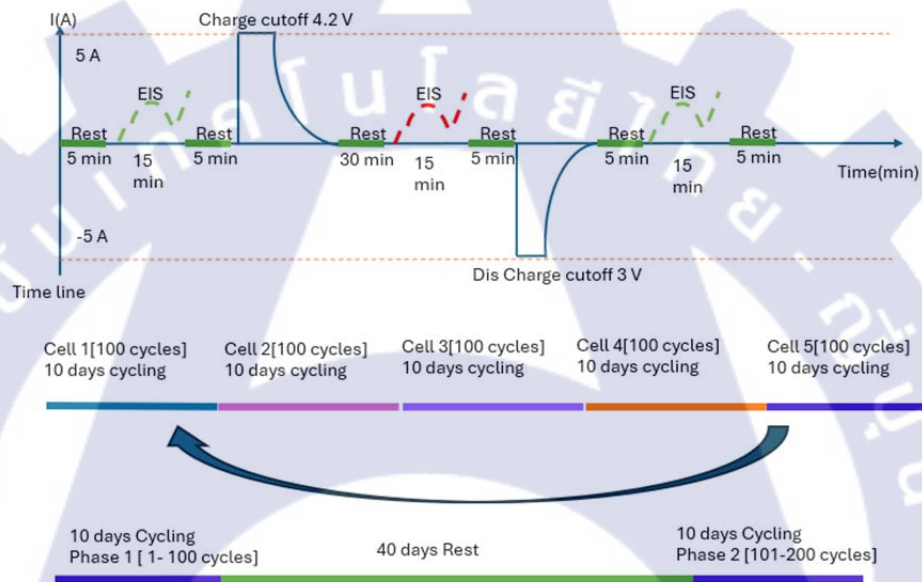


Figure 3.3 Experimental operational workflow

3.2 ECM Modeling

ECM fitting converts the raw impedance spectrum at each cycle into a set of four physically meaningful resistance parameters that serve as inputs to the LSTM. The fitting pipeline combines geometric pre-fitting (to constrain a difficult-to-fit parameter) with non-linear least-squares optimization and is summarized in five steps below.

3.2.1 Defining the ECM

Following the discussion of model topologies in Section 2.6, this study adopts the 2RC + Warburg-in-series model shown in Figure 3.4. The corresponding impedance is given by Equation (3.1).

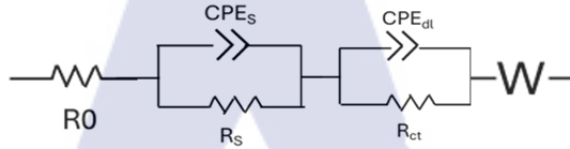


Figure 3.4 Experimental ECM (2RC + Warburg-in-series)

$$Z_{LIB(\omega)} = R_0 + \frac{R_s}{1 + R_s(j\omega)^{\alpha_s} Q_s} + \frac{R_{ct}}{1 + R_{ct}(j\omega)^{\alpha_{dl}} Q_{dl}} + \frac{R_w \coth \sqrt{j\omega\sigma}}{\sqrt{j\omega\sigma}} \quad (3.1)$$

3.2.2 Geometric Pre-fitting

The full ECM equation is highly non-linear and contains many coupled parameters, so a direct fit of all variables simultaneously is prone to convergence on local minima. To stabilise the fit, the algorithm first analyses the geometry of the Nyquist plot, as illustrated in Figure 3.5: it fits a circle to the high-to-mid frequency semicircle in the charge-transfer region. Reference [41] established that, when the State of Charge (SOC) is at a high (~90%) or low (~20%) extreme, the charge-transfer resistance R_{ct} is relatively large compared to the mid-SOC value. The depression angle of the fitted circle is then used to extract the double-layer CPE exponent α_{dl} directly:

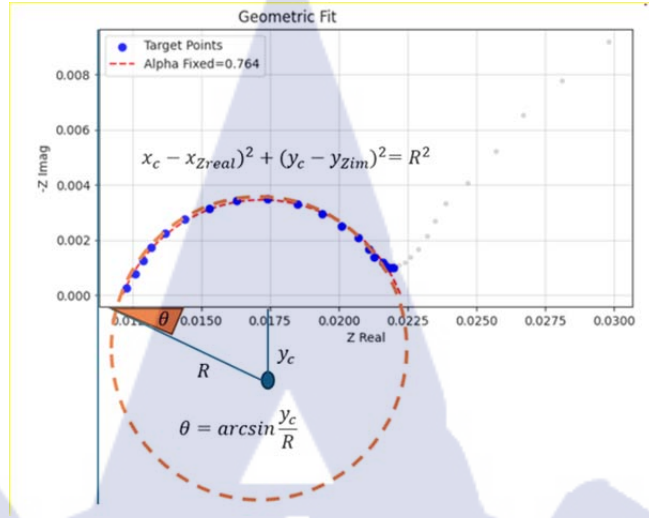


Figure 3.4 Geometric fit to extract the depression angle

$$\alpha_{dl} = 1 - \left(\frac{\theta}{90^\circ} \right) \quad (3.2)$$

Fixing α_{dl} at this pre-determined value substantially simplifies the remaining optimization problem and allows the algorithm to find the other parameters more quickly and more reliably.

3.2.3 Physical Bounds and Initial Guesses

To prevent the optimizer from converging on physically meaningless local minima, the algorithm follows the guidelines of [41]: initial guesses must lie within physically reasonable ranges for a lithium-ion battery, and parameters are constrained to physically valid bounds throughout. Two safety rules are applied.

- Absolute bounds. No parameter is permitted to be negative or zero; the absolute lower limit is 10^{-6} .
- Initial-guess ranges. Starting values are drawn at random from the following physically realistic ranges (eight free parameters):
 - R_0 (ohmic resistance): $[0.001, 0.2] \Omega$
 - R_s (SEI/film resistance): $[0.001, 0.1] \Omega$
 - Q_s (SEI pseudo-capacitance): $[10^{-4}, 10^{-1}]$

- αs (SEI roughness exponent): [0.6, 0.9]
- R_{ct} (charge-transfer resistance): [0.01, 0.5] Ω
- Q_{dl} (double-layer pseudo-capacitance): [10^{-4} , 10^{-1}]
- R_w (Warburg diffusion resistance): [0.01, 0.5] Ω
- σ (Warburg diffusion coefficient): [0.01, 1.0]

3.2.4 Optimization

With the bounds and initial guesses in place, a non-linear least-squares algorithm (`scipy.optimize.least_squares`) adjusts the free parameters to minimize the cost function the sum of squared residuals between the measured and modeled impedance. To make the fit robust to local minima, the entire random-guess + fit cycle is repeated five times for each spectrum, and the final parameter set is taken from the run that achieves the lowest cost. Each spectrum is also tested for KK-compliance using the Lin-KK procedure of Section 2.7 alongside the ECM fit. The full set of fitting and validation results is given in Appendix A.

3.2.5 Evaluation

The reliability of the extracted parameters is assessed by two standard metrics:

- RMSE measures the absolute error between modeled and measured impedance; a lower RMSE indicates a closer fit.
- R^2 measures the fraction of variance explained by the model; values close to 1 confirm that the ECM and its parameters faithfully capture the measured electrochemical behavior.

3.3 LSTM Modelling and Diagnostic Framework

The extracted resistance parameters are then used to train, test, and diagnostically interpret a Long Short-Term Memory model. The LSTM architecture is shown in Figure 3.6 and the many-to-one configuration used for SOH estimation is shown in Figure 3.7.

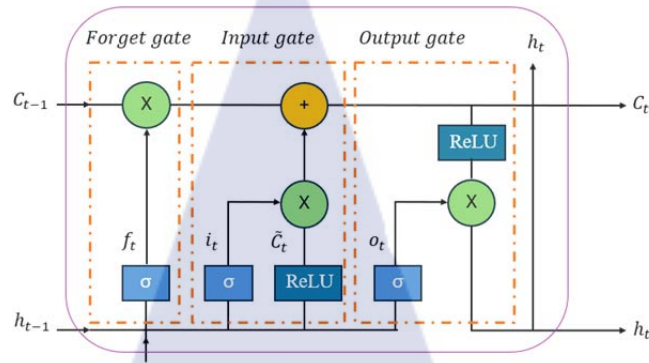


Figure 3.5 LSTM model architecture

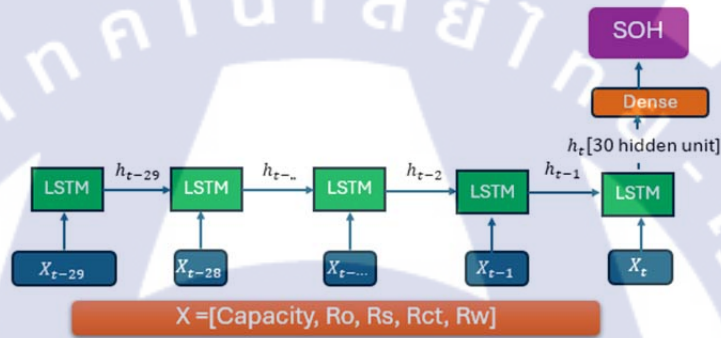


Figure 3.6 Many-to-one structure for SOH estimation

The network receives an input sequence spanning a 30-cycle window, from time step X_{t-29} to the current step x_t . At each time step, the input vector X contains five physical features: [Capacity, R_0 , R_s , R_{ct} , R_w]. A single LSTM layer of 30 units, with ReLU activation to mitigate the vanishing-gradient problem, processes the sequence; the hidden state h is propagated from one time step to the next, allowing the model to capture long-term degradation patterns. At the end of the 30-cycle sequence, the final cell outputs a hidden state vector h_t of 50 hidden units. This vector is passed through a Dropout layer with a rate of 0.5 (50%), which randomly deactivates half of the neurons during training, serving as a regularization step that distributes learning across parameters and helps prevent overfitting. The signal then passes through a final Dense layer with a single unit, which outputs the predicted capacity, which is then converted to SOH.

Optimization uses the Adam optimizer with a learning rate of 0.0005. This deliberately conservative rate (lower than the Adam default of 0.001) allows the model to converge more precisely toward the global minimum and helps avoid oscillations during training. The complete diagnostic framework is divided into three phases training, testing, and Feature Importance analysis and is illustrated in Figure 3.7.

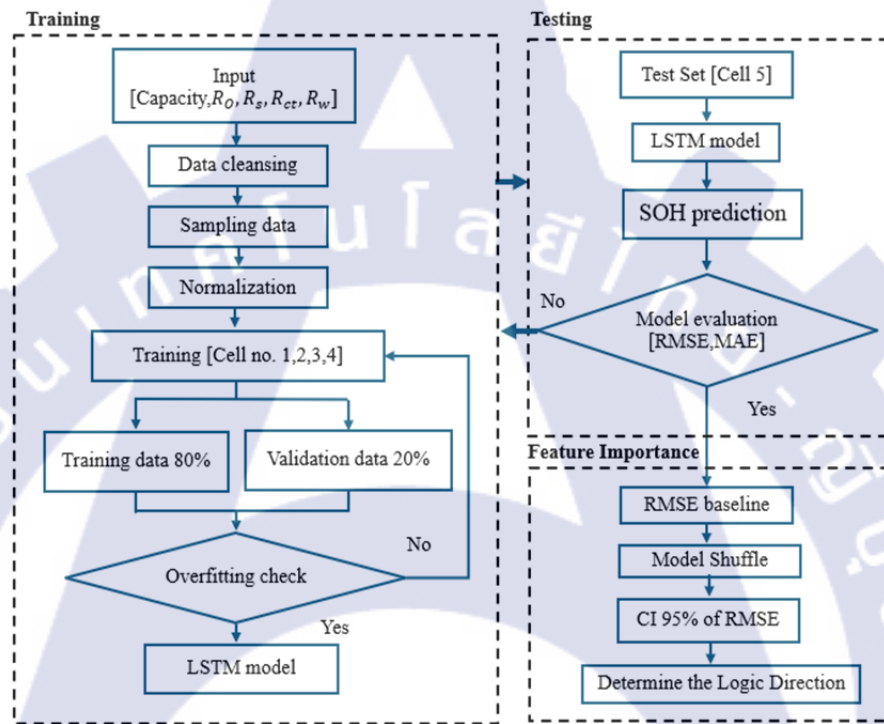


Figure 3.7 Flowchart of the LSTM modeling and Feature Importance framework

3.3.1 Model Training Phase

Training is performed on data from cells 1-4. The five input variables Capacity, R_0 , R_s , R_{ct} , and R_w are extracted from the ECM pipeline and processed in four steps:

1. Data cleansing and sampling. The raw input data are cleaned to remove measurement outliers and abnormalities. The cleaned data are then sampled into time-series sequences (a sliding window) so that the model can learn the temporal dependencies of degradation.

2. Normalisation. To prevent scaling disparities between variables and to avoid out-of-distribution (OOD) issues, all input features are scaled to a common range using Min–Max normalisation.

3. Training/validation split. The pre-processed data from cells 1–4 are split 80% for training and 20% for validation.

4. Overfitting check. During training, the validation loss is monitored continuously. If the validation error rises while the training error falls the classical signature of overfitting the training is adjusted accordingly through Early Stopping. Once the model passes the overfitting check and reaches optimal convergence, the final LSTM is established.

3.3.2 Model Testing Phase

The testing phase evaluates the generalisation capability of the trained model on completely unseen data the time series from a separate cell, Cell 5. The test data are fed into the LSTM, which produces SOH predictions, and accuracy is evaluated using RMSE and MAE.

A decision node then checks whether the testing errors fall within the acceptable threshold. If the criteria are not met, the framework loops back to the training phase to refine the architecture or hyperparameters; if the criteria are met, the framework proceeds to the diagnostic phase.

3.3.3 Feature Importance and Diagnostic Phase

To overcome the black-box character of neural networks and to extract physical meaning from the predictions, a Feature Importance procedure is applied to the validated model. The procedure has two parts: a permutation-based magnitude analysis with confidence intervals, and a perturbation-based directional analysis.

3.3.3.1 Magnitude Permutation with Confidence Intervals

The RMSE obtained in the testing phase is set as the baseline reference. The Permutation Feature Importance method then systematically shuffles the time sequence of one feature at a time, which temporarily destroys the relationship between that feature and the SOH target. To average out random noise, the shuffling is repeated for $K = 50$ independent iterations per feature, where the feature $x \in$

{Capacity, R_0 , R_s , R_{ct} , R_w }. The mean permuted RMSE E_x over the 50 iterations gives the magnitude of importance, and a 95% confidence interval around this mean is computed as:

$$CI_{95\%} = \bar{E}_x \pm (1.96 \times \frac{SD_x}{\sqrt{k}}) \quad (3.3)$$

where SD_x is the standard deviation of the RMSE across the 50 iterations. If this confidence interval lies significantly above the baseline RMSE, the model relies heavily on that feature for accurate prediction.

3.3.3.2 Direction Perturbation Method

The permutation procedure identifies the magnitude of a feature's importance but says nothing about its direction. To recover the sign whether an increase in the feature corresponds to an increase or decrease in SOH a perturbation procedure adds a small, controlled offset to the feature being evaluated. Specifically, the value of the feature is increased by 10% of its standard deviation:

$$x_{new} = x_{baseline} + (0.1 \times SD_x) \quad (3.4)$$

The perturbed dataset is fed back into the model to produce a new prediction, and the difference relative to the original prediction is computed:

$$\Delta \bar{y} = \bar{y}_{new} - \bar{y}_{baseline} \quad (3.5)$$

The direction is then read off straightforwardly:

- $\Delta y > 0$ (positive correlation): an increase in the feature leads to an increase in SOH.
- $\Delta y < 0$ (negative correlation): an increase in the feature leads to a decrease in SOH.

Together, the permutation magnitude and the perturbation direction give a two-dimensional Feature Importance description for each variable, which is compared in Chapter 4 against the Pearson correlation benchmark to test whether the LSTM's diagnostic logic agrees with the underlying physical evidence.



Chapter 4

Results and Discussion

This chapter presents the experimental and modeling results, organized to follow the framework set out in Chapter 3. Section 4.1 reports the capacity-fade behavior of the five test cells over 200 cycles. Section 4.2 then presents the per-cell ECM-derived resistance evolution alongside the SOH curves ("comprehensive degradation profiles"). Section 4.3 describes the LSTM model's training and its predictive performance on the unseen test cell, separately for Phase 1 and Phase 2. Section 4.4 compares the model's Feature Importance rankings against a Pearson correlation benchmark in each phase. Finally, Section 4.5 synthesizes these results into a discussion of the underlying degradation mechanism including the regime shift during the 40-day rest period and the LSTM's strengths and limitations as a diagnostic tool.

4.1 Experimental Results: Capacity Fade

Figure 4.1 shows the capacity-fade profiles of the five NMC cells over 200 cycles. The horizontal axis is cycle number; the vertical axis is measured capacity (mAh). Even though the five cells were drawn from the same production batch and prepared simultaneously, their degradation behaviors differ substantially.

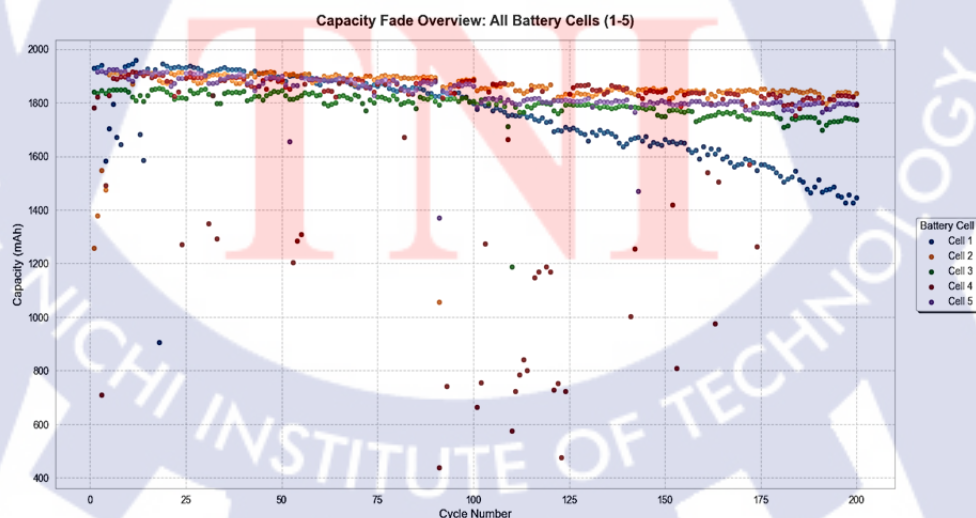


Figure 4.1 Capacity profile of five NMC cells over 200 cycles

Cells 2, 3, and 5 maintain a highly stable profile, with measurements clustered tightly between 1,800 and 1,900 mAh throughout the test. Cell 1 shows a clear, steady downward trend, indicating a gradual loss of capacity as cycling progresses. Cell 4 shows highly scattered and fluctuating data points, with measured capacity dropping randomly to as low as 400 mAh at various points; this is most likely the result of measurement anomalies during testing for example, a power outage rather than genuine capacity loss. The diversity across cells provides a richer training signal for the LSTM than a single homogeneous trajectory would.

4.2 EIS Measurement and Equivalent Circuit Modeling

ECM parameter extraction was implemented in Python using a non-linear least-squares algorithm. As anticipated in the methodology, the experimental ECM (Figure 3.4), in which the Warburg element Z_W is connected within the parallel charge-transfer branch ($C_{dl} \parallel (R_{ct} + Z_W)$), produces a strongly non-linear system in which R_{ct} , C_{dl} , and the Warburg term are mutually coupled a structural feature that the fitting algorithm has to handle explicitly.

Experimental Nyquist data, comprising real and imaginary impedance components, were imported from CSV files, and the ECM was defined according to Equation (3.1). To stabilize the fit and avoid local minima, the geometric semicircle fit described in Section 3.2.2 was first applied to the charge-transfer region; this estimated the depression angle and thus predetermined α_{dl} , the constant-phase-element exponent. The remaining parameters were then optimized by `scipy.optimize.least_squares`, minimizing the weighted sum of squared residuals between the measured and modeled impedance, subject to the physical bounds listed in Section 3.2.3 (resistances non-negative, CPE exponents between 0.4 and 1.0). The fit quality of every spectrum was evaluated by RMSE and R^2 ; the complete fitting and Lin-KK validation results are reported in Appendix A.

The extracted resistance parameters are then plotted alongside the SOH curve for each cell the "comprehensive degradation profile" to give a single, compact view of how each resistance component evolves with cycle number and with capacity loss. These per-cell profiles are presented next.

4.2.1 Comprehensive Degradation Profile of Cell 1

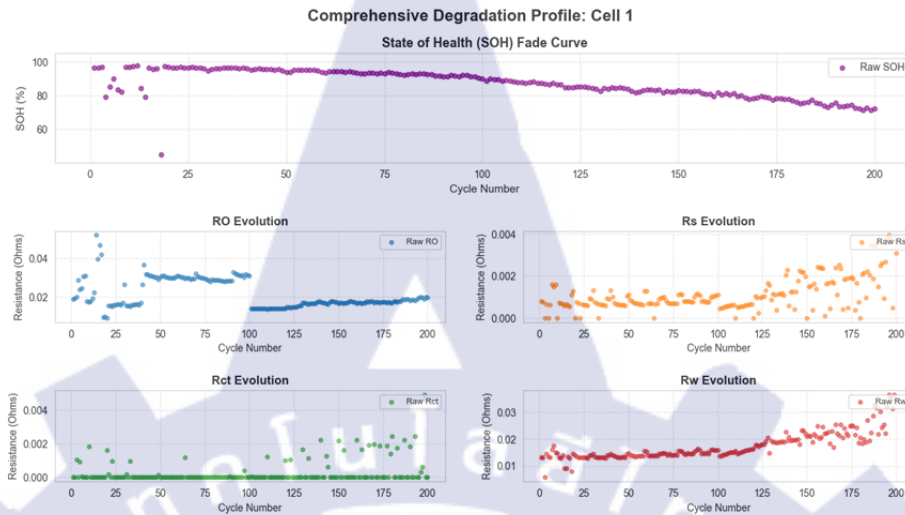


Figure 4.2 Comprehensive degradation profile of Cell 1

Figure 4.2 combines the SOH and resistance evolution of Cell 1 over 200 cycles. Cell 1 shows the clearest evidence of progressive degradation in the dataset. The SOH profile declines gradually during cycles 1–100, remaining above 90% despite several abnormal drops within the first 20 cycles; from cycle 101 onwards the capacity falls in a non-linear, accelerating fashion, dropping to approximately 70% by cycle 200. The ohmic resistance R_0 shows severe and irregular fluctuations during the first 100 cycles, reaching values as high as $\sim 0.05 \Omega$ before settling around 0.03Ω ; at cycle 101 it abruptly decreases to $\sim 0.015 \Omega$ and then rises gradually and approximately linearly to $\sim 0.02 \Omega$ by cycle 200. The surface-film resistance R_s and charge-transfer resistance R_{ct} remain very low (~ 0.000 – 0.001Ω) during the first 100 cycles but show a clear upward trend, with greater variance, during cycles 101–200. The diffusion resistance R_w is relatively stable at $\sim 0.015 \Omega$ during the first 100 cycles, but rises exponentially during cycles 101–200, exceeding 0.03Ω toward the end of the test.

4.2.2 Comprehensive Degradation Profile of Cell 2

Figure 4.3 shows that Cell 2 maintains a stable, approximately linear SOH decline, remaining above 90% over the full 200 cycles. All four resistance

components R_0 , R_s , R_{ct} , and R_w exhibit significant fluctuations and noise during the first 100 cycles but settle to consistent baseline values during cycles 101-200. R_0 and R_s remain highly stable through the second 100 cycles; the R_{ct} baseline rises slightly compared with the first phase; and R_w shows a gradual increase.

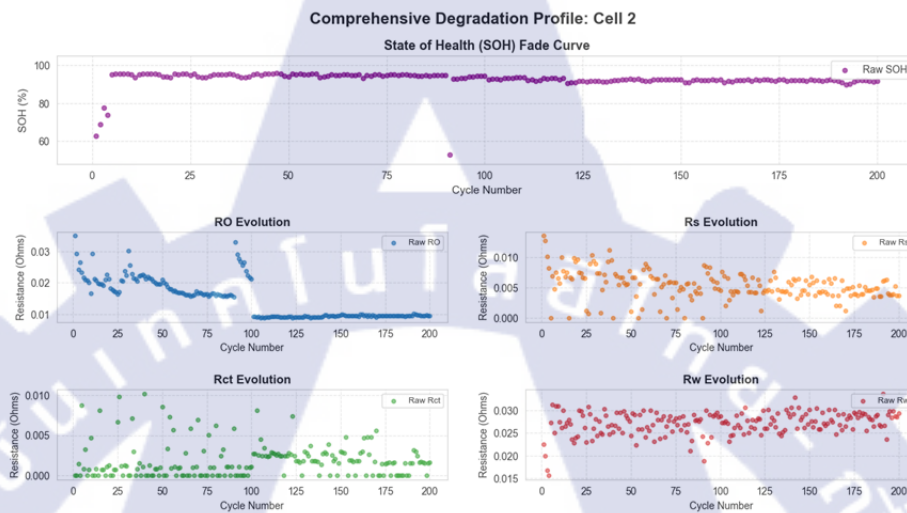


Figure 4.3 Comprehensive degradation profile of Cell 2

4.2.3 Comprehensive Degradation Profile of Cell 3

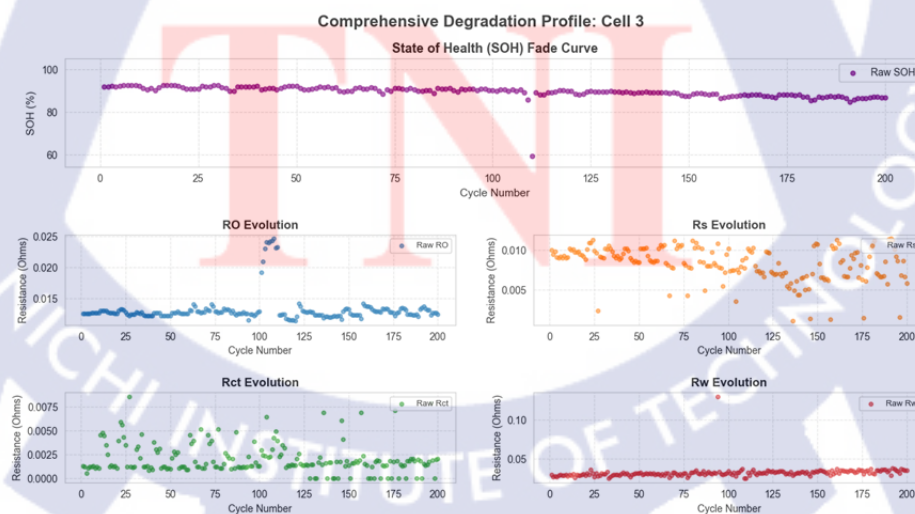


Figure 4.4 Comprehensive degradation profile of Cell 3

Figure 4.4 shows that Cell 3 exhibits the slowest and most stable degradation of the five cells, with a slow, linear SOH decline over the full 200 cycles. The ohmic resistance R_0 stays tightly clustered between ~ 0.012 and $\sim 0.014 \Omega$ throughout, except for a sudden spike to $\sim 0.024 \Omega$ at the start of cycle 101 after which it returns rapidly to baseline. The surface-film resistance R_s and charge-transfer resistance R_{ct} show some scatter but no significant upward drift. The Warburg diffusion resistance R_w is the most stable of all, holding an essentially horizontal line at $\sim 0.030 \Omega$ from the first cycle to the last with no exponential growth.

4.2.4 Comprehensive Degradation Profile of Cell 4

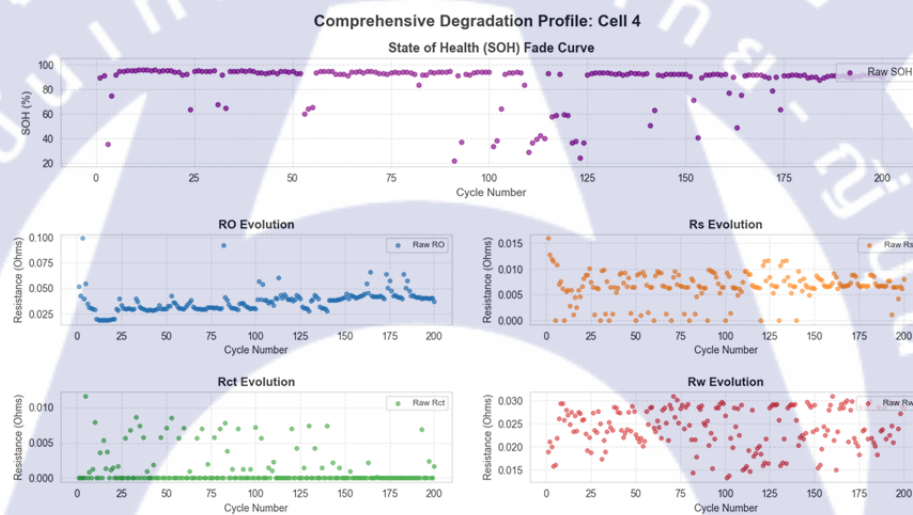


Figure 4.5 Comprehensive degradation profile of Cell 4

Figure 4.5 shows that Cell 4 is the noisiest of the five cells: every variable fluctuates and exhibits severe scatter throughout the 200 cycles. The SOH curve clusters around 90–95% but is interrupted by continuous random drops to between 20% and 80%. R_0 varies over a wide range, with an initial spike to $\sim 0.10 \Omega$ and irregular fluctuation between ~ 0.03 and $\sim 0.06 \Omega$ thereafter. R_s , R_{ct} , and R_w all exhibit significant scatter without forming a stable baseline; R_w , for example, fluctuates randomly between 0.015 and 0.030Ω from the first to the last cycle. The behavior of Cell 4 is consistent with the

measurement-anomaly interpretation given in Section 4.1 rather than with intrinsic capacity loss.

4.2.5 Comprehensive Degradation Profile of Cell 5

Cell 5 is the held-out test cell on which all subsequent LSTM evaluation is performed. Figure 4.6 shows the degradation profile of Cell 5. SOH decreases gradually during the first 100 cycles, then drops abruptly between cycles 100 and 101, and finally stabilizes at around 80% for the remaining 100 cycles. The ohmic resistance R_0 starts at $\sim 0.022 \Omega$, decreases and stabilizes at $0.012\text{--}0.013 \Omega$ during cycles 10–100, and then jumps back to $\sim 0.022 \Omega$ at cycle 101 before gradually decreasing again. The surface-film resistance R_s is distributed over the range $0.005\text{--}0.012 \Omega$ throughout. The charge-transfer resistance R_{ct} shows a baseline upward shift from $\sim 0.001 \Omega$ in the early cycles to $0.002\text{--}0.003 \Omega$ in the latter 100 cycles. The Warburg diffusion resistance R_w is the most stable variable in this cell, remaining essentially horizontal at $\sim 0.030 \Omega$ over the full 200 cycles. The abrupt step at cycle 101 both in capacity and in R_0 is the central observation that motivates the phase-by-phase analysis in the next sections.

Overall, the five detailed degradation profiles verify that, despite originating from the same manufacturing batch, the cells display notably different operational behaviors and degradation patterns illustrating the well-recognized cell-to-cell variation. This variability offers a diverse training signal for the LSTM. Sections 4.3 and 4.4 employ resistance time series from cells 1–4 for training the model and use the held-out series from cell 5 for testing.

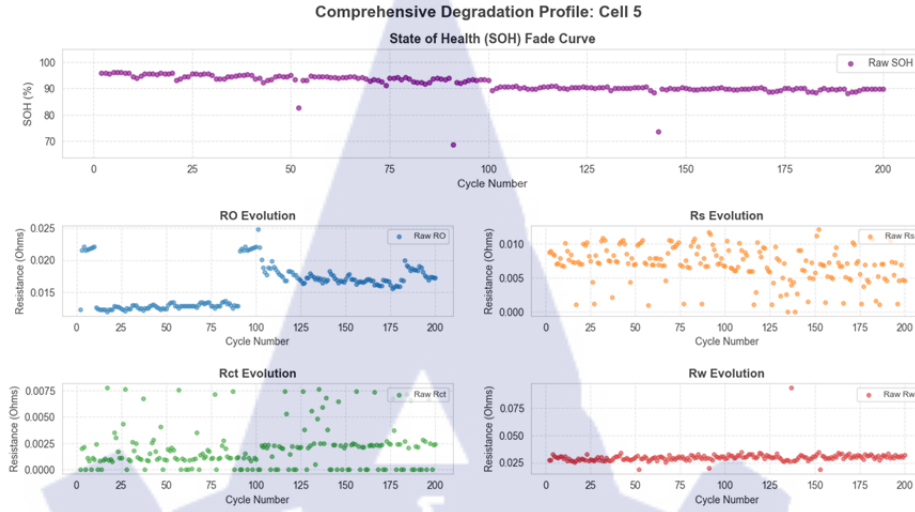


Figure 4.6 Comprehensive degradation profile of Cell 5+

4.3 LSTM Modeling

With the four resistance parameters extracted at each cycle for each cell, the next step is to train the LSTM to map the evolving resistance values to their corresponding SOH. The development proceeds in four stages: input data preparation, model architecture and hyperparameter selection, training convergence, and final prediction performance.

4.3.1 Sequential Data Preparation

Before training, the raw data were cleaned using hybrid logic, as illustrated in the data-cleaning inspection plot in Figure 4.7. Data points with SOH below the 80% threshold were classified as measurement abnormalities and removed, with one exception: an explicit exception zone was defined for Cell 1's final cycles, in order to preserve the deep-degradation behavior as a learning signal. The filtered dataset retains five input variables: Capacity, R_0 , R_s , R_{ct} , and R_w with Capacity included primarily as a navigational variable for the model. The series was then smoothed (window length 20) to suppress measurement noise, and structured into time-series sequences of length 30 so that the model could learn from the recent degradation history. Finally, all data were rescaled to $[0, 1]$ using a single global Min–Max scaler whose minimum and maximum values were derived from the combined dataset of cells 1-5. Using a single global scaler

rather than per-cell scalers prevents out-of-distribution issues when the model is later evaluated on a held-out cell.

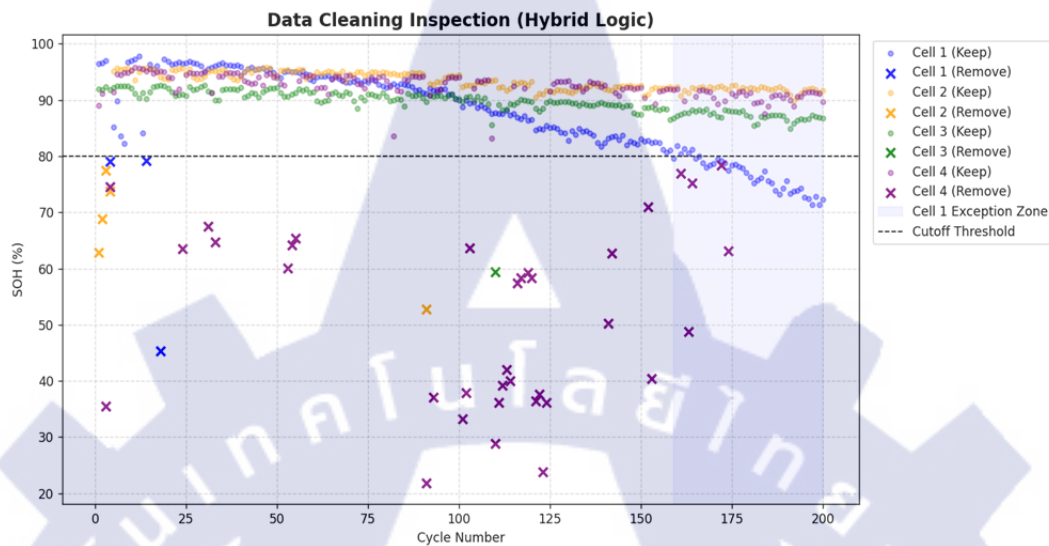


Figure 4.7 Data cleaning inspection

4.3.2 Model Architecture and Hyperparameters

Figure 4.8 illustrates the model architecture, which was deliberately matched to the dataset size. It combines established deep-learning best practices with empirically tuned hyperparameters specific to this battery dataset.

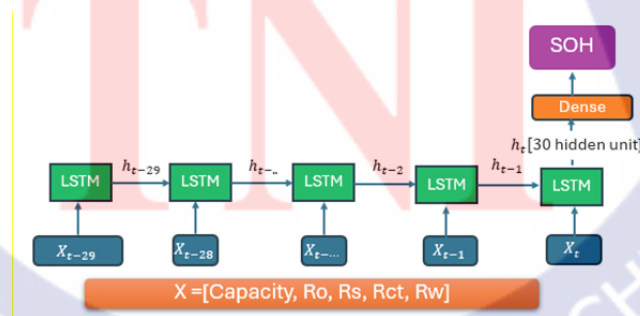


Figure 4.8 LSTM model architecture

Standard configurations were adopted for optimization and regularization. The Adam optimizer was selected for its proven effectiveness on noisy, non-stationary time-series data through adaptive moment estimation. The ReLU activation function mitigates the vanishing gradient problem. A Dropout layer with a rate of 0.5 follows the LSTM layer; this is a standard strong-regularization baseline and forces the network to learn distributed features rather than memorizing specific samples. A final Dense layer with a single unit outputs the predicted capacity.

While the optimizer and dropout rate followed standard best practice, the specific network capacity and three training hyperparameters were determined by systematic empirical tuning, monitoring training and validation loss trajectories. The chosen values, with rationale, are:

1. 30 hidden units. This LSTM layer size was empirically the best balance enough complexity to capture nonlinear degradation trends, but small enough to avoid overparameterization and overfitting on the limited dataset.
2. Learning rate 0.0005. The Adam default of 0.001 caused minor oscillations around the minimum; halving the learning rate to 0.0005 produced more precise convergence and avoided overshoot.
3. Batch size 16. The relatively small batch introduces a slight beneficial noise into the gradient updates, acts as a secondary regularization mechanism, and helps the optimizer escape local minima improving generalization to unseen cells.

4.3.3 Training Convergence and Loss Dynamics

The model was trained with a batch size of 16 for up to 100 epochs using mean squared error (MSE) loss. A 20% random validation split was used to monitor predictive capability during training, covering the overall battery behavior: the training set contained 572 samples, and the validation set 144 samples, as shown in Figure 4.9.

Early Stopping with patience = 15 epochs was applied to prevent overfitting: if the validation loss does not decrease for 15 consecutive epochs, training is halted and the model weights from the best-performing epoch are restored. From the learning curves as shown in Figure 4.9, the validation loss is consistently lower than or close to the training loss. This pattern reflects the effect of the Dropout layer Dropout is active during training but inactive during validation, so the validation pass effectively

benefits from a richer ensemble of neurons. The pattern indicates a healthy training dynamic and confirms that the architecture is robust and captures the degradation patterns without overfitting.

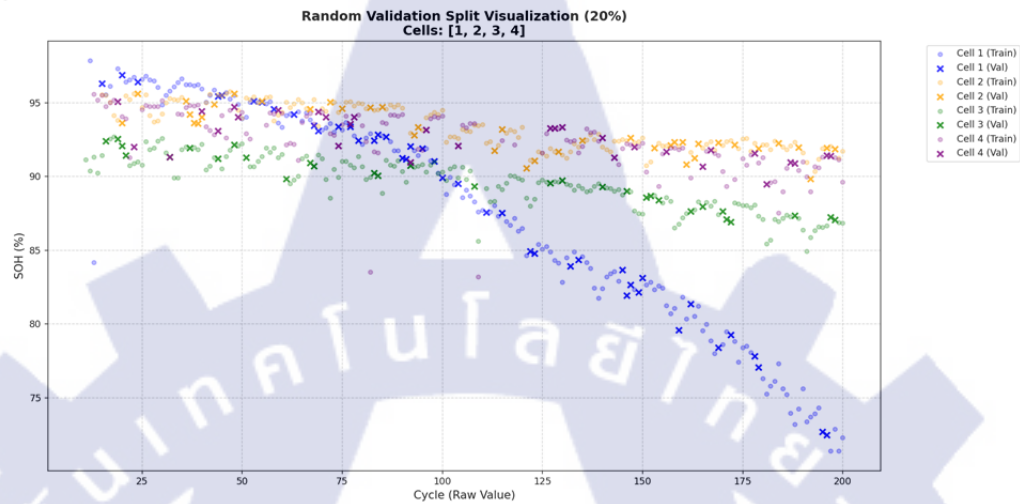


Figure 4.9 20% random validation split visualization

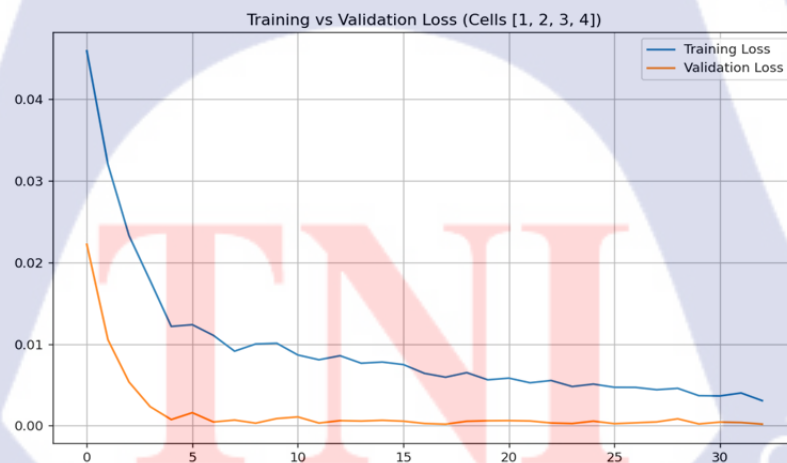


Figure 4.10 Training and validation loss curves

4.3.4 Model Prediction on Cell 5

The trained LSTM was loaded and applied to Cell 5, which it had not seen during training. The time-series input was fed into the model and SOH predictions were generated separately for the two phases. Splitting the evaluation by phase enables an independent comparison of prediction error (RMSE) before and after the 40-day rest and directly tests whether the LSTM's memory mechanism can absorb the abrupt change in the resistance scale between Phase 1 (cycles 1-100) and Phase 2 (cycles 101-200). The Feature Importance procedure in Section 3.3.3 is then applied to each phase separately, providing a complementary diagnostic view of which resistance components dominate the model's accuracy in each regime.

4.3.4.1 SOH Prediction in Phase 1 (Cycles 1-100)

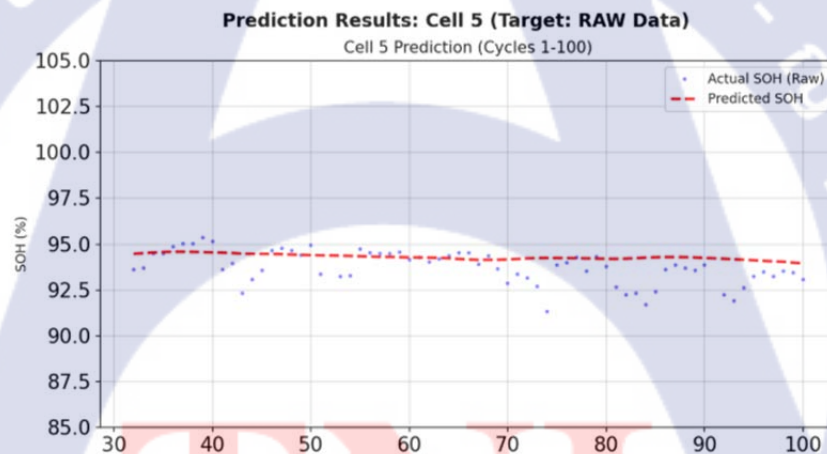


Figure 4.11 SOH prediction graph at cycles 1-100

Figure 4.11 compares the LSTM prediction (red dashed line) against the actual SOH measurements (blue points) for Cell 5 in Phase 1. The model reproduces a smooth degradation trend that closely follows the actual data. Statistical evaluation gives $MAE = 0.7473\%$, $RMSE = 0.9979\%$, and $R^2 = -0.2686$. The MAE and RMSE values, both below 1%, indicate strong predictive capability under normal operating conditions. The negative R^2 is discussed below.

4.3.4.2 SOH Prediction in Phase 2 (Cycles 101-200)

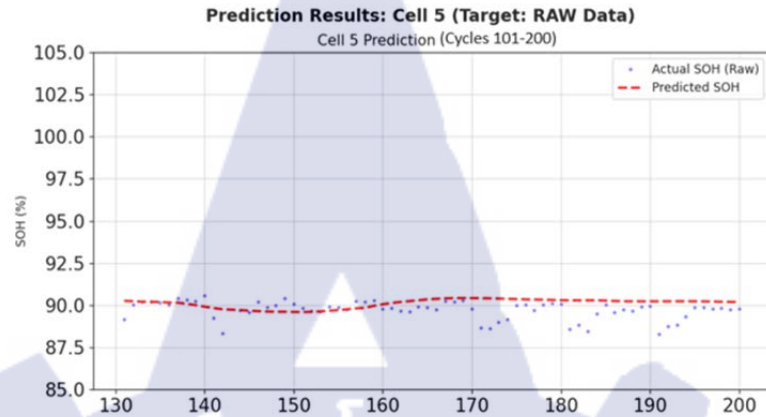


Figure 4.12 SOH prediction graph at cycles 101-200

Figure 4.12 shows the LSTM prediction for Phase 2, the post-rest period. Although the actual capacity shows slight fluctuations after the 40-day rest, the model still accurately captures the degradation trend. The evaluation gives MAE = 0.5526%, RMSE = 0.7471%, and $R^2 = -0.9722$. The model therefore adapts to the new behavior of the cell in this phase, with even lower error than in Phase 1.

4.3.4.3 Note on the Negative R^2 Values

The two phases give RMSE values of 0.9979% and 0.7471% both excellent but negative R^2 values (-0.2686 and -0.9722). A negative R^2 occurs when the residual sum of squares (SS_{res}) exceeds the total sum of squares (SS_{tot}), which is a known mathematical artefact when evaluating time-series data with extremely low variance. As Figure 4.8 shows, the SOH of Cell 5 fluctuates within only a 1-2% band over each 100-cycle phase, which drives SS_{tot} toward zero and amplifies any residual into a strongly negative R^2 . The negative R^2 in this specific case therefore does not indicate poor model performance but rather reflects the metric's hypersensitivity to low-variance datasets. The RMSE and MAE values, both below 1%, remain the primary and most reliable indicators of accuracy here. R^2 is not a suitable evaluation metric when the SOH range is narrow and degradation is shallow.

4.3.5 Feature Importance and Correlation Direction

To probe the model's internal decision-making, Feature Importance was evaluated using the permutation method described in Section 3.3.3, with the perturbation method providing the direction of each feature's effect.

4.3.5.1 Feature Importance in Phase 1

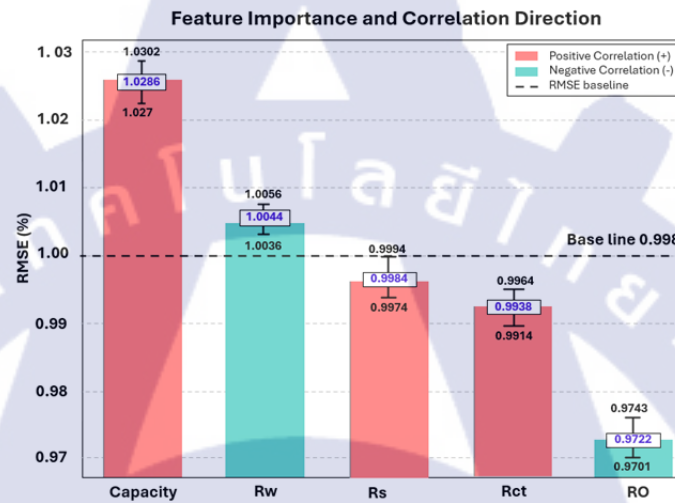


Figure 4.13 Feature Importance diagnosis at cycles 1-100

Figure 4.13 shows the per-feature Feature Importance for Phase 1. The horizontal dashed line represents the baseline RMSE of 0.998%; each bar shows the mean RMSE after perturbation of one feature, with 95% CI error bars; bar color encodes the direction of correlation (red = positive, cyan = negative).

Capacity has the largest effect on model accuracy: perturbing it raises the RMSE significantly above the baseline to 1.0286%, with a positive correlation. The next-largest effect comes from the diffusion resistance R_w , which increases RMSE to 1.0044% and shows a negative correlation. The surface-film resistance R_s is essentially at the baseline (0.9984%, positive correlation). The charge-transfer resistance R_{ct} (0.9938%, positive correlation) and the ohmic resistance R_o (0.9722%, negative correlation; the largest decrease in the set) both fall below the baseline upon perturbation.

4.3.5.2 Feature Importance in Phase 2

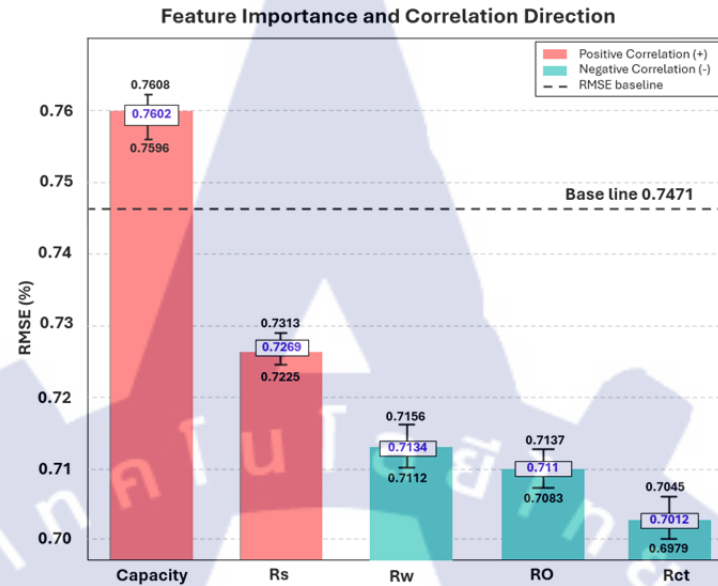


Figure 4.14 Feature Importance diagnosis at cycles 101-200

Figure 4.14 shows the equivalent Feature Importance analysis for Phase 2 (baseline RMSE 0.7471%). Capacity remains the most influential variable with a positive effect: perturbing it raises RMSE to 0.7602%. Crucially, however, none of the resistance variables now raises RMSE above the baseline; perturbing any of them lowers the error. The ranking by direction is also different: Rs has a positive influence at 0.7269%, followed by Rw (0.7134%) and R_0 (0.7110%) with negative correlations, and Rct produces the largest decrease, to 0.7012%, with a direction that has now flipped to negative.

These results indicate a clear shift in the model's decision-making logic between the two phases. Whether this internal shift correctly reflects the physical reality of the post-rest cell or whether it is an artefact of the model adapting mathematically to a discontinuity it cannot interpret physically is the question addressed in Section 4.4 by direct comparison against the Pearson correlation benchmark.

4.4 Comparison with Pearson Correlation

The diagnostic claim made by a Feature Importance ranking is only as trustworthy as the model that produced it. To test whether the LSTM's internal logic aligns with the data's actual statistical structure, the linear relationship between each resistance parameter (R_0 , R_s , R_{ct} , R_w) and SOH was quantified independently for each phase using the Pearson correlation coefficient r .

4.4.1 Pearson Correlation in Phase 1

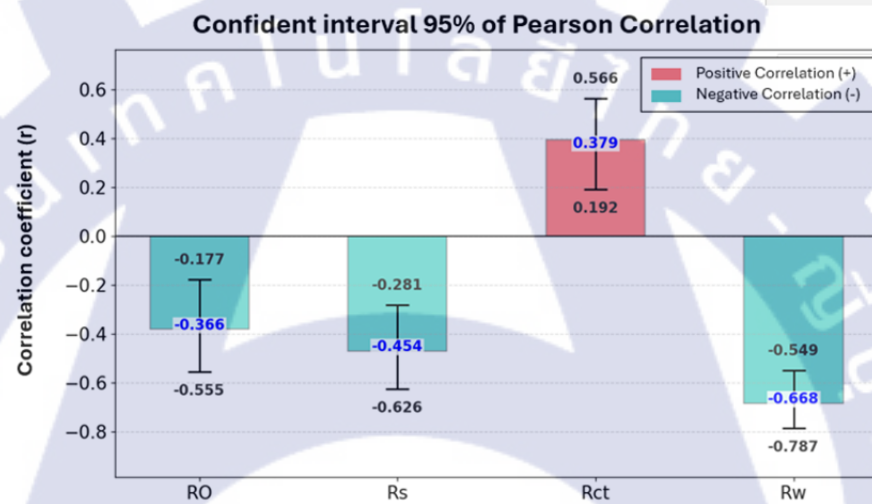


Figure 4.15 Pearson correlation of resistance with SOH at cycles 1-100

Figure 4.15 shows the mean correlation coefficients with 95% CI error bars for Phase 1; cyan bars indicate negative correlation (resistance up $\rightarrow$ SOH down), red bars indicate positive correlation. The diffusion resistance R_w shows the strongest negative correlation with SOH (mean $r = -0.668$, 95% CI $[-0.787, -0.549]$). It is followed by R_s ($r = -0.454$) and R_0 ($r = -0.366$), both also negative. The charge-transfer resistance R_{ct} shows a moderate positive correlation ($r = +0.379$, 95% CI $[+0.192, +0.566]$), which is plausibly attributable to transient relaxation effects during the early stages of operation.

These statistical findings reinforce the LSTM's Feature Importance result for Phase 1: both the model and the independent statistical benchmark identify R_w as the resistance parameter most strongly associated with capacity degradation in this phase. Under continuous operation, the LSTM's internal logic therefore tracks the physical reality faithfully.

4.4.2 Pearson Correlation in Phase 2

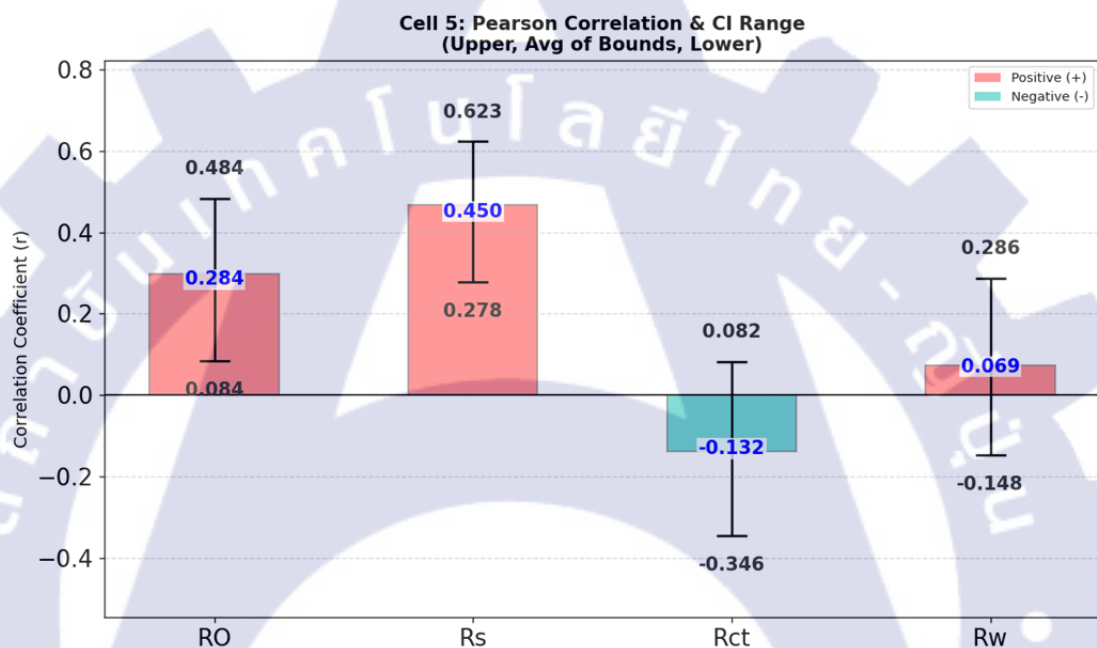


Figure 4.16 Pearson correlation of resistance with SOH at cycles 101-200

Figure 4.16 shows the same analysis applied to Phase 2 (cycles 101-200). The results reveal a substantial change in the correlation structure, summarised below.

- R_s and R_0 re-emerge as the dominant variables, both now with positive linear relationships. The mean r for R_s is +0.450 (95% CI [+0.278, +0.623]); for R_0 , +0.284 (95% CI [+0.084, +0.484]).
- R_{ct} and R_w lose their previous correlations almost entirely. R_{ct} shifts to a weak negative correlation ($r = -0.132$); R_w becomes a very weak positive correlation ($r = +0.069$). The 95% CIs of both R_{ct} [-0.346, +0.082] and R_w [-0.148, +0.286] cross

zero, indicating that neither variable has a statistically significant linear relationship with SOH in this phase.

The Pearson analysis therefore identifies a regime shift across the 40-day rest: the dominant physical indicator changes from R_w (in Phase 1) to R_s and R_0 (in Phase 2). Crucially, the LSTM's Feature Importance in Phase 2 does not match this shift. The model continues to rely most heavily on the historical capacity trace and does not promote R_s and R_0 to the top of its diagnostic ranking. This divergence between the two analyses is the central diagnostic finding of the thesis and is interpreted physically in the next section.

4.5 Degradation Mechanism and Diagnostic Interpretation

This section synthesizes the cycling and resistance evidence into a coherent physical interpretation of the degradation mechanism and then evaluates the LSTM's diagnostic behavior against that interpretation. A schematic summarizing the regime shift and its location in the capacity-fade trace is shown in Figure 4.17. The discussion that follows draws together the comprehensive degradation profile of Cell 5 (Section 4.2.5), the Pearson correlations (Section 4.4), and the schematic relationship between mechanism and resistance (Figure 2.6).

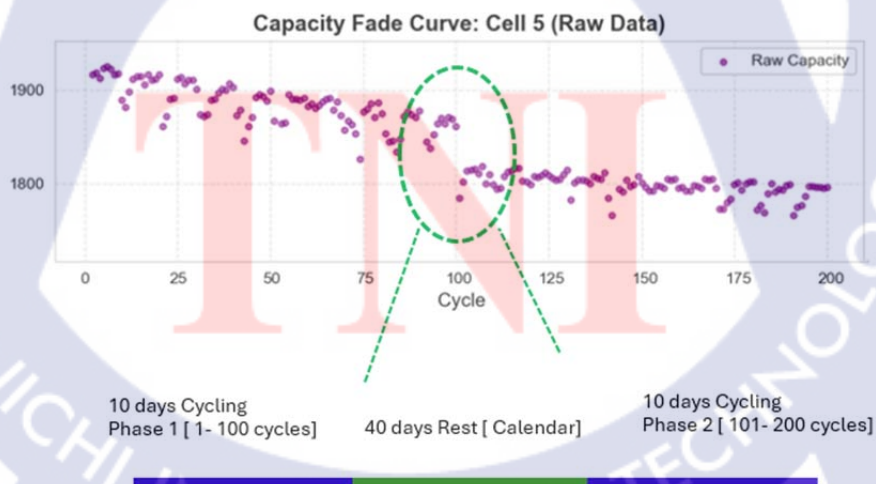


Figure 4.17 Regime shift from cycling aging to calendar aging across the 40-day rest period; the circle indicates the capacity-fade range

4.5.1 Phase 1 Cycling Aging Driven by Diffusion-pathway Changes and SEI Growth

During the first 100 cycles, the dominant degradation mechanism is cycling aging driven by changes in diffusion pathways and surface-film growth. The Pearson analysis directly supports this interpretation: the strong negative correlations between R_w ($r = -0.668$) and R_s ($r = -0.454$) and SOH indicate that the gradual capacity fade in this phase is consistent with progressive obstruction of lithium-ion transport pathways and steady thickening of the SEI layer. The moderate positive correlation of R_{ct} ($r = +0.379$) reflects an activation phase, in which continued electrolyte penetration into the porous electrode structure improves charge-transfer efficiency at the interface even as the overall capacity slowly declines.

4.5.2 Phase 2 Regime Shift Across the 40-Day Rest

After the 40-day rest period, the dominant mechanism shifts from cycling aging to calendar aging. Three candidate causes can be considered for the abrupt capacity drop observed at cycle 101 in Figure 4.17; the evidence rules out two and supports the third.

- SEI growth unlikely. SEI growth typically occurs when a cell is rested at high SOC, but the present cells were rested in a fully discharged state (0% SOC). The R_s trace in Figure 4.8 confirms that no significant SEI growth occurred thereafter.
- Oxygen release and corrosion unlikely. This chemical breakdown pathway is active only at high voltages (near 4.5 V), which the resting cell did not experience.
- Inhomogeneous reaction distribution most likely. The high 2.5 C cycling rate caused the reaction to be distributed unevenly within each electrode, with the outer regions overworked while the inner regions remained underutilized. Even after 40 days at rest, this uneven state evidently did not redistribute, and the locked-in inhomogeneity permanently reduced the cell's usable capacity.

Two further phenomena in Phase 2 deserve specific mention. First, the sudden increase in R_0 at the start of the phase is most plausibly attributed to measurement errors specifically, contact resistance at the interface between the measurement setup and the cell after reinstallation of the cell rather than to intrinsic degradation. Second, and

more importantly, the correlation structure undergoes a complete regime shift. The correlation between R_w and SOH is statistically negligible ($r = +0.069$), indicating that the primary electrode structure has not undergone severe cracking or collapse. At the same time, the correlation of R_s flips from negative to positive ($r = +0.450$), indicating that capacity loss in this phase is no longer driven by SEI growth in the conventional sense. This later-stage degradation is therefore decoupled from the physical changes captured by the resistance variables, which reinforces the conclusion that the dominant cause of the abrupt capacity drop and its subsequent slow drift is the loss of lithium inventory (LLI) during the 40-day rest.

4.5.3 Phase 1 LSTM Diagnostic Behavior

Within the continuously cycled Phase 1, the LSTM accurately captures the dominant degradation factors. Its Feature Importance identifies the Warburg diffusion resistance R_w as the most influential resistance variable, consistent with the Pearson correlation result indicating that R_w has the strongest negative correlation with SOH ($r = -0.668$). Under continuous data conditions, the model therefore captures the genuine electrochemical behaviour of the battery, not just a statistical surface fit.

4.5.4 Phase 2 LSTM Diagnostic Behaviour

In Phase 2, however, the LSTM and the Pearson benchmark disagree, and that disagreement is the diagnostically important result of the thesis. The Pearson analysis identifies a complete shift in the correlation structure: the dominant relationships move to R_0 and R_s , while the correlation of R_w weakens to the point that its 95% CI crosses zero. The LSTM produces a lower prediction error than in Phase 1 (RMSE drops to 0.7471%), so on accuracy alone the model would be judged successful. But its diagnostic interpretation contradicts the physical evidence: the model correctly down-weights R_w , but it does not promote R_0 and R_s to the dominant positions that the statistical analysis demands, and instead shifts most of its predictive weight onto the historical capacity trace itself. Moreover, perturbing any of the resistance variables in this phase reduces the RMSE below the baseline a pattern that, from a machine-learning perspective, indicates that the model is treating these variables as noise rather than as informative inputs.

The combined picture is that the LSTM remains a strong forecaster across the discontinuity, but its diagnostic logic becomes unreliable. Predictive accuracy and physical interpretability come apart in Phase 2, which is exactly the failure mode that the regime-shift experiment was designed to expose.



Chapter 5

Conclusion and Future Work

5.1 Conclusion

This thesis investigated the use of a Long Short-Term Memory (LSTM) neural network to estimate the State of Health (SOH) of NMC lithium-ion batteries and, equally importantly, evaluated the network's ability to identify the physical relationships that drive battery degradation. The study integrated Electrochemical Impedance Spectroscopy (EIS) with an Equivalent Circuit Model (ECM) so that the LSTM's input features the four internal-resistance parameters R_0 , R_s , R_{ct} , and R_w carry direct physical meaning rather than being purely abstract statistical predictors.

Under continuous cycling (Phase 1: cycles 1–100), the LSTM both predicted SOH accurately and correctly identified the dominant physical indicator of degradation. Its Feature Importance ranking placed the Warburg diffusion resistance R_w at the top, in full agreement with the independent Pearson correlation benchmark, which also identified R_w as the variable most strongly (negatively) correlated with SOH during this phase. Under continuous operation, accuracy and interpretability therefore align.

After the 40-day rest period (Phase 2: cycles 101–200), the picture changes. The Pearson analysis revealed a complete regime shift: the directions of R_0 and R_s flipped to positive correlations with SOH, while the correlations of R_{ct} and R_w weakened to the point that their confidence intervals crossed zero. Despite this severe disruption of the underlying physical and linear relationships, the LSTM did not fail. Instead, it adapted mathematically: rather than re-prioritising the resistance variables, it shifted its predictive weight onto the historical capacity trace and continued to produce low-error SOH predictions (RMSE = 0.7471%). The model preserved its forecasting accuracy, but its ability to diagnose which specific resistance parameters were responsible for the degradation became unreliable.

The overall finding is therefore twofold. First, the proposed hybrid EIS–ECM–LSTM framework is a highly accurate tool for time-series SOH forecasting, and under stable continuous operation it also identifies the dominant physical drivers of degradation faithfully. Second, that diagnostic capability is not unconditional: when the operating

history contains a discontinuity such as a long rest period, the LSTM can maintain predictive accuracy by leaning on the capacity trace and effectively bypass the resistance features it was designed to interpret. Predictive accuracy and physical interpretability are therefore separable properties of these models, and the second property is the one that becomes fragile under operational discontinuities.

5.2 Limitations and Future Work

While the proposed framework demonstrates high accuracy, several limitations remain that point to specific avenues for future research before deployment in a real Battery Management System.

1. Data initialization latency. The LSTM requires a continuous historical window here, 30 cycles to capture temporal dependencies. It cannot generate an SOH prediction immediately after system start-up or after a memory reset. Future work should integrate a hybrid baseline estimator (e.g., a simple model-based estimator) to provide preliminary predictions while the LSTM accumulates the necessary history.

2. Validation under discontinuous operation. This study evaluated model adaptability using a single 40-day rest period. Real electric-vehicle usage is far more erratic, with frequent rests of varying length. Future experiments should incorporate multiple rest intervals randomized in both length and timing to test the model's robustness and diagnostic limits under more realistic conditions.

3. Deep degradation analysis. Testing was limited to the first 200 cycles, which represent only the early-life region of the battery. The severe degradation mechanisms that appear nearer the end of life significant particle fracture, large losses of active material were not yet pronounced in this dataset. Future work should extend testing to the End-of-Life threshold (70-80% SOH) to verify whether the LSTM maintains both predictive accuracy and physical interpretability as degradation progresses.

Addressing these three issues would convert the present framework from a promising laboratory result into a candidate deployable component of an in-vehicle Battery Management System.



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Appendices

TNI

Appendix A.

**Python Code for Equivalent Circuit Model Parameter Extraction
and Linear-Kramar Kronig testing**

Python Code for Equivalent Circuit Model Parameter Extraction

```

import numpy as np
from scipy.optimize import least_squares

def Z_model(params, omega):
    """
    Calculates the impedance of the 2RC + Warburg Equivalent Circuit Model.
    params: [R0, Rs, Qs, alpha_s, Rct, Qdl, alpha_dl, Rw, delta]
    omega: angular frequency (2 * pi * f)
    R0, Rs, Qs, alpha_s, Rct, Qdl, alpha_dl, Rw, delta = params
    # 1. Solid Electrolyte Interphase (SEI) Layer
    Z_cpe_s = 1 / (Qs * (1j * omega) ** alpha_s)
    Z_s = 1 / (1 / Rs + 1 / Z_cpe_s)
    # 2. Charge Transfer & Double Layer Capacitance
    Z_cpe_dl = 1 / (Qdl * (1j * omega) ** alpha_dl)
    Z_dl = 1 / (1 / Rct + 1 / Z_cpe_dl)
    # 3. Warburg Diffusion Element
    arg = delta * np.sqrt(1j * omega)
    tanh_val = np.tanh(arg)
    denom = np.where(np.abs(arg) < 1e-10, 1e-10, arg) # Prevent division by zero
    Z_w = Rw * (tanh_val / denom)
    # Total Impedance
    return R0 + Z_s + Z_dl + Z_w

def residuals_constrained(params_opt, omega, Z_meas, alpha_dl_fixed):
    """
    Calculates the weighted residuals for Least Squares optimization.
    R0, Rs, Qs, alpha_s, Rct, Qdl, Rw, delta = params_opt
    full_params = [R0, Rs, Qs, alpha_s, Rct, Qdl, alpha_dl_fixed, Rw, delta]
    Z_fit = Z_model(full_params, omega)
    weight = 1 / (np.abs(Z_meas) + 1e-6)
    res_real = weight * (Z_fit.real - Z_meas.real)
    res_imag = weight * (Z_fit.imag - Z_meas.imag)
    return np.concatenate([res_real, res_imag])

```

```
def extract_ecm_parameters(freq_array, Z_real_array, Z_imag_array,
alpha_dl_fixed):
```

Executes the Non-Linear Least Squares optimization to extract internal resistance.

```
omega = 2 * np.pi * freq_array
```

```
Z_meas = Z_real_array - 1j * np.abs(Z_imag_array)
```

```
# Absolute Bounds: [R0, Rs, Qs, alpha_s, Rct, Qdl, Rw, delta]
```

```
lower_bounds = [1e-6, 1e-6, 1e-6, 0.4, 1e-6, 1e-6, 1e-6, 1e-6]
```

```
upper_bounds = [1, 1, 10, 1.0, 1, 10, 1, 10]
```

```
best_res = None
```

```
best_cost = np.inf
```

```
# Run optimization 5 times with random initial guesses to avoid Local Minima
```

```
for _ in range(5):
```

```
    initial_guess = [
```

```
        np.random.uniform(0.001, 0.2), # R0
```

```
        np.random.uniform(0.001, 0.1), # Rs
```

```
        np.random.uniform(1e-4, 1e-1), # Qs
```

```
        np.random.uniform(0.6, 0.9), # alpha_s
```

```
        np.random.uniform(0.01, 0.5), # Rct
```

```
        np.random.uniform(1e-4, 1e-1), # Qdl
```

```
        np.random.uniform(0.01, 0.5), # Rw
```

```
        np.random.uniform(0.01, 1.0) # delta
```

```
    ]
```

```
    try:
```

```
        res = least_squares(
```

```
            residuals_constrained,
```

```
            initial_guess,
```

```
            bounds=(lower_bounds, upper_bounds),
```

```
            args=(omega, Z_meas, alpha_dl_fixed)
```

```
        )
```

```
        if res.cost < best_cost:
```

```
            best_cost = res.cost
```

```
            best_res = res
```

```
except Exception:
    continue
if best_res is not None:
    p = best_res.x
    return {
        "R0": p[0], "Rs": p[1], "Qs": p[2], "alpha_s": p[3],
        "Rct": p[4], "Qdl": p[5], "alpha_dl": alpha_dl_fixed,
        "Rw": p[6], "delta": p[7]
    }
return None
```



Python Code for Linear-Kramar Kronig testing

```

import numpy as np
from scipy.optimize import least_squares
def Lin_KK_model(params, omega):
    Generalized Equivalent Circuit Model (ECM) used specifically to test
    Kramers-Kronig compliance. It serves as a mathematical construct to check
    if the data is linear, causal, and time-invariant.
    R0, Rs, Qs, alpha_s, Rct, Qdl, alpha_dl, Rw, delta = params
    Z_ohm = R0
    Z_s = 1 / (1 / Rs + Qs * (1j * omega) ** alpha_s)
    Z_dl = 1 / (1 / Rct + Qdl * (1j * omega) ** alpha_dl)
    Z_w = Rw * (np.tanh(delta * np.sqrt(1j * omega)) / (delta * np.sqrt(1j * omega)))
    return Z_ohm + Z_s + Z_dl + Z_w
def kk_residuals(params, omega, Z_meas):
    Calculates the weighted residuals between measured impedance and the Lin-KK
    model.
    Z_fit = Lin_KK_model(params, omega)
    weight = 1 / (np.abs(Z_meas) + 1e-6)
    # Return flattened array of weighted Real and Imaginary residuals
    return np.concatenate([
        weight * (Z_fit.real - Z_meas.real),
        weight * (Z_fit.imag - Z_meas.imag)
    ])
def validate_lin_kk(freq_array, Z_real_array, Z_imag_array):
    Performs the Lin-KK validation on a single impedance spectrum.
    Returns the fit parameters, relative residual percentages, and RMSE.
    omega = 2 * np.pi * freq_array
    Z_meas = Z_real_array - 1j * np.abs(Z_imag_array)
    # Mathematical Constraints to ensure physical plausibility
    # [R0, Rs, Qs, alpha_s, Rct, Qdl, alpha_dl, Rw, delta]
    lower_bounds = [1e-6, 1e-6, 1e-6, 0.4, 1e-6, 1e-6, 0.4, 1e-6, 1e-6]

```



```

upper_bounds = [1, 1, 10, 1.0, 1, 10, 1.0, 1, 10]
best_res = None
best_cost = np.inf
# Multi-start optimization to avoid local minima
for _ in range(5):
    initial_guess = [np.random.uniform(l, u) for l, u in zip(lower_bounds,
upper_bounds)]
    try:
        res = least_squares(
            kk_residuals,
            initial_guess,
            bounds=(lower_bounds, upper_bounds),
            args=(omega, Z_meas)
        )
        if res.cost < best_cost:
            best_cost = res.cost
            best_res = res
    except Exception:
        continue
if best_res is not None:
    p_opt = best_res.x
    Z_fit = Lin_KK_model(p_opt, omega)
    # Calculate Relative Residuals (%) for validity checking
    res_re_pct = 100 * (Z_real_array - Z_fit.real) / np.abs(Z_meas)
    res_im_pct = 100 * (-np.abs(Z_imag_array) - Z_fit.imag) / np.abs(Z_meas)
    # Calculate Root Mean Square Error (RMSE)
    rmse = np.sqrt(np.mean(np.abs(Z_meas - Z_fit) ** 2))
    return {
        "Valid": True,
        "Parameters": p_opt,
        "Real_Residuals_Pct": res_re_pct,
        "Imaginary_Residuals_Pct": res_im_pct,

```

```
    "RMSE": rmse  
  }  
  else:  
    return {"Valid": False}
```



The background of the page features a large, light blue watermark logo of the Thai-Nichi Institute of Technology (TNI). The logo is circular with a gear-like outer edge. Inside the circle, the text "THAI-NICHI INSTITUTE OF TECHNOLOGY" is written in a circular path. In the center of the logo, the letters "TNI" are prominently displayed in a large, red, serif font.

Appendix B.

Python Code for LSTM Modeling (Training and Testing)

Python Code for LSTM Modeling (Training and Testing)

This Python script is used to develop and evaluate a Long Short-Term Memory (LSTM) model for predicting the State of Health (SOH) of batteries. It is divided into two main parts:

Part 1 (Training Code): Handles data preparation, building the model architecture, and training the model using data from battery cells 1–4.

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from sklearn.preprocessing import MinMaxScaler
from sklearn.model_selection import train_test_split
from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import LSTM, Dense, Dropout
from tensorflow.keras.optimizers import Adam
from tensorflow.keras.callbacks import EarlyStopping
import tensorflow as tf
import random

# =====
# 1. INITIALIZATION & CONFIGURATION
# =====
# Fix random seed for reproducibility
SEED = 42
np.random.seed(SEED)
random.seed(SEED)
tf.random.set_seed(SEED)

FILENAME = 'Parameter_example_No1.csv'
MODEL_FILENAME = 'battery_lstm_Capacity_200cycles_seq3.h6'
NOMINAL_CAPACITY = 2000.0
SEQUENCE_LENGTH = 30
SOH_LIMIT = 80.0
```



```

# Input Features and Target
FEATURES = ['Capacity', 'RO', 'Rs', 'Rct', 'Rw']
TARGET = 'Capacity'

# Load Data
try:
    df = pd.read_csv(FILENAME, encoding='latin1')
except FileNotFoundError:
    print(f"Error: '{FILENAME}' not found.")
    exit()

# =====
# 2. GLOBAL SCALER PREPARATION
# =====

# Prepare global scaler using all cells (1-5) to prevent
# Out-Of-Distribution (OOD) issues during testing.
full_df = df.copy()

# Standardize 'Cycle' column
if 'Cycle' not in full_df.columns:
    cycle_col = next((c for c in full_df.columns if 'cycle' in c.lower()), None)
    full_df.rename(columns={cycle_col: 'Cycle'} if cycle_col else {'Cycle':
    full_df.groupby('Cell.Num').cumcount() + 1}, inplace=True)
    full_df['Cycle'] = pd.to_numeric(full_df['Cycle'], errors='coerce')

# Clean object columns (remove '%' symbols)
cols_to_clean = ['RO', 'Rs', 'Rct', 'Rw', 'Capacity']
for col in cols_to_clean:
    if full_df[col].dtype == 'object':
        full_df[col] = full_df[col].astype(str).str.replace('%', '', regex=False)
        full_df[col] = pd.to_numeric(full_df[col], errors='coerce')

# Fit Scalers on full dataset
scaler_features = MinMaxScaler()
scaler_target = MinMaxScaler()
scaler_features.fit(full_df[FEATURES])
scaler_target.fit(full_df[[TARGET]])

```

```

# =====
# 3. TRAINING DATA PREPROCESSING (Cells 1-4)
# =====

train_cells = [1, 2, 3, 4]
train_df = full_df[full_df['Cell.Num'].isin(train_cells)].copy()
# Calculate State of Health (SoH)
train_df['SoH'] = (train_df['Capacity'] / NOMINAL_CAPACITY) * 100
# Hybrid Filter Logic: Remove SoH < 80%, except Cell 1 late cycles
mask_basic_keep = train_df['SoH'] >= SOH_LIMIT
mask_exception_keep = (train_df['Cell.Num'] == 1) & (train_df['Cycle'] >= 159) &
(train_df['Cycle'] <= 200)
final_mask_keep = mask_basic_keep | mask_exception_keep
train_df = train_df[final_mask_keep].copy()
# Apply Moving Average Smoothing (Window = 20)
res_cols = ['Capacity', 'RO', 'Rs', 'Rct', 'Rw']
for cell in train_df['Cell.Num'].unique():
    mask = train_df['Cell.Num'] == cell
    if mask.sum() > 0:
        train_df.loc[mask, res_cols] = train_df.loc[mask, res_cols].rolling(window=20,
min_periods=1).mean()
# Transform Data using Global Scaler
train_df[FEATURES] = scaler_features.transform(train_df[FEATURES])
train_df[[TARGET]] = scaler_target.transform(train_df[[TARGET]])
# =====
# 4. SEQUENCE CREATION & TRAIN/VAL SPLIT
# =====

def create_sequences_with_meta(df_in, seq_len):
    """ Generates time-series sequences and corresponding targets. """
    X, y, m_cyc, m_SoH, m_cell = [], [], [], [], []
    f_data, t_data = df_in[FEATURES].values, df_in[TARGET].values
    c_data, s_data, ce_data = df_in['Cycle'].values, df_in['SoH'].values,
df_in['Cell.Num'].values

```

```

for i in range(len(f_data) - seq_len):
    X.append(f_data[i:i + seq_len])
    y.append(t_data[i + seq_len])
    m_cyc.append(c_data[i + seq_len])
    m_SoH.append(s_data[i + seq_len])
    m_cell.append(ce_data[i + seq_len])
return np.array(X), np.array(y), np.array(m_cyc), np.array(m_SoH),
np.array(m_cell)
X_list, y_list, m_cycle, m_SoH, m_cell = [], [], [], [], []
for cell_id in train_cells:
    cell_data = train_df[train_df['Cell.Num'] == cell_id]
    if len(cell_data) > SEQUENCE_LENGTH:
        X_c, y_c, mc_cycle, mc_SoH, mc_cell = create_sequences_with_meta(cell_data,
SEQUENCE_LENGTH)
        X_list.extend(X_c); y_list.extend(y_c)
        m_cycle.extend(mc_cycle); m_SoH.extend(mc_SoH); m_cell.extend(mc_cell)
# 80/20 Random Split
X_train, X_val, y_train, y_val = train_test_split(
    np.array(X_list), np.array(y_list), test_size=0.2, random_state=SEED, shuffle=True
)
# =====
# 5. LSTM MODEL ARCHITECTURE & TRAINING
# =====
model = Sequential()
model.add(LSTM(units=50, activation='relu', input_shape=(X_train.shape[1],
X_train.shape[2])))
model.add(Dropout(0.5))
model.add(Dense(units=1))
optimizer = Adam(learning_rate=0.0005)
model.compile(optimizer=optimizer, loss='mean_squared_error')
# Early Stopping to prevent overfitting

```

```

early_stop = EarlyStopping(monitor='val_loss', patience=15,
restore_best_weights=True)
history = model.fit(
    X_train, y_train,
    epochs=100,
    batch_size=16,
    validation_data=(X_val, y_val),
    callbacks=[early_stop],
    verbose=1
)

```

```

model.save(MODEL_FILENAME)
# Plot Training vs Validation Loss
plt.figure(figsize=(10, 6))
plt.plot(history.history['loss'], label='Training Loss')
plt.plot(history.history['val_loss'], label='Validation Loss')
plt.title('Training vs Validation Loss')
plt.xlabel('Epoch')
plt.ylabel('Loss (MSE)')
plt.legend()
plt.grid(True)
plt.show()

```

Part 2 (Testing Code): Tests the model's accuracy using data from cell 5 (which the model has never seen before) and calculates the RMSE, MAE values and R-squared.

```

import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from tensorflow.keras.models import load_model
from sklearn.preprocessing import MinMaxScaler
from sklearn.metrics import mean_squared_error, mean_absolute_error, r2_score
import tensorflow as tf
import random

```

```

# =====
# 1. INITIALIZATION & CONFIGURATION
# =====

SEED = 42
np.random.seed(SEED)
random.seed(SEED)
tf.random.set_seed(SEED)

MODEL_PATH = 'battery_lstm_Capacity_200cycles_seq3.h5'
DATA_PATH = 'Parameter_example_No1.csv'
NOMINAL_CAPACITY = 2000.0
FEATURES = ['Capacity', 'RO', 'Rs', 'Rct', 'Rw']
TARGET = 'Capacity'
SEQUENCE_LENGTH = 30
TEST_CELLS = [5]
# =====
# 2. LOAD DATA & EXTRACT MODEL LOGIC
# =====

model = load_model(MODEL_PATH)
df = pd.read_csv(DATA_PATH, encoding='latin1')
# Extract Mathematical Logic from Final Dense Layer
final_layer = model.layers[-1]
if isinstance(final_layer, tf.keras.layers.Dense):
    weights, biases = final_layer.get_weights()
    w_flat = weights.flatten()
    bias = biases[0]
    num_hidden = len(w_flat)
    print(f"\nFinal Dense Layer Equation ({num_hidden} Hidden States):")
    eq_str = "Predicted_Scaled_Capacity = \n"
    for i in range(num_hidden):
        eq_str += f" ({w_flat[i]:+8.4f} * h_{i + 1})\n"
    eq_str += f" {bias:+8.4f} (Bias)\n"

```



```

    print(eq_str)
# =====
# 3. PRE-PROCESSING & GLOBAL SCALING
# =====
# Generate Cycle column if missing
if 'Cycle' not in df.columns:
    df['Cycle'] = df.groupby('Cell.Num').cumcount() + 1
# Standardize Columns
cols_to_process = FEATURES + [TARGET]
for col in cols_to_process:
    if col in df.columns and df[col].dtype == 'object':
        df[col] = df[col].astype(str).str.replace('%', '', regex=False)
        df[col] = pd.to_numeric(df[col], errors='coerce')
df['SoH_Calc'] = (df['Capacity'] / NOMINAL_CAPACITY) * 100
# Fit Global Scaler (on ALL Cells 1-5, ALL Cycles) to maintain baseline
scaler_features = MinMaxScaler()
scaler_target = MinMaxScaler()
scaler_features.fit(df[FEATURES])
scaler_target.fit(df[[TARGET]])
# =====
# 4. DATA FILTERING (EXTRAPOLATION TEST)
# =====
# Limit Data to Phase 2 (Cycles > 100)
df = df[df['Cycle'] > 100].copy()
# Filter Exceptions and SOH Limit
df = df[~((df['Cell.Num'] == 5) & (df['Cycle'] == 52))].copy()
df = df[df['SoH_Calc'] >= 80.0].copy()
df_raw_plot = df.copy()
# Apply Smoothing to Resistances only (Window = 20)
features_to_smooth = ['Capacity', 'RO', 'Rs', 'Rct', 'Rw']
for cell in df['Cell.Num'].unique():
    mask = df['Cell.Num'] == cell

```

```

df.loc[mask, features_to_smooth] = df.loc[mask,
features_to_smooth].rolling(window=20, min_periods=1).mean()
def create_sequences(features_data, sequence_length):
    """ Generates time-series sequences for testing data. """
    X = []
    for i in range(len(features_data) - sequence_length):
        X.append(features_data[i:i + sequence_length])
    return np.array(X)
# =====
# 5. MODEL TESTING & EVALUATION
# =====
for cell_num in TEST_CELLS:
    input_df = df[df['Cell.Num'] == cell_num].copy()
    truth_df = df_raw_plot[df_raw_plot['Cell.Num'] == cell_num].copy()
    if len(input_df) <= SEQUENCE_LENGTH:
        continue
    # Scale Data
    cell_features_scaled = scaler_features.transform(input_df[FEATURES])
    # Check for Out-Of-Distribution (OOD) Data
    feat_max = np.max(cell_features_scaled, axis=0)
    feat_min = np.min(cell_features_scaled, axis=0)
    if np.any(feat_max > 1.05) or np.any(feat_min < -0.05):
        print(f"Warning: Out of Distribution data detected for Cell {cell_num}.")
    # Sequence Creation
    X_cell = create_sequences(cell_features_scaled, SEQUENCE_LENGTH)
    real_SoH_values = truth_df['SoH_Calc'].values[SEQUENCE_LENGTH:]
    real_cycles = truth_df['Cycle'].values[SEQUENCE_LENGTH:]
    # Model Prediction
    predictions_scaled = model.predict(X_cell, verbose=0)
    pred_real_cap = scaler_target.inverse_transform(predictions_scaled)
    SoH_pred_raw = (pred_real_cap / NOMINAL_CAPACITY) * 100

```

```

# Calibration Bias Adjustment
start_check = 0
end_check = min(10, len(SoH_pred_raw))
initial_bias = np.mean(SoH_pred_raw.flatten()[start_check:end_check] -
real_SoH_values[start_check:end_check])
SoH_pred_final = np.clip(SoH_pred_raw - initial_bias, 0, 100.0)
# Calculate Evaluation Metrics
rmse = np.sqrt(mean_squared_error(real_SoH_values, SoH_pred_final))
mae = mean_absolute_error(real_SoH_values, SoH_pred_final)
r2 = r2_score(real_SoH_values, SoH_pred_final)
print(f"\nEvaluation Results for Cell {cell_num}:")
print(f"RMSE: {rmse:.4f}% | MAE: {mae:.4f}% | R-squared: {r2:.4f}")
# Plot Prediction vs Actual
plt.figure(figsize=(10, 5))
plt.plot(real_cycles, real_SoH_values, 'b.', label='Actual SOH (Raw)', alpha=0.5)
plt.plot(real_cycles, SoH_pred_final.flatten(), 'r--', label='Predicted SOH',
linewidth=2)
plt.title(f'Cell {cell_num} SOH Prediction (Phase 2: Cycles > 100)')
plt.xlabel('Cycle Number')
plt.ylabel('SOH (%)')
plt.legend()
plt.grid(True, linestyle='--', alpha=0.6)
plt.tight_layout()
plt.show()

```


Appendix C.

Python Code for Feature Importance and Logic Direction

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Python Code for Feature Importance and Logic Direction: This Python script was

developed to analyze and provide a physical interpretation of battery degradation mechanisms using an LSTM model with a Feature Importance Algorithm. However, the code in this appendix has been specifically separated out to clearly demonstrate the working logic.

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from matplotlib.patches import Patch
from tensorflow.keras.models import load_model
from sklearn.preprocessing import MinMaxScaler
from sklearn.metrics import mean_squared_error
import random
import tensorflow as tf
# =====
# 1. INITIALIZATION & CONFIGURATION
# =====
SEED = 42
np.random.seed(SEED)
random.seed(SEED)
tf.random.set_seed(SEED)
MODEL_PATH = 'battery_lstm_Capacity_200cycles_seq3.h5'
DATA_PATH = 'Parameter_example_No1.csv'
NOMINAL_CAPACITY = 2000.0
FEATURES = ['Capacity', 'RO', 'Rs', 'Rct', 'Rw']
TARGET = 'Capacity'
SEQUENCE_LENGTH = 30
N_REPEATS = 50 # For 95% Confidence Interval calculation
TEST_CELLS = [5]
```



```

# =====
# 2. LOAD DATA & PRE-PROCESSING
# =====

model = load_model(MODEL_PATH)
df = pd.read_csv(DATA_PATH, encoding='latin1')
# Generate Cycle column if missing
if 'Cycle' not in df.columns:
    df['Cycle'] = df.groupby('Cell.Num').cumcount() + 1
# Standardize Columns
for col in FEATURES + [TARGET]:
    if df[col].dtype == 'object':
        df[col] = pd.to_numeric(df[col].astype(str).str.replace('%', ''), errors='coerce')
df['SoH_Calc'] = (df['Capacity'] / NOMINAL_CAPACITY) * 100
# Fit Global Scaler (on all data to maintain baseline)
scaler_features = MinMaxScaler()
scaler_target = MinMaxScaler()
scaler_features.fit(df[FEATURES])
scaler_target.fit(df[[TARGET]])
# =====
# 3. DATA FILTERING
# =====

# Limit Data to Phase 2 (Cycles > 100) for Extrapolation Test
df = df[df['Cycle'] > 100].copy()
# Filter Exceptions and SOH Limit
df = df[~((df['Cell.Num'] == 5) & (df['Cycle'] == 52))].copy()
df = df[df['SoH_Calc'] >= 80.0].copy()
df_raw_plot = df.copy()
# Apply Smoothing to Resistances only (Window = 20)
features_to_smooth = ['Capacity', 'RO', 'Rs', 'Rct', 'Rw']
for cell in df['Cell.Num'].unique():
    mask = df['Cell.Num'] == cell

```

```

df.loc[mask, features_to_smooth] = df.loc[mask,
features_to_smooth].rolling(window=20, min_periods=1).mean()
def create_sequences(features_data, sequence_length):
    X = []
    for i in range(len(features_data) - sequence_length):
        X.append(features_data[i:i + sequence_length])
    return np.array(X)
# =====
# 4. FEATURE IMPORTANCE DIAGNOSIS
# =====
for cell_num in TEST_CELLS:
    print(f"\nProcessing Feature Importance for Cell {cell_num}...")
    input_df = df[df['Cell.Num'] == cell_num].copy()
    truth_df = df_raw_plot[df_raw_plot['Cell.Num'] == cell_num].copy()
    if len(input_df) <= SEQUENCE_LENGTH:
        continue
    # Scale Data and create sequences
    cell_features_scaled = scaler_features.transform(input_df[FEATURES])
    X_cell = create_sequences(cell_features_scaled, SEQUENCE_LENGTH)
    real_SoH_values = truth_df['SoH_Calc'].values[SEQUENCE_LENGTH:]
    # Get Baseline Prediction
    predictions_scaled = model.predict(X_cell, verbose=0)
    pred_real_cap = scaler_target.inverse_transform(predictions_scaled)
    SoH_pred_raw = (pred_real_cap / NOMINAL_CAPACITY) * 100
    # Calibration Bias Adjustment
    start_check = 0
    end_check = min(10, len(SoH_pred_raw))
    initial_bias = np.mean(SoH_pred_raw.flatten()[start_check:end_check] -
real_SoH_values[start_check:end_check])
    SoH_pred_final = np.clip(SoH_pred_raw - initial_bias, 0, 100.0)
    # Calculate Baseline RMSE
    base_rmse = np.sqrt(mean_squared_error(real_SoH_values, SoH_pred_final))

```

```

fi_means, fi_cis, fi_names, fi_directions = [], [], [], []
for feature_index, feature_name in enumerate(FEATURES):
    scores = []
    # -----
    # Step A: Permutation of Importance & 95% CI
    # -----
    for _ in range(N_REPEATS):
        features_permuted = cell_features_scaled.copy()
        np.random.shuffle(features_permuted[:, feature_index])
        X_permuted = create_sequences(features_permuted, SEQUENCE_LENGTH)
        perm_pred_scaled = model.predict(X_permuted, verbose=0)
        perm_cap = scaler_target.inverse_transform(perm_pred_scaled)
        perm_SoH = np.clip(((perm_cap / NOMINAL_CAPACITY) * 100) -
initial_bias, 0, 100.0)
        scores.append(np.sqrt(mean_squared_error(real_SoH_values, perm_SoH)))
    mean_score = np.mean(scores)
    se_score = np.std(scores) / np.sqrt(N_REPEATS)
    ci = 1.96 * se_score
    # -----
    # Step B: Logical Direction
    # -----
    perturb_amount = np.std(cell_features_scaled[:, feature_index]) * 0.1
    if perturb_amount == 0: perturb_amount = 0.001
    features_perturbed = cell_features_scaled.copy()
    features_perturbed[:, feature_index] += perturb_amount
    X_perturbed = create_sequences(features_perturbed, SEQUENCE_LENGTH)
    pert_pred_scaled = model.predict(X_perturbed, verbose=0)
    diff = np.mean(pert_pred_scaled) - np.mean(predictions_scaled)
    direction_val = 1.0 if diff > 0 else -1.0
    fi_names.append(feature_name)
    fi_means.append(mean_score)
    fi_cis.append(ci)

```

```

    fi_directions.append(direction_val)
# =====
# 5. VISUALIZATION & OUTPUT
# =====

sorted_indices = np.argsort(fi_means)[::-1]
sorted_names = [fi_names[i] for i in sorted_indices]
sorted_means = [fi_means[i] for i in sorted_indices]
sorted_cis = [fi_cis[i] for i in sorted_indices]
sorted_dirs = [fi_directions[i] for i in sorted_indices]
colors = ['#ff6b6b' if d > 0 else '#4ecdc4' for d in sorted_dirs]
Fig, ax_f = plt.subplots(FigureSize=(10, 6))
bars = ax_f.bar(sorted_names, sorted_means, yerr=sorted_cis, capsize=5,
color=colors, edgecolor='gray', alpha=0.9)
for bar, d_val, rmse_v in zip(bars, sorted_dirs, sorted_means):
    height = bar.get_height()
    dir_sym = "(+)" if d_val > 0 else "(-)"
    ax_f.text(bar.get_x() + bar.get_width() / 2., height + max(sorted_cis) * 0.5,
        f"{dir_sym}\n{rmse_v:.3f}", ha='center', va='bottom', fontsize=10,
        fontweight='bold')
    ax_f.axhline(y=base_rmse, color='black', linestyle='--', linewidth=1.5,
label=f'Baseline RMSE: {base_rmse:.3f}')
    ax_f.legend([Patch(facecolor='#ff6b6b'), Patch(facecolor='#4ecdc4')],
        ['Positive Correlation (+)', 'Negative Correlation (-)'])
    ax_f.set_title(f'Feature Importance & Correlation Direction (Cell {cell_num})')
    ax_f.set_ylabel('RMSE (%)')
    plt.tight_layout()
    plt.show()
# Print Terminal Report
print(f"\n{'=' * 75}")
print(f"MODEL LOGIC ANALYSIS: CELL {cell_num}")
print(f"\n{'=' * 75}")

```

```
print(f"{'Feature':<10} | {'Model Direction':<15} | {'Importance (RMSE)':<18} |  
{'95% CI':<10}")  
print(f"{'-' * 75}")  
for name, mean, ci, direction in zip(fi_names, fi_means, fi_cis, fi_directions):  
    dir_str = "Positive (+)" if direction > 0 else "Negative (-)"  
    print(f"{'name':<10} | {'dir_str':<15} | {'mean':>10.4f}%    | +/-{'ci':.4f}")  
print(f"{'=' * 75}\n")
```



Appendix D.
Python Code for Pearson Correlation

TNI

Python code for Pearson Correlation: This Python script is used to calculate the Pearson Correlation Coefficient (r) and to determine the 95% Confidence Interval using Fisher's Z-Transformation.

```
import pandas as pd
import numpy as np
import scipy.stats as stats

# =====
# 1. INITIALIZATION & CONFIGURATION
# =====

FILENAME = 'Parameter_example_No1.csv'
NOMINAL_CAPACITY = 2000.0
CELLS_TO_ANALYZE = [1, 2, 3, 4, 5]
RESISTANCE_PARAMS = ['RO', 'Rs', 'Rct', 'Rw']
WINDOW_SIZE = 20      # Moving average window
CONFIDENCE_LEVEL = 0.95 # 95% Confidence Interval
# =====
# 2. LOAD & PREPROCESS DATA
# =====

try:
    df = pd.read_csv(FILENAME, encoding='latin1')
except FileNotFoundError:
    print(f"Error: File '{FILENAME}' not found.")
    exit()

# Handle Cycle Column
if 'Cycle' not in df.columns:
    df['Cycle'] = df.groupby('Cell.Num').cumcount() + 1

# Clean Numeric Columns and Calculate SOH
for col in RESISTANCE_PARAMS + ['Capacity']:
    if col in df.columns and df[col].dtype == 'object':
        df[col] = pd.to_numeric(df[col].astype(str).str.replace('%', ''), errors='coerce')
df['SoH'] = (df['Capacity'] / NOMINAL_CAPACITY) * 100
```

```

# =====
# 3. PEARSON CORRELATION & FISHER'S Z-TRANSFORM
# =====

for cell_id in CELLS_TO_ANALYZE:
    print(f"\nProcessing Cell {cell_id}...")
    # Filter by cell and specific cycle range (e.g., Phase 2: Cycles > 100)
    cell_df = df[(df['Cell.Num'] == cell_id) & (df['Cycle'] > 100) & (df['Cycle'] <=
200)].copy()
    if len(cell_df) < WINDOW_SIZE:
        print(f"Not enough data (< {WINDOW_SIZE}). Skipping.")
        continue
    cell_df.sort_values(by='Cycle', inplace=True)
    # Apply Smoothing (Moving Average)
    cols_to_smooth = RESISTANCE_PARAMS + ['SoH']
    smoothed_df = cell_df.copy()
    smoothed_df[cols_to_smooth] =
cell_df[cols_to_smooth].rolling(window=WINDOW_SIZE).mean()
    smoothed_df.dropna(subset=cols_to_smooth, inplace=True)
    # Filter SOH threshold after smoothing
    final_df = smoothed_df[smoothed_df['SoH'] >= 80].copy()
    n = len(final_df)
    if n <= 3:
        print("Not enough data points after filtering for statistical significance.")
        continue
    print(f"{'Parameter':<10} | {'r-value':<10} | {'95% CI Lower':<15} | {'95% CI
Upper':<15}")
    print("-" * 55)
    for param in RESISTANCE_PARAMS:
        x = final_df[param]
        y = final_df['SoH']
        # Calculate Pearson correlation (r)
        r, p_value = stats.pearsonr(x, y)

```

```
# Fisher's Z-transformation for 95% Confidence Interval
z = np.arctanh(r)
se = 1 / np.sqrt(n - 3)
z_crit = stats.norm.ppf(1 - (1 - CONFIDENCE_LEVEL) / 2)
z_lower = z - z_crit * se
z_upper = z + z_crit * se
# Inverse transform back to r (Correlation space)
r_lower = np.tanh(z_lower)
r_upper = np.tanh(z_upper)
print(f"param:<10} | {r:<10.4f} | {r_lower:<15.4f} | {r_upper:<15.4f}")
```



Appendix E.

**Table of The Equivalent Circuit Model (ECM) Curve Fitting and
Linear -Kramers Kronig validation**

TNI

Table E.1 Parameters and SOH values extracted from the ECM of Cell 1

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
1	0.019018	0.000803	1.264798	1	0.000001	0.000001	0.698041	0.013149	10	1929.091	98.82649	0.000152
2	0.019296	0.000749	1.306595	1	0.000001	0.000001	0.654754	0.013063	10	1932.504	98.88104	0.000149
3	0.019966	0.000006	0.000001	0.85291	0.001073	5.29534	0.685396	0.005659	3.815436	1939.682	96.94903	0.000258
4	0.028523	0.000654	1.357396	1	0.000001	0.000001	0.680614	0.014595	10	1582.465	98.17224	0.000216
5	0.023627	0.000001	0.000001	0.419523	0.00094	3.792429	0.738421	0.013331	10	1703.753	98.08547	0.000189
6	0.024356	0.000639	1.294801	1	0.00005	0.000001	0.720131	0.013058	10	1795.544	98.8653	0.000157
7	0.030588	0.001611	0.750183	1	0.00001	0.000001	0.7589	0.016257	10	1671.021	97.16308	0.000292
8	0.031128	0.001502	0.73143	1	0.000001	0.000001	0.760708	0.01742	10	1644.538	97.47293	0.000341
9	0.017668	0.001594	0.782151	1	0.000001	0.000001	0.760373	0.015024	10	1934.432	99.16228	0.000193
10	0.017325	0.000001	0.001887	0.4	0.001819	2.864945	0.753212	0.014697	10	1939.328	98.84036	0.000228
11	0.017883	0.000721	1.283811	1	0.000001	0.000001	0.674072	0.013058	10	1946.374	98.52286	0.000158
12	0.0194	0.000703	1.303521	1	0.000001	0.000001	0.69734	0.013021	10	1957.308	98.66548	0.000152
13	0.022112	0.000644	1.299418	1	0.000001	0.000001	0.717229	0.013897	10	1683.182	98.46897	0.000183
14	0.052083	0.000588	1.769483	1	0.000001	0.000001	0.654507	0.009087	5.187455	1584.2	97.23148	0.000415
15	0.03959	0.000643	1.625874	1	0.000006	0.000001	0.697198	0.009001	7.322198	1925.985	98.70035	0.000175
16	0.046875	0.000601	1.543618	1	0.000001	0.000001	0.626741	0.013413	10	1911.043	97.87956	0.000176
17	0.04212	0.000554	1.522777	1	0.000003	0.000001	0.584568	0.012876	10	1922.514	97.40005	0.000191
18	0.009325	0.001125	1.140563	1	0.000005	0.000001	0.738652	0.007981	6.613613	906.1552	98.71792	0.000174
19	0.009816	0.001287	0.902843	1	0.000001	0.000001	0.733128	0.014615	10	1945.955	99.0232	0.000182
20	0.009014	0.00001	0.000001	0.549775	0.001622	3.060132	0.734615	0.01411	10	1937.428	98.48104	0.000214

Table E.1 Parameters and SOH values extracted from the ECM of Cell 1 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
21	0.015438	0.000773	1.298489	1	0.000185	0.000001	0.694324	0.013454	10	1927.799	98.45857	0.000175
22	0.015523	0.000689	1.459626	1	0.000001	0.000001	0.681686	0.013205	10	1930.689	99.04362	0.000159
23	0.015184	0.000006	0.000001	0.441556	0.000969	5.729238	0.673317	0.013042	10	1934.921	98.26671	0.000193
24	0.015645	0.000643	1.509545	1	0.000001	0.000001	0.666318	0.013129	10	1928.308	98.92376	0.000158
25	0.015852	0.00063	1.58643	1	0.000001	0.000001	0.642649	0.013036	10	1931.922	98.7147	0.000163
26	0.016093	0.000639	1.481951	1	0.000002	0.000001	0.708067	0.013101	10	1936.317	99.04525	0.000156
27	0.016251	0.000595	1.631056	1	0.000006	0.000001	0.647836	0.012876	10	1931.067	98.86748	0.000157
28	0.015716	0.000937	1.124089	1	0.000002	0.000001	0.713094	0.014055	10	1929.828	99.14624	0.000169
29	0.016899	0.000909	1.125302	1	0.000004	0.000001	0.721327	0.013959	10	1921.129	98.98249	0.000171
30	0.02643	0.001304	0.895513	1	0.000003	0.000001	0.733799	0.014672	10	1897.16	99.19946	0.000185
31	0.015438	0.000773	1.298489	1	0.000185	0.000001	0.694324	0.013454	10	1909.952	98.45857	0.000175
32	0.015523	0.000689	1.459626	1	0.000001	0.000001	0.681686	0.013205	10	1915.483	99.04362	0.000159
33	0.015184	0.000006	0.000001	0.441556	0.000969	5.729238	0.673317	0.013042	10	1921.968	98.26671	0.000193
34	0.015645	0.000643	1.509545	1	0.000001	0.000001	0.666318	0.013129	10	1927.242	98.92376	0.000158
35	0.015852	0.00063	1.58643	1	0.000001	0.000001	0.642649	0.013036	10	1932.211	98.7147	0.000163
36	0.016093	0.000639	1.481951	1	0.000002	0.000001	0.708067	0.013101	10	1924.812	99.04525	0.000156
37	0.016251	0.000595	1.631056	1	0.000006	0.000001	0.647836	0.012876	10	1924.154	98.86748	0.000157
38	0.015716	0.000937	1.124089	1	0.000002	0.000001	0.713094	0.014055	10	1922.773	99.14624	0.000169
39	0.016899	0.000909	1.125302	1	0.000004	0.000001	0.721327	0.013959	10	1924.547	98.98249	0.000171
40	0.02643	0.001304	0.895513	1	0.000003	0.000001	0.733799	0.014672	10	1918.555	99.19946	0.000185

Table E.1 Parameters and SOH values extracted from the ECM of Cell 1 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
41	0.036758	0.000993	1.086844	1	0.000001	0.000001	0.737183	0.013967	10	1900.594	98.97813	0.000177
42	0.031844	0.000725	1.347249	1	0.000001	0.000001	0.710935	0.013694	10	1910.206	98.0301	0.000194
43	0.031542	0.000651	1.448581	1	0.000001	0.000001	0.690063	0.013502	10	1917.128	98.02991	0.000188
44	0.030986	0.000644	1.503153	1	0.000001	0.000001	0.70848	0.013127	10	1908.311	98.75428	0.000171
45	0.030817	0.000626	1.631242	1	0.000003	0.000001	0.619149	0.013099	10	1909.701	98.89318	0.000164
46	0.030621	0.000626	1.493822	1	0.000005	0.000001	0.650491	0.013249	10	1913.961	98.8014	0.000174
47	0.030359	0.000615	1.508903	1	0.000002	0.000001	0.640024	0.013309	10	1904.727	98.79658	0.000154
48	0.030318	0.0006	1.597888	1	0.000006	0.000001	0.63951	0.013074	10	1910.007	98.94531	0.000165
49	0.029181	0.001035	1.011649	1	0.00017	0.000001	0.760518	0.014532	10	1897.93	99.17894	0.000182
50	0.030048	0.0011	0.992268	1	0.000003	0.000001	0.730312	0.014775	10	1878.461	98.94857	0.000175
51	0.031072	0.000875	1.124677	1	0.000001	0.000001	0.695425	0.014005	10	1880.099	98.86249	0.000166
52	0.030803	0.000802	0.990583	1	0.000001	0.000001	0.558036	0.013988	10	1900.642	98.12409	0.000181
53	0.03032	0.000718	1.343502	1	0.000001	0.000001	0.688839	0.013734	10	1902.317	98.18728	0.000202
54	0.030109	0.000697	1.37164	1	0.000002	0.000001	0.746773	0.013408	10	1900.341	98.90677	0.000171
55	0.029889	0.000677	1.398598	1	0.000001	0.000001	0.642049	0.0136	10	1900.925	98.85311	0.000179
56	0.029803	0.000664	1.50696	1	0.000001	0.000001	0.686728	0.013805	10	1898.473	98.67123	0.000158
57	0.029764	0.000654	1.448134	1	0.000004	0.000001	0.653685	0.013675	10	1901.652	98.4337	0.000187
58	0.029767	0.000625	1.48342	1	0.000001	0.000001	0.659025	0.01373	10	1891.534	98.9978	0.000164
59	0.030729	0.001281	0.881376	1	0.000006	0.000001	0.728798	0.015617	10	1872.821	98.73862	0.000219
60	0.031053	0.001282	0.866903	1	0.000009	0.000001	0.734013	0.015419	10	1867.078	99.13703	0.00019

Table E.1 Parameters and SOH values extracted from the ECM of Cell 1 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
61	0.030458	0.000708	1.331845	1	0.000002	0.000001	0.673459	0.014125	10	1882.822	97.87874	0.000197
62	0.030317	0.000695	1.346361	1	0.000001	0.000001	0.677862	0.013755	10	1884.956	98.87462	0.000178
63	0.03004	0.000679	1.459701	1	0.000001	0.023429	0.639889	0.013897	9.999993	1883.828	98.82642	0.000157
64	0.02942	0.000001	0.000004	0.4	0.001171	6.121069	0.58228	0.013722	10	1887.321	98.10489	0.000212
65	0.029745	0.000675	1.404241	1	0.000001	0.000001	0.664665	0.014057	10	1875.237	98.58698	0.000164
66	0.029724	0.000686	1.46103	1	0.000005	0.000001	0.751613	0.013798	10	1886.252	98.70005	0.000191
67	0.029263	0.000918	1.102921	1	0.000006	0.000001	0.678641	0.014503	10	1877.117	99.02713	0.000179
68	0.029325	0.000964	1.066449	1	0.000001	0.000001	0.721128	0.014645	10	1869.24	98.92564	0.000175
69	0.0293	0.000969	1.06392	1	0.000012	0.000001	0.728929	0.014882	10	1861.797	98.92993	0.000195
70	0.032052	0.000999	1.030768	1	0.000001	0.000001	0.712498	0.014859	10	1863.182	99.00283	0.00019
71	0.030688	0.000816	1.256643	1	0.000001	0.000001	0.799798	0.014526	10	1865.933	98.55872	0.000174
72	0.030348	0.000729	1.342352	1	0.000001	0.000001	0.671409	0.013936	10	1871.855	98.91446	0.000166
73	0.030023	0.00069	1.383501	1	0.000001	0.000001	0.692146	0.014408	10	1860.544	98.3058	0.000177
74	0.029749	0.00071	1.362841	1	0.000001	0.000001	0.656268	0.013939	10	1867.173	98.86533	0.00017
75	0.029498	0.000677	1.393677	1	0.000007	0.000001	0.651046	0.013918	10	1863.176	98.89235	0.000173
76	0.029239	0.000686	1.406538	1	0.000001	0.000001	0.667626	0.01419	10	1872.911	98.61022	0.000192
77	0.028773	0.000678	1.299379	1	0.000001	0.000001	0.655726	0.014076	10	1867.477	98.92418	0.000177
78	0.027784	0.001117	0.968298	1	0.000001	0.000001	0.729437	0.015572	10	1855.159	98.93896	0.000178
79	0.029103	0.001132	0.967951	1	0.000002	0.000001	0.710799	0.015498	10	1848.772	98.87213	0.000186
80	0.028881	0.001096	0.975039	1	0.000036	0.000001	0.713588	0.015455	10	1843.968	99.04139	0.000185

Table E.1 Parameters and SOH values extracted from the ECM of Cell 1 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
81	0.028789	0.000808	1.191238	1	0.000001	0.000001	0.67573	0.014559	10	1852.346	98.96818	0.000192
82	0.028732	0.000789	1.220988	1	0.000001	0.000001	0.670599	0.014391	10	1858.426	98.96719	0.000167
83	0.028538	0.000789	1.198327	1	0.000002	0.000001	0.703365	0.014769	10	1848.565	98.64802	0.000169
84	0.028294	0.000812	1.144815	1	0.000003	0.000001	0.711684	0.014533	10	1856.378	98.9109	0.000166
85	0.02818	0.000759	1.260863	1	0.000001	0.000001	0.709857	0.014625	10	1855.421	98.9273	0.00019
86	0.028035	0.000755	1.260218	1	0.000001	0.000001	0.728083	0.014428	10	1853.438	98.92318	0.000179
87	0.028471	0.001001	1.010411	1	0.000001	0.000001	0.710879	0.015406	10	1847.399	99.09726	0.000197
88	0.028348	0.001137	0.936302	1	0.000003	0.000001	0.713485	0.015905	10	1834.982	99.09852	0.000199
89	0.028275	0.001146	0.938943	1	0.000055	0.000001	0.739575	0.016348	10	1835.289	98.52079	0.000199
90	0.028138	0.001071	0.908796	1	0.000004	0.000001	0.718793	0.015885	10	1824.854	98.94621	0.00021
91	0.032748	0.000805	1.173881	1	0.000001	0.000001	0.692037	0.014567	10	1823.783	98.94917	0.000191
92	0.032283	0.00083	1.081727	1	0.000001	0.000001	0.737135	0.014752	10	1840.704	98.80328	0.000169
93	0.031751	0.000767	1.251599	1	0.000001	0.000001	0.673543	0.014555	10	1834.766	98.94334	0.000171
94	0.031484	0.000754	1.249861	1	0.000001	0.000001	0.654393	0.015111	10	1828.217	97.84936	0.000208
95	0.031101	0.000765	1.243314	1	0.000001	0.000001	0.696219	0.014521	10	1838.163	98.95279	0.000179
96	0.031209	0.000978	1.042676	1	0.000001	0.000001	0.69172	0.015857	10	1837.884	98.65751	0.000214
97	0.030253	0.001027	0.947976	1	0.000411	0.000001	0.695174	0.016076	10	1821.26	98.35967	0.000199
98	0.031724	0.001045	0.97409	1	0.000001	0.000001	0.749839	0.015969	10	1820.883	98.38984	0.000228
99	0.031292	0.00107	0.976579	1	0.000001	0.008921	0.706111	0.01589	10	1804.769	99.15219	0.000202
100	0.030855	0.001099	0.927773	1	0.000001	0.000001	0.69922	0.01595	10	1798.314	99.13006	0.000204

Table E.1 Parameters and SOH values extracted from the ECM of Cell 1 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
101	0.013942	0.000464	1.683033	1	0.000053	0.000001	0.466914	0.013698	10	1775.465	98.35626	0.000174
102	0.013974	0.000483	1.615372	0.999953	0.000001	0.392551	0.551573	0.013844	10	1798.773	98.81587	0.000166
103	0.013943	0.000502	1.527469	1	0.000001	0.000001	0.56595	0.01418	10	1788.436	98.9988	0.00015
104	0.013911	0.00054	1.376275	1	0.000004	0.000001	0.512237	0.014264	10	1790.251	98.76531	0.000172
105	0.013957	0.000549	1.392367	1	0.000002	0.000001	0.560154	0.014499	10	1771.5	98.81291	0.000172
106	0.013959	0.000574	1.34321	1	0.000001	0.000001	0.605266	0.0148	10	1781.311	99.14225	0.000165
107	0.013971	0.000589	1.319622	1	0.000002	0.000001	0.577204	0.014964	10	1773.775	99.15582	0.000165
108	0.013966	0.000615	1.220259	1	0.000001	0.000001	0.595557	0.015102	10	1765.368	99.07897	0.000156
109	0.013956	0.000628	1.208196	1	0.000001	0.000001	0.624894	0.015186	10	1752.128	98.84616	0.000181
110	0.013399	0.000001	0.000001	0.999996	0.001243	3.502955	0.62385	0.015502	10	1753.769	98.39125	0.000202
111	0.013895	0.000516	1.416377	1	0.000001	0.00212	0.474939	0.014672	10	1751.465	98.9209	0.000169
112	0.013885	0.000529	1.369965	1	0.000001	0.000001	0.479833	0.014873	10	1751.984	98.78411	0.000179
113	0.013909	0.000539	1.373877	1	0.000001	0.000001	0.540395	0.01518	10	1760.736	99.12156	0.00017
114	0.013942	0.000558	1.316031	1	0.000001	0.000001	0.547745	0.015222	10	1745.923	98.94827	0.000175
115	0.013985	0.000594	1.234843	1	0.000002	0.000001	0.547797	0.015747	10	1750.461	98.6946	0.000183
116	0.014017	0.00062	1.16227	1	0.000002	0.000001	0.563009	0.015818	10	1739.195	99.13886	0.000161
117	0.014033	0.000629	1.158551	1	0.000001	0.000001	0.568693	0.015991	10	1734.009	99.05922	0.00018
118	0.01408	0.000648	1.140585	1	0.000001	0.000001	0.584043	0.016158	10	1743.592	99.18507	0.000177
119	0.014087	0.000662	1.123572	1	0.000006	0.000001	0.582915	0.016272	10	1726.316	99.10528	0.000181
120	0.013844	0.000001	0.023108	0.400001	0.000996	4.955926	0.673357	0.016322	10	1729.23	98.62618	0.000219

Table E.1 Parameters and SOH values extracted from the ECM of Cell 1 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
121	0.014688	0.001027	0.829498	1	0.000005	0.000001	0.686997	0.01769	10	1692.595	98.91776	0.000195
122	0.01473	0.000984	0.858836	1	0.000001	0.000001	0.670182	0.017736	10	1698.877	98.92593	0.000193
123	0.014463	0.000255	8.525656	0.913212	0.001058	4.035869	0.696442	0.017361	9.985032	1695.452	98.90003	0.00022
124	0.014773	0.000986	0.831162	1	0.000004	0.000001	0.673617	0.017912	10	1707.991	98.70276	0.000216
125	0.014769	0.001007	0.818491	1	0.000001	0.000001	0.670281	0.017996	10	1701.396	99.26446	0.000201
126	0.014762	0.00103	0.786334	1	0.000009	0.000001	0.668681	0.018132	10	1704.796	98.85551	0.00022
127	0.014945	0.001335	0.658575	1	0.00002	0.000001	0.698625	0.019244	10	1697.976	99.22182	0.000204
128	0.015523	0.001662	0.568882	1	0.000001	0.000001	0.694858	0.020652	10	1686.233	99.32886	0.000236
129	0.015461	0.001575	0.580945	1	0.000001	0.000001	0.693747	0.014922	7.505939	1682.485	99.45614	0.000203
130	0.017069	0.000855	2.776072	0.911815	0.001663	3.022271	0.706942	0.019566	9.21252	1656.453	99.02289	0.000302
131	0.016822	0.001151	0.722237	1	0.000001	0.000001	0.691697	0.018998	10	1689.583	98.95785	0.000204
132	0.01674	0.001111	0.750268	1	0.000001	0.000001	0.683576	0.018832	10	1677.991	99.28486	0.000212
133	0.016325	0.000378	5.856071	0.904237	0.001158	3.769158	0.676103	0.018662	9.976089	1697.496	98.8494	0.00024
134	0.016671	0.001152	0.730828	1	0.000001	0.000001	0.737335	0.018883	10	1686.888	99.13188	0.000215
135	0.01669	0.001145	0.724759	1	0.000001	0.000001	0.67699	0.019038	10	1691.584	99.2332	0.000199
136	0.016662	0.001165	0.694816	1	0.000013	0.000001	0.683542	0.019316	10	1683.482	99.09323	0.000226
137	0.016599	0.001078	0.733267	1	0.000001	0.000001	0.689593	0.019029	10	1675.194	99.03222	0.000224
138	0.017191	0.002029	0.463611	1	0.000001	0.000001	0.709666	0.022807	10	1648.91	99.01173	0.000271
139	0.017709	0.002285	0.490381	0.982754	0.000001	0.000001	0.705551	0.019489	8.605166	1635.132	99.20534	0.000259
140	0.017277	0.000591	6.294366	0.833019	0.002234	2.708678	0.704259	0.020952	9.324963	1648.123	99.02329	0.000331

Table E.1 Parameters and SOH values extracted from the ECM of Cell 1 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
141	0.017057	0.001245	0.669341	1	0.000001	0.000001	0.696559	0.019586	10	1663.587	98.9314	0.000237
142	0.016968	0.001258	0.648379	1	0.000001	0.000001	0.661012	0.019826	10	1668.104	99.34797	0.000213
143	0.016583	0.000411	5.838999	0.883427	0.001281	3.46649	0.687698	0.01975	9.995046	1670.948	98.93469	0.000251
144	0.016274	0.001241	0.637429	1	0.000622	0.000001	0.697934	0.019791	10	1657.803	99.19332	0.000205
145	0.017157	0.001784	0.501597	1	0.000011	0.000001	0.702773	0.020104	9.184907	1673.596	98.97432	0.000251
146	0.017632	0.002266	0.467816	0.986237	0.000001	0.000001	0.707541	0.018044	7.958705	1638.908	99.29871	0.000254
147	0.017567	0.002201	0.433839	0.998229	0.000005	0.000001	0.70401	0.023252	10	1652.694	99.04451	0.000268
148	0.017522	0.002174	0.447666	0.994903	0.000001	0.000001	0.699432	0.023275	10	1646.863	99.33171	0.000276
149	0.01741	0.001961	0.45512	1	0.000001	0.000001	0.704597	0.022276	10	1642.945	99.25022	0.00026
150	0.016486	0.000003	0.000001	0.400009	0.002174	2.245088	0.686019	0.021037	10	1662.343	98.90472	0.000275
151	0.017048	0.001501	0.545197	1	0.000002	0.000001	0.68628	0.021349	10	1653.335	98.86288	0.000248
152	0.017063	0.001522	0.54228	1	0.000001	0.000001	0.679505	0.021209	10	1656.376	99.29144	0.000226
153	0.01668	0.000395	7.333562	0.85438	0.0016	3.329132	0.696375	0.018964	8.973445	1646.716	98.94892	0.000295
154	0.017027	0.001634	0.504363	1	0.000001	0.000001	0.695456	0.022033	10	1651.687	99.10296	0.000235
155	0.016964	0.001403	0.564752	1	0.000001	0.000001	0.683591	0.021149	10	1648.62	99.25514	0.000228
156	0.017555	0.002442	0.42121	0.984323	0.000001	0.000001	0.70541	0.02493	10	1624.823	99.06713	0.000277
157	0.017554	0.002402	0.428056	0.985583	0.000002	0.000001	0.700521	0.020352	8.51623	1614.307	99.26549	0.000281
158	0.017514	0.002377	0.43702	0.979704	0.000001	0.000001	0.696038	0.020863	8.630869	1621.543	99.19528	0.000266
159	0.017484	0.002357	0.414073	0.989095	0.000002	0.000001	0.708178	0.024628	10	1591.545	99.07291	0.00028
160	0.016548	0.000088	0.000001	0.4	0.002224	2.32925	0.698188	0.022274	10	1636.7	98.9304	0.000308

Table E.1 Parameters and SOH values extracted from the ECM of Cell 1 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
161	0.017027	0.00164	0.493536	1	0.000001	0.000001	0.68467	0.022106	10	1607.149	99.26961	0.000247
162	0.017047	0.00168	0.472911	1	0.000001	0.000001	0.690653	0.022766	10	1627.237	98.97059	0.000258
163	0.016754	0.000439	7.138962	0.832998	0.001672	3.195252	0.700074	0.018354	8.395198	1610.468	98.91558	0.000296
164	0.01711	0.001749	0.454088	1	0.000001	0.000001	0.689996	0.023085	10	1624.213	99.4113	0.000247
165	0.017063	0.001672	0.483834	1	0.000001	0.000001	0.693816	0.017078	7.454552	1591.083	99.27593	0.000248
166	0.017599	0.002386	0.400269	0.983338	0.000001	0.000001	0.696866	0.025409	10	1599.265	99.43606	0.000274
167	0.017301	0.001117	3.855658	0.77902	0.001896	3.159902	0.699984	0.022249	8.941675	1577.09	98.92661	0.000346
168	0.01765	0.002518	0.430736	0.968352	0.000001	0.000001	0.688962	0.021501	8.509023	1560.232	99.28658	0.000304
169	0.01762	0.002369	0.399524	0.984404	0.000004	0.000001	0.694808	0.025506	10	1568.08	99.46438	0.000285
170	0.016903	0.000418	7.815379	0.821647	0.001959	2.695761	0.696213	0.020542	8.786979	1572.279	98.87798	0.000321
171	0.017271	0.001841	0.419391	1	0.000001	0.000001	0.69486	0.0242	10	1589.704	99.44078	0.000258
172	0.017319	0.001875	0.412644	1	0.000001	0.000001	0.689447	0.022089	9.11955	1585.099	99.23422	0.000253
173	0.016968	0.000495	6.885071	0.808369	0.001876	2.868725	0.693445	0.021444	8.86851	1576.24	98.54748	0.000331
174	0.017384	0.001913	0.401706	1	0.000003	0.000001	0.687572	0.024952	10	1548.168	99.25918	0.000286
175	0.017467	0.001952	0.390623	1	0.000001	0.000001	0.67907	0.025177	10	1568.093	99.41773	0.000263
176	0.017443	0.001873	0.400035	1	0.000001	0.000001	0.687378	0.024962	10	1569.675	99.38895	0.000258
177	0.016847	0.000365	6.37171	0.87892	0.001859	2.573219	0.682677	0.021688	9.082451	1561.618	99.11108	0.000305
178	0.01732	0.001671	0.430129	1	0.000001	0.000001	0.684899	0.024491	10	1556.491	99.39971	0.000253
179	0.01698	0.000756	2.703301	0.881132	0.001408	3.050116	0.690082	0.018617	7.843166	1540.848	98.98148	0.000314
180	0.01685	0.000001	0.3923	0.40485	0.002422	2.064227	0.688496	0.020666	8.457931	1525.695	98.80736	0.000338

Table E.1 Parameters and SOH values extracted from the ECM of Cell 1 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
181	0.01761	0.002086	0.378793	0.999496	0.000001	0.000001	0.683855	0.018345	7.462739	1505.299	99.29538	0.000273
182	0.017681	0.002163	0.37517	0.993852	0.000001	0.000001	0.695373	0.019912	7.847692	1516.023	99.21306	0.000298
183	0.01732	0.000962	3.56562	0.804205	0.001764	3.154375	0.684615	0.018822	7.484868	1522.169	99.05059	0.000323
184	0.017842	0.002229	0.338798	0.998447	0.000008	0.000001	0.678959	0.027041	10	1546.238	99.17925	0.000291
185	0.017731	0.00206	0.361751	1	0.000001	0.000001	0.68006	0.019449	7.399334	1512.304	99.1483	0.000289
186	0.01868	0.003464	0.40687	0.924327	0.000001	0.000001	0.685452	0.022349	7.603747	1503.983	99.39298	0.000315
187	0.018394	0.001886	2.532995	0.755486	0.002206	2.89696	0.677128	0.028754	9.074399	1478.724	99.03897	0.000421
188	0.018968	0.003395	0.307737	0.958428	0.000001	0.000001	0.684608	0.032696	9.846688	1464.041	99.31977	0.000355
189	0.019004	0.003584	0.381061	0.922202	0.000011	0.000001	0.663248	0.031724	10	1485.148	99.36151	0.000337
190	0.018115	0.001486	2.216552	0.800129	0.001823	2.931795	0.681423	0.02206	7.839701	1512.348	99.03782	0.000364
191	0.018458	0.00251	0.306811	0.988697	0.000001	0.000001	0.679984	0.030399	10	1467.672	99.1547	0.000309
192	0.018594	0.00261	0.319306	0.978377	0.000001	0.000001	0.679315	0.02426	8.127475	1473.883	99.39454	0.000296
193	0.018141	0.00092	4.553822	0.757191	0.002423	2.300559	0.683009	0.025539	8.53801	1478.077	99.00443	0.000388
194	0.018666	0.002666	0.33261	0.966103	0.000011	0.000001	0.684818	0.022095	7.538606	1486.438	99.20821	0.000323
195	0.01951	0.003806	0.312505	0.933569	0.000001	0.024125	0.67009	0.0322	9.018208	1453.603	99.46248	0.000378
196	0.019854	0.003944	0.311065	0.935166	0.000333	3.65894	0.669726	0.036572	10	1449.418	99.3333	0.000403
197	0.019719	0.003776	0.272427	0.957673	0.000609	1.784684	0.674279	0.035958	9.505323	1427.707	99.46493	0.000425
198	0.018968	0.000484	5.635743	0.883686	0.004899	1.089214	0.669515	0.031434	9.000922	1457.251	99.03438	0.000442
199	0.020017	0.003637	0.26949	0.950275	0.000001	0.000001	0.667238	0.036769	10	1427.762	99.44741	0.000374
200	0.019578	0.003082	0.268694	0.966992	0.000004	0.000001	0.664699	0.034776	10	1445.995	99.54314	0.000314

Table E.2 Parameters and SOH values extracted from the ECM of Cell 2

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
1	0.03494	0.013572	0.558281	0.875225	0.000001	0.000001	0.808877	0.022595	7.105879	1257.608	99.80364	0.000402
2	0.02927	0.01275	0.582008	0.870765	0.000001	0.000001	0.803474	0.020021	7.068184	1377.32	99.86561	0.000325
3	0.024114	0.01013	0.673972	0.886018	0.001468	3.937843	0.800885	0.016828	6.797035	1548.527	99.90407	0.000265
4	0.026515	0.00829	0.599973	0.885849	0.000001	0.000001	0.798817	0.015581	6.678381	1476.035	99.79335	0.000266
5	0.023358	0.000001	0.000001	0.4	0.008695	1.19503	0.757899	0.027328	9.023305	1903.666	99.65793	0.000372
6	0.021688	0.006944	0.748974	0.881739	0.000834	8.84987	0.754101	0.031354	10	1912.355	99.83228	0.000293
7	0.020889	0.004762	1.606309	0.819262	0.003243	3.168276	0.752238	0.025107	8.442611	1909.372	99.77348	0.000312
8	0.020677	0.007516	0.720208	0.8656	0.000001	0.000001	0.745387	0.030984	9.999989	1911.066	99.83815	0.000267
9	0.020137	0.006594	0.74885	0.884516	0.000743	9.914732	0.747624	0.030945	9.999968	1913.4	99.78656	0.000284
10	0.01664	0.005691	1.520387	0.831285	0.004696	2.433426	0.763011	0.027445	8.587114	1904.429	99.84086	0.000325
11	0.02931	0.010082	0.693087	0.853886	0.000001	0.000001	0.769164	0.026257	8.707246	1871.037	99.83701	0.000301
12	0.021325	0.00776	0.728578	0.860363	0.000001	0.000001	0.752792	0.030022	9.999998	1900.926	99.8135	0.000274
13	0.020723	0.006849	0.806162	0.869984	0.000847	8.034341	0.74961	0.026551	8.878969	1910.296	99.86506	0.000258
14	0.019822	0.007542	0.75266	0.857349	0.000007	0.000001	0.744317	0.027288	9.04022	1912.344	99.87822	0.000254
15	0.019575	0.000004	0.000001	0.94645	0.008098	1.295715	0.748217	0.0279	9.434258	1910.885	99.67299	0.00036
16	0.019597	0.006666	0.801967	0.872986	0.00079	8.933543	0.74379	0.027024	9.03255	1909.903	99.86126	0.000263
17	0.019062	0.006385	0.793607	0.874861	0.000749	9.797902	0.74995	0.023654	8.262681	1900.911	99.8399	0.000238
18	0.021044	0.009862	0.744018	0.844782	0.000001	0.000001	0.762205	0.022889	7.39001	1882.375	99.8852	0.000259
19	0.022528	0.009303	0.79864	0.859179	0.001138	6.079514	0.764169	0.02404	7.882504	1875.975	99.90529	0.00027
20	0.021118	0.009612	0.80534	0.858178	0.001297	5.606761	0.766733	0.024317	7.972082	1872.695	99.88839	0.000266

Table E.2 Parameters and SOH values extracted from the ECM of Cell 2 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
21	0.018256	0.007542	0.767681	0.85622	0.000005	0.000001	0.742684	0.030048	9.888391	1909.389	99.85437	0.000253
22	0.017653	0.00744	0.762633	0.857168	0.000001	0.000001	0.74274	0.029878	9.999994	1904.218	99.81024	0.000258
23	0.017294	0.006658	0.847584	0.864539	0.000794	9.914307	0.735284	0.02899	9.589866	1912.066	99.85076	0.000259
24	0.017039	0.006595	0.847581	0.865531	0.000799	9.917516	0.738293	0.026146	8.752513	1912.228	99.86951	0.000239
25	0.016483	0.001156	4.437508	0.923393	0.006659	1.519616	0.745818	0.022967	8.290867	1893.782	99.72691	0.000302
26	0.017028	0.000656	9.124728	0.947904	0.009825	1.28359	0.747318	0.030834	9.433936	1910.494	99.82364	0.000356
27	0.02077	0.008968	0.8093	0.862425	0.001169	6.056282	0.760287	0.029237	9.460473	1882.511	99.90315	0.000288
28	0.020571	0.010359	0.744813	0.845056	0.000001	0.000001	0.763393	0.02328	7.672344	1873.994	99.89128	0.000251
29	0.023647	0.00945	0.800163	0.864379	0.001272	5.374752	0.764014	0.025981	8.368511	1875.277	99.85645	0.000267
30	0.022364	0.008995	0.828801	0.860354	0.001246	6.06089	0.759913	0.028036	8.913915	1884.947	99.88782	0.000296
31	0.030189	0.007436	0.792223	0.855035	0.000013	0.000001	0.744191	0.02448	8.429649	1899.946	99.83899	0.000237
32	0.025465	0.007401	0.799738	0.853599	0.000001	0.000001	0.735791	0.027655	9.277282	1906.016	99.87576	0.000253
33	0.02277	0.000818	6.483495	0.928412	0.00709	1.528139	0.738308	0.025062	8.72474	1904.082	99.75278	0.000323
34	0.021474	0.004704	2.166005	0.768082	0.003001	3.945561	0.736614	0.024759	8.600082	1903.264	99.63388	0.000337
35	0.021147	0.007184	0.805771	0.854044	0.000006	0.000001	0.730723	0.030281	10	1906.901	99.79673	0.00026
36	0.020525	0.006004	0.862986	0.872335	0.000828	9.60362	0.735601	0.028981	9.979947	1902.05	99.85269	0.000247
37	0.022093	0.009285	0.88576	0.854631	0.001595	4.573672	0.749297	0.026507	8.26518	1884.208	99.91385	0.000242
38	0.022362	0.011158	0.784093	0.833155	0.000001	0.000001	0.759074	0.024691	7.875434	1872.681	99.90624	0.000268
39	0.022674	0.009517	0.856473	0.848971	0.001147	6.92265	0.75801	0.026838	8.637501	1871.931	99.8841	0.000271
40	0.022075	0.000001	0.000001	0.4	0.010178	1.219701	0.750512	0.025217	8.671929	1880.713	99.78765	0.000363

Table E.2 Parameters and SOH values extracted from the ECM of Cell 2 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
41	0.021143	0.007222	0.817803	0.852079	0.000003	0.000001	0.739259	0.026645	9.27749	1899.94	99.86421	0.000266
42	0.021992	0.006861	0.835454	0.853114	0.000001	0.000001	0.725493	0.029517	9.999742	1911.241	99.86631	0.000263
43	0.021495	0.005485	0.927786	0.879853	0.00129	6.418883	0.736106	0.026088	9.192584	1897.946	99.77779	0.000248
44	0.02111	0.006711	0.843683	0.853464	0.000001	0.000001	0.727395	0.029618	10	1910.822	99.85051	0.000243
45	0.020574	0.006706	0.876894	0.846267	0.000007	0.000001	0.722318	0.025095	8.718293	1909.152	99.85922	0.000228
46	0.020096	0.005852	0.903934	0.868233	0.000838	9.999148	0.723894	0.029853	9.999571	1912.206	99.80823	0.000247
47	0.019488	0.005471	0.923373	0.872528	0.000837	9.997704	0.718501	0.028908	9.950659	1914.858	99.87573	0.000251
48	0.019621	0.005651	0.892652	0.856625	0.000001	0.000001	0.708593	0.028245	10	1912.415	99.81672	0.000241
49	0.019604	0.007754	0.909069	0.851095	0.00102	8.347513	0.738654	0.027606	9.087979	1889.818	99.87594	0.000274
50	0.021045	0.00103	5.435213	0.948576	0.008554	1.289856	0.764823	0.024433	8.392884	1878.753	99.85982	0.000313
51	0.020116	0.006647	0.882556	0.846994	0.000005	0.000001	0.719098	0.029389	9.999998	1906.591	99.87917	0.00025
52	0.019533	0.006625	0.889218	0.846202	0.000001	0.000001	0.719483	0.029024	10	1904.264	99.8742	0.00025
53	0.018646	0.003634	2.301355	0.802163	0.003376	3.641361	0.714204	0.022349	7.955252	1908.228	99.69839	0.000325
54	0.017988	0.000002	0.000001	0.98335	0.00725	1.689629	0.716565	0.025826	9.267546	1900.036	99.71822	0.000327
55	0.018066	0.00565	0.954993	0.866774	0.000901	9.987913	0.716379	0.029028	9.997189	1901.972	99.85469	0.000259
56	0.017349	0.001376	4.250756	0.898887	0.005639	2.142431	0.706237	0.025816	9.092364	1907.421	99.74076	0.00032
57	0.017428	0.007953	0.955717	0.843829	0.001089	9.162546	0.72681	0.030024	9.112286	1907.624	99.90079	0.000242
58	0.016982	0.008922	0.857066	0.833368	0.000001	0.000001	0.742512	0.024186	8.194817	1875.452	99.87519	0.000254
59	0.016825	0.008417	0.92523	0.842044	0.000959	9.57656	0.740168	0.026295	8.5287	1883.285	99.91526	0.000256
60	0.016735	0.008152	0.942201	0.84174	0.001047	9.999995	0.735056	0.025568	8.278469	1887.032	99.90152	0.00024

Table E.2 Parameters and SOH values extracted from the ECM of Cell 2 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
61	0.016862	0.006935	0.900156	0.842042	0.000002	0.000001	0.716924	0.030002	10	1900.461	99.80491	0.000244
62	0.016521	0.006548	0.903494	0.845015	0.000005	0.000001	0.718918	0.026803	9.392102	1893.333	99.79304	0.000237
63	0.016145	0.003922	1.59116	0.851803	0.002853	3.924293	0.716056	0.023209	8.241229	1898.162	99.68735	0.000286
64	0.01621	0.006489	0.919489	0.842939	0.000001	0.000001	0.711865	0.029584	9.956469	1903.957	99.80073	0.000236
65	0.01612	0.006424	0.943785	0.83976	0.000003	0.000001	0.707327	0.027956	9.623761	1899.987	99.82223	0.000231
66	0.015734	0.001059	5.28612	0.900956	0.005867	2.009805	0.713138	0.023798	8.667336	1891.977	99.72426	0.000291
67	0.016018	0.005102	1.002595	0.86647	0.001046	10	0.714446	0.02794	10	1891.561	99.87306	0.000244
68	0.016143	0.005629	0.949827	0.849012	0.000001	0.000001	0.699769	0.02879	10	1903.988	99.76158	0.000243
69	0.017288	0.007024	0.983684	0.844736	0.001118	10	0.731397	0.024141	8.448224	1868.088	99.89008	0.000223
70	0.016642	0.000001	0.000001	0.401118	0.006942	1.8758	0.702485	0.02647	9.603239	1891.698	99.63188	0.000337
71	0.016807	0.005883	0.957338	0.84421	0.000001	0.000001	0.706158	0.027742	9.999987	1888.627	99.84903	0.000232
72	0.016571	0.005909	0.977307	0.84174	0.000036	0.000001	0.698117	0.028812	10	1900.325	99.84696	0.000224
73	0.016159	0.003308	2.653117	0.786198	0.003065	4.270923	0.692474	0.025405	8.998954	1900.313	99.7077	0.000283
74	0.016394	0.005854	0.9557	0.844898	0.000001	0.000001	0.705709	0.027692	10	1887.273	99.85057	0.00023
75	0.016302	0.005853	0.967743	0.84357	0.000001	0.000001	0.702105	0.028291	9.999999	1891.959	99.82203	0.000226
76	0.015757	0.001413	4.345664	0.878002	0.005053	2.553572	0.6858	0.026869	9.46291	1900.381	99.66398	0.000309
77	0.016152	0.004569	1.080234	0.869372	0.001043	9.99926	0.691376	0.028368	10	1901.103	99.80236	0.00025
78	0.016536	0.005148	1.013577	0.845777	0.000007	0.000001	0.6869	0.02565	9.360714	1895.875	99.8375	0.000214
79	0.016697	0.004733	1.073511	0.864025	0.00105	10	0.695153	0.02868	10	1899.036	99.84817	0.000227
80	0.015933	0.000001	0.000001	0.4	0.006256	2.147017	0.688834	0.026852	9.73831	1898.757	99.66855	0.000326

Table E.2 Parameters and SOH values extracted from the ECM of Cell 2 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
81	0.016304	0.005659	1.02368	0.836668	0.000004	0.000001	0.691948	0.025271	9.028885	1891.68	99.83609	0.000216
82	0.016183	0.005693	1.012818	0.839333	0.000006	0.000001	0.693722	0.027006	9.458517	1893.67	99.81221	0.000217
83	0.015839	0.003702	2.700257	0.763114	0.002477	5.380782	0.690905	0.021014	7.845926	1890.204	99.70829	0.000292
84	0.015709	0.003005	4.391814	0.713956	0.003304	4.519569	0.686887	0.023371	8.668555	1890.325	99.63046	0.000324
85	0.015975	0.005746	1.002845	0.840059	0.000001	0.000001	0.691828	0.029057	9.999999	1894.527	99.77681	0.000235
86	0.015809	0.00443	1.100614	0.869014	0.001134	10	0.691761	0.02787	10	1890.999	99.83641	0.000242
87	0.015862	0.004076	1.150375	0.871935	0.001107	9.993468	0.677818	0.027979	9.999999	1896.885	99.80075	0.000224
88	0.016086	0.005063	1.043731	0.843235	0.000032	0.000001	0.678828	0.027592	10	1894.105	99.82263	0.000236
89	0.016019	0.004075	1.157014	0.871197	0.001078	10	0.674243	0.028043	10	1897.003	99.77213	0.000237
90	0.015547	0.000006	0.000001	0.400013	0.005855	2.259637	0.68885	0.024296	9.059489	1893.08	99.7092	0.000301
91	0.033026	0.008656	0.771616	0.853829	0.000001	0.000001	0.768559	0.018791	7.312055	1055.818	99.85532	0.000242
92	0.028964	0.008415	0.93753	0.826357	0.000028	0.000001	0.725639	0.030012	9.99999	1858.658	99.8871	0.000249
93	0.027532	0.007457	1.0532	0.834187	0.001108	9.999992	0.725468	0.022821	7.790529	1855.626	99.90517	0.000222
94	0.026746	0.008396	0.979867	0.821594	0.000002	0.000001	0.715258	0.02915	9.440885	1866.405	99.87372	0.000251
95	0.025513	0.006485	1.015317	0.831589	0.000007	0.000001	0.702648	0.024061	8.673298	1863.021	99.80335	0.00023
96	0.026414	0.006034	1.004207	0.838362	0.000001	0.000001	0.701442	0.028692	9.99997	1880.067	99.87236	0.000233
97	0.023721	0.004917	1.138666	0.85862	0.00105	9.999878	0.688311	0.029054	10	1883.085	99.77384	0.00025
98	0.022372	0.005817	1.064012	0.832577	0.000037	0.000001	0.675228	0.029506	10	1887.231	99.77443	0.000246
99	0.021691	0.004771	1.143624	0.86097	0.001056	9.999959	0.693968	0.028648	9.999999	1884.244	99.84523	0.000236
100	0.021137	0.004584	1.214588	0.860707	0.001092	9.183404	0.689733	0.028826	9.979334	1889.752	99.86601	0.00024

Table E.2 Parameters and SOH values extracted from the ECM of Cell 2 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
101	0.009249	0.007615	0.811554	0.871303	0.002742	10	0.736011	0.027372	8.723445	1846.637	99.9233	0.000246
102	0.009251	0.00688	0.815223	0.877931	0.002696	10	0.72841	0.027381	8.619323	1853.612	99.85914	0.000261
103	0.008941	0.002046	3.491424	0.900602	0.008065	1.868171	0.728872	0.027702	8.954255	1853.592	99.86864	0.000306
104	0.009215	0.006561	0.833558	0.878446	0.002541	10	0.726223	0.02722	8.806766	1851.789	99.8558	0.00027
105	0.008807	0.002957	2.753185	0.830504	0.004541	3.182719	0.708349	0.023235	8.128636	1864.125	99.71686	0.000321
106	0.009086	0.00447	0.7832	0.917308	0.002481	10	0.705645	0.024498	8.492021	1861.794	99.85693	0.00025
107	0.008813	0.003781	2.68095	0.784811	0.003465	4.370754	0.704643	0.024569	8.591462	1860.993	99.79644	0.000289
108	0.009069	0.004407	0.826151	0.912227	0.002466	10	0.700248	0.026211	8.869173	1869.485	99.8675	0.000258
109	0.00906	0.004417	0.845459	0.909202	0.002398	10	0.699488	0.028967	9.723247	1868.576	99.84198	0.000267
110	0.009041	0.004239	0.872076	0.909956	0.002502	10	0.689096	0.026845	9.03583	1870.132	99.86185	0.000254
111	0.009353	0.007299	0.84772	0.868671	0.00288	10	0.724879	0.026275	8.110657	1845.017	99.92073	0.000241
112	0.009339	0.007241	0.852871	0.868571	0.002851	10	0.723863	0.029447	8.911859	1846.925	99.849	0.000275
113	0.009312	0.00688	0.840833	0.872999	0.002741	10	0.72591	0.024807	7.971902	1835.022	99.88684	0.000244
114	0.009259	0.00632	0.861212	0.876415	0.00255	10	0.721512	0.030592	10	1842.296	99.87437	0.000264
115	0.009193	0.005314	0.856001	0.892324	0.002722	10	0.705417	0.027864	8.849477	1864.134	99.88718	0.000252
116	0.009106	0.004333	0.847132	0.910678	0.00248	10	0.698417	0.025097	8.585276	1858.486	99.85266	0.000242
117	0.009093	0.004248	0.869922	0.909511	0.002489	10	0.695282	0.026424	8.864426	1863.012	99.8394	0.000245
118	0.009065	0.006639	1.167515	0.815872	0.000003	0.000001	0.677778	0.027959	9.397143	1860.744	99.87553	0.000219
119	0.009102	0.004184	0.831029	0.915849	0.002431	10	0.699151	0.025964	9.018057	1852.819	99.83575	0.000257
120	0.009088	0.004154	0.894502	0.909532	0.002464	10	0.690282	0.027775	9.293514	1866.882	99.86432	0.000261

Table E.2 Parameters and SOH values extracted from the ECM of Cell 2 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
121	0.009289	0.006314	0.85174	0.878675	0.002822	10	0.715285	0.028346	8.832082	1811.111	99.83881	0.000271
122	0.009192	0.005383	0.894998	0.885701	0.00265	10	0.703421	0.028165	8.942509	1822.222	99.85775	0.00025
123	0.00881	0.001218	6.104559	0.879345	0.007357	2.181026	0.705757	0.024633	8.175655	1821.266	99.83298	0.000312
124	0.009098	0.004131	0.882978	0.912206	0.00249	10	0.685582	0.030058	10	1833.333	99.84228	0.000266
125	0.009023	0.004574	1.28262	0.857272	0.001827	10	0.671596	0.026009	8.837128	1831.208	99.88137	0.000203
126	0.009015	0.004447	1.270081	0.860595	0.001835	10	0.669911	0.026065	8.931068	1827.778	99.85608	0.000204
127	0.008985	0.004653	1.360128	0.850964	0.001623	10	0.660551	0.030151	10	1837.558	99.85878	0.000222
128	0.009061	0.006164	1.247686	0.812366	0.000001	0.000001	0.660243	0.02704	9.073009	1833.333	99.88904	0.0002
129	0.008994	0.004447	1.344379	0.855802	0.001792	10	0.661042	0.028424	9.521732	1833.333	99.87622	0.000217
130	0.009416	0.007598	0.889915	0.859742	0.002979	10	0.719265	0.027831	8.313348	1829.253	99.91028	0.000246
131	0.009364	0.0067	0.878791	0.869481	0.002794	10	0.718745	0.026325	8.349031	1824.672	99.88544	0.000252
132	0.009198	0.00463	0.893107	0.89844	0.002424	10	0.701016	0.029465	10	1833.348	99.81775	0.000257
133	0.008866	0.003147	3.618728	0.765361	0.00369	4.446223	0.688709	0.024971	8.767174	1844.423	99.7129	0.000313
134	0.009078	0.0044	1.272465	0.860287	0.001855	10	0.673219	0.0245	8.631882	1840.203	99.84214	0.000204
135	0.009047	0.004368	1.325019	0.856594	0.001838	10	0.667081	0.025297	8.810863	1848.97	99.87846	0.000214
136	0.009041	0.004334	1.354603	0.856197	0.00183	10	0.662383	0.025687	8.814539	1849.526	99.86629	0.000201
137	0.009014	0.004422	1.413399	0.851321	0.001741	10	0.654841	0.030118	10	1856.433	99.87652	0.000217
138	0.009114	0.005948	1.2534	0.81513	0.000001	0.000001	0.660596	0.029463	10	1850.375	99.83499	0.00022
139	0.008926	0.003948	1.500948	0.855747	0.001425	10	0.642874	0.028587	10	1857.149	99.78642	0.000226
140	0.009293	0.005529	0.949202	0.876086	0.002715	10	0.699578	0.030724	9.63982	1840.303	99.86764	0.000267

Table E.2 Parameters and SOH values extracted from the ECM of Cell 2 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
141	0.009808	0.006422	0.953136	0.863565	0.002929	10	0.704629	0.029189	8.708751	1836.454	99.88286	0.000253
142	0.009772	0.006207	0.984647	0.862635	0.002749	10	0.70241	0.032851	10	1833.318	99.86843	0.000267
143	0.009327	0.003224	3.643768	0.76851	0.003864	4.506257	0.6785	0.026003	8.716114	1847.905	99.76651	0.000309
144	0.009572	0.006429	1.202429	0.818271	0.000001	0.000001	0.673137	0.030691	9.999976	1847.98	99.84451	0.000248
145	0.009558	0.00387	1.020334	0.900857	0.002573	10	0.671838	0.027894	9.232557	1850.24	99.87411	0.000254
146	0.009482	0.004551	1.461402	0.843722	0.001849	10	0.654165	0.028624	9.462559	1848.832	99.88164	0.000217
147	0.009306	0.004536	2.649509	0.753331	0.002118	8.538471	0.652748	0.026176	8.851604	1852.561	99.75522	0.000279
148	0.009576	0.006152	1.293829	0.808443	0.000001	0.000001	0.658965	0.029277	9.740444	1845.826	99.86374	0.0002
149	0.009417	0.003968	1.508409	0.854615	0.001586	10	0.645646	0.026929	9.470209	1847.325	99.87466	0.000203
150	0.009807	0.005451	1.021198	0.869562	0.003014	10	0.684264	0.030217	8.75699	1852.452	99.85108	0.000263
151	0.009854	0.006745	0.940617	0.860376	0.00289	10	0.712098	0.027568	8.561538	1815.088	99.86428	0.000253
152	0.009781	0.005857	0.944398	0.870939	0.00284	10	0.704612	0.026343	8.48087	1819.857	99.86234	0.000251
153	0.009405	0.003715	3.566304	0.759781	0.004759	3.879529	0.689618	0.027682	8.974702	1838.333	99.78275	0.000324
154	0.009558	0.006246	1.225393	0.819163	0.000002	0.000001	0.672893	0.030473	10	1845.406	99.82777	0.000247
155	0.009467	0.004335	1.443196	0.849523	0.001903	10	0.654316	0.025948	8.823241	1841.134	99.87227	0.000199
156	0.009472	0.004229	1.440234	0.851771	0.001917	10	0.656141	0.025926	8.950643	1841.828	99.88686	0.000214
157	0.009438	0.004371	1.495383	0.845771	0.001742	10	0.649108	0.029561	10	1842.336	99.86404	0.000216
158	0.00952	0.00602	1.367939	0.802007	0.000001	0.000001	0.647999	0.027206	9.168352	1846.79	99.90069	0.000204
159	0.009448	0.004288	1.478272	0.847993	0.001815	10	0.651648	0.0266	9.123345	1840.722	99.87642	0.000203
160	0.00937	0.003946	1.596914	0.850355	0.001788	10	0.633241	0.027173	9.273914	1846.599	99.87937	0.000204

Table E.2 Parameters and SOH values extracted from the ECM of Cell 2 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
161	0.009917	0.00648	1.002728	0.856902	0.002799	10	0.704141	0.030127	9.406897	1816.475	99.8794	0.000264
162	0.009843	0.005712	0.987879	0.869335	0.003014	10	0.692379	0.027887	8.531554	1833.067	99.88807	0.000245
163	0.00959	0.003746	2.046396	0.864398	0.00473	3.457537	0.692931	0.027425	8.707002	1824.684	99.81299	0.000275
164	0.009665	0.006593	1.252004	0.812422	0.000009	0.000001	0.672835	0.03017	9.686486	1844.22	99.88224	0.000233
165	0.009335	0.002006	3.766117	0.854214	0.004774	3.507482	0.673555	0.024786	8.474083	1838.368	99.795	0.000279
166	0.009612	0.003723	1.089487	0.898545	0.002633	10	0.663987	0.029008	9.575742	1843.718	99.85372	0.000252
167	0.009299	0.002003	4.959739	0.804612	0.004759	3.78985	0.666084	0.026853	9.013777	1846.998	99.73757	0.000315
168	0.009631	0.006158	1.282087	0.813505	0.000006	0.000001	0.67086	0.025717	8.718508	1835.833	99.87295	0.000227
169	0.00953	0.004549	1.560886	0.838864	0.001763	10	0.645736	0.029175	9.543298	1845.771	99.88039	0.000204
170	0.009115	0.00118	7.120064	0.852181	0.005574	3.240758	0.650919	0.026563	9.075758	1842.435	99.70979	0.000293
171	0.009555	0.004911	1.515881	0.806446	0.000001	0.000001	0.621599	0.028099	9.733998	1847.057	99.83449	0.00019
172	0.009558	0.004934	1.513875	0.806351	0.000001	0.000001	0.622081	0.028977	10	1849.003	99.78621	0.000216
173	0.009423	0.003706	1.650083	0.853846	0.001482	10	0.63035	0.028487	10	1842.628	99.81065	0.000219
174	0.009576	0.005097	1.465229	0.807308	0.000001	0.000001	0.635867	0.025944	9.209765	1837.518	99.84723	0.000187
175	0.009391	0.003926	1.72956	0.842713	0.001469	10	0.619817	0.029614	9.945803	1851.09	99.85886	0.000201
176	0.009399	0.003904	1.724961	0.8444	0.001556	10	0.620777	0.0293	9.807485	1851.596	99.86764	0.0002
177	0.009454	0.003743	1.588597	0.856302	0.001637	10	0.635929	0.028372	10	1834.205	99.82368	0.000204
178	0.009573	0.005347	1.536327	0.796798	0.000003	0.000001	0.620662	0.029726	10	1845.119	99.88546	0.000201
179	0.009457	0.00391	1.630889	0.848919	0.001526	10	0.635076	0.028855	10	1838.018	99.83247	0.000201
180	0.009428	0.003895	1.681237	0.846413	0.001628	10	0.626694	0.02936	10	1843.245	99.84122	0.000223

Table E.2 Parameters and SOH values extracted from the ECM of Cell 2 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
181	0.009569	0.005137	1.547846	0.799771	0.000001	0.000001	0.620283	0.029169	10	1842.877	99.83303	0.000211
182	0.00954	0.004518	1.571885	0.808597	0.000001	0.000001	0.619556	0.02557	9.417313	1836.401	99.85936	0.00019
183	0.009538	0.004503	1.624174	0.805572	0.000001	0.000001	0.600703	0.028666	10	1848.154	99.7897	0.000201
184	0.009545	0.00455	1.582098	0.808042	0.000001	0.000001	0.611026	0.028178	9.987765	1845.183	99.86645	0.000186
185	0.009551	0.004633	1.582089	0.805892	0.000001	0.000001	0.614381	0.028018	10	1839.913	99.82091	0.000203
186	0.009375	0.003426	1.751125	0.854983	0.001519	10	0.616787	0.026499	9.561632	1836.502	99.87618	0.000203
187	0.009556	0.004842	1.579439	0.801425	0.000001	0.000001	0.614368	0.028686	10	1841.628	99.8073	0.000205
188	0.00957	0.0049	1.596822	0.800209	0.000001	0.000001	0.610056	0.029144	10	1846.447	99.87382	0.000207
189	0.00938	0.003596	1.806719	0.847217	0.00155	10	0.614936	0.026788	9.335696	1839.443	99.86244	0.000192
190	0.00942	0.003555	1.755346	0.850666	0.001555	10	0.621167	0.026538	9.413173	1832.373	99.82338	0.000193
191	0.010074	0.006134	1.073715	0.853569	0.003144	10	0.686549	0.033747	10	1818.808	99.89699	0.000277
192	0.010052	0.006241	1.022826	0.855606	0.002954	10	0.703704	0.026649	8.509208	1796.853	99.89435	0.000257
193	0.009721	0.006265	2.387649	0.740475	0.002493	7.745491	0.687895	0.023691	7.711133	1806.888	99.8111	0.000301
194	0.00962	0.004105	1.648166	0.842393	0.001679	10	0.641112	0.029122	10	1823.265	99.81536	0.000205
195	0.009517	0.003857	1.790149	0.841562	0.00171	10	0.619012	0.029888	10	1837.765	99.83522	0.000214
196	0.009509	0.003802	1.808632	0.84299	0.001668	10	0.61702	0.028441	9.656403	1838.506	99.8913	0.000208
197	0.009491	0.00389	1.808244	0.840571	0.001556	10	0.615229	0.029935	10	1841.001	99.80459	0.000223
198	0.009674	0.00521	1.594223	0.794821	0.000001	0.000001	0.618146	0.028687	9.743218	1837.286	99.89195	0.000191
199	0.009548	0.003755	1.721305	0.847318	0.001537	10	0.631083	0.028594	10	1825.09	99.79419	0.000204
200	0.009505	0.003744	1.831078	0.842827	0.001651	10	0.617546	0.029409	10	1834.479	99.84959	0.000211

Table E.3 Parameters and SOH values extracted from the ECM of Cell 3

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
1	0.012518	0.010007	0.600658	0.873792	0.001352	4.074741	0.76893	0.029765	8.859566	1839.372	99.85322	0.000333
2	0.01248	0.009418	0.601838	0.873681	0.00121	4.55728	0.767067	0.026862	8.337581	1836.168	99.87528	0.000304
3	0.012512	0.009816	0.591444	0.86181	0.000555	9.897283	0.76236	0.027914	8.593268	1846.598	99.86214	0.000313
4	0.012479	0.009056	0.617973	0.869314	0.001088	5.198272	0.762495	0.026949	8.562153	1835.416	99.85242	0.00031
5	0.01252	0.009003	0.626905	0.870895	0.001229	4.626977	0.759435	0.028239	8.787632	1845.384	99.87637	0.000318
6	0.01257	0.009136	0.630438	0.868785	0.001211	4.758069	0.758236	0.029453	8.931594	1849.785	99.84643	0.000328
7	0.012576	0.009011	0.642629	0.868474	0.001328	4.519959	0.756923	0.028782	8.852551	1849.74	99.88186	0.000314
8	0.012587	0.009223	0.642162	0.862506	0.001066	5.552327	0.754723	0.02862	8.806557	1849.522	99.8681	0.00031
9	0.012581	0.00895	0.654107	0.865803	0.001273	4.716974	0.753911	0.029226	8.908139	1849.569	99.83931	0.000324
10	0.012595	0.009045	0.647904	0.862937	0.001094	5.499472	0.754765	0.02712	8.529385	1841.072	99.85729	0.000297
11	0.01298	0.010194	0.775524	0.893486	0.004591	1.560269	0.765674	0.02933	8.452407	1822.814	99.91917	0.000299
12	0.012961	0.009944	0.788147	0.897022	0.004803	1.476578	0.768734	0.028078	8.351379	1807.257	99.92148	0.000286
13	0.012934	0.010094	0.785238	0.890938	0.004466	1.608392	0.763823	0.030127	8.699942	1826.345	99.92675	0.000312
14	0.012943	0.009727	0.760705	0.882003	0.003505	1.903331	0.764753	0.025479	7.847311	1804.664	99.9191	0.00028
15	0.012747	0.009732	0.72385	0.872063	0.002509	2.552242	0.758484	0.029564	9.121082	1828.189	99.90447	0.000329
16	0.012613	0.009755	0.686868	0.856083	0.001238	5.041131	0.750894	0.028542	8.658542	1847.901	99.90456	0.000308
17	0.012582	0.009399	0.704684	0.856937	0.001359	4.852981	0.74702	0.028509	8.574493	1850.939	99.90079	0.000292
18	0.012571	0.009372	0.69583	0.856102	0.001222	5.236947	0.747313	0.029359	8.813161	1853.578	99.89485	0.000314
19	0.012554	0.009132	0.709453	0.85631	0.001327	5.056481	0.744619	0.029901	9.021736	1850.963	99.88125	0.000301
20	0.012485	0.008764	0.689123	0.858521	0.001085	5.982718	0.746225	0.028704	9.038951	1841.583	99.86874	0.000302

Table E.3 Parameters and SOH values extracted from the ECM of Cell 3 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
21	0.012947	0.010047	0.807913	0.879609	0.003984	1.833832	0.756749	0.030956	8.90292	1828.624	99.91938	0.000303
22	0.013197	0.010867	0.864062	0.8944	0.005877	1.386564	0.763177	0.029514	8.252052	1814.403	99.95679	0.00026
23	0.013157	0.010842	0.846836	0.895041	0.005647	1.419578	0.762082	0.03589	9.999963	1817.868	99.92679	0.000339
24	0.013049	0.011209	0.849662	0.867229	0.004317	1.887905	0.753232	0.031714	8.940222	1819.925	99.94705	0.000292
25	0.012775	0.009904	0.793978	0.87681	0.003493	2.025384	0.757892	0.02698	8.141287	1815.197	99.90881	0.000297
26	0.012421	0.009651	0.73456	0.848863	0.001241	5.551768	0.742005	0.030956	9.221825	1847.053	99.89258	0.000293
27	0.012154	0.00236	2.464798	0.911817	0.008567	1.294335	0.74528	0.02718	8.57736	1836.315	99.83523	0.000343
28	0.012388	0.009161	0.736786	0.850456	0.001204	5.843409	0.742164	0.028616	8.886749	1838.627	99.89597	0.000283
29	0.012372	0.009092	0.730979	0.851664	0.001162	6.135978	0.741177	0.030864	9.258523	1847.915	99.88101	0.000308
30	0.012344	0.008968	0.751622	0.849012	0.001215	6.019632	0.735199	0.030707	9.138537	1851.777	99.8601	0.0003
31	0.012787	0.010132	0.816931	0.862253	0.003028	2.417947	0.749464	0.030612	8.812892	1832.251	99.92736	0.000286
32	0.012677	0.010065	0.815165	0.86949	0.003359	2.202084	0.748975	0.033011	9.653953	1826.517	99.91123	0.00033
33	0.012558	0.01052	0.796225	0.846111	0.002138	3.336204	0.74933	0.024443	7.701107	1797.954	99.93388	0.000245
34	0.012779	0.010124	0.880704	0.878736	0.004646	1.685944	0.75674	0.02681	7.952825	1798.274	99.94709	0.00025
35	0.012284	0.009794	0.763963	0.841768	0.001204	5.986517	0.738075	0.028925	8.786458	1836.337	99.91725	0.000291
36	0.012208	0.009222	0.764702	0.845646	0.001243	6.036366	0.736145	0.029842	9.065712	1839.89	99.89862	0.000282
37	0.012174	0.008954	0.77317	0.846811	0.001297	5.794603	0.735665	0.029554	8.967257	1838.5	99.87121	0.000285
38	0.012176	0.009238	0.753693	0.840392	0.000884	8.600237	0.733235	0.02967	9.085097	1839.223	99.90349	0.000281
39	0.01216	0.008841	0.774229	0.844234	0.001152	6.613001	0.734568	0.028482	8.813147	1836.443	99.88921	0.000269
40	0.012151	0.008979	0.775842	0.838885	0.000932	8.60209	0.726438	0.030112	9.078996	1843.763	99.9	0.000276

Table E.3 Parameters and SOH values extracted from the ECM of Cell 3 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
41	0.01267	0.009524	0.861807	0.875569	0.003831	1.949103	0.750091	0.032472	9.656845	1808.935	99.91259	0.000309
42	0.012643	0.010186	0.856071	0.85458	0.003011	2.531332	0.745537	0.02997	8.769554	1813.898	99.927	0.00027
43	0.012612	0.010187	0.854284	0.85141	0.00277	2.759492	0.741004	0.030954	8.86448	1825.37	99.92448	0.000275
44	0.012614	0.009847	0.858167	0.860313	0.003159	2.415925	0.741299	0.029279	8.463158	1823.792	99.9238	0.000281
45	0.012198	0.008997	0.781782	0.840717	0.001093	6.759001	0.736991	0.026228	8.558559	1810.49	99.9054	0.000256
46	0.012183	0.008734	0.790883	0.843595	0.001211	6.267201	0.732641	0.029263	9.081431	1827.229	99.87851	0.000279
47	0.012158	0.008473	0.804934	0.843292	0.001274	6.563561	0.726528	0.029978	9.16955	1836.056	99.90116	0.000271
48	0.012149	0.008659	0.800329	0.838803	0.001007	8.199088	0.721974	0.031053	9.279237	1842.723	99.878	0.000285
49	0.012141	0.008426	0.800441	0.841553	0.001093	7.671391	0.721589	0.031422	9.433619	1841.339	99.89162	0.000289
50	0.012138	0.00846	0.808715	0.839565	0.00104	7.987093	0.71812	0.031602	9.368115	1844.551	99.8651	0.000294
51	0.012588	0.010158	0.841449	0.842697	0.002125	3.556852	0.734964	0.032178	9.231507	1825.678	99.91844	0.000284
52	0.012662	0.010159	0.871678	0.848378	0.002792	2.78137	0.739029	0.029689	8.691738	1813.646	99.94463	0.000266
53	0.012627	0.010129	0.870778	0.84449	0.002525	3.044723	0.739034	0.030126	8.921629	1813.595	99.93326	0.000264
54	0.012917	0.010217	0.87763	0.846363	0.002733	2.893118	0.736302	0.031165	8.873093	1820.238	99.92949	0.000267
55	0.012596	0.009289	0.812705	0.833817	0.001066	7.368791	0.727292	0.030644	9.306782	1826.792	99.91612	0.000272
56	0.012521	0.008679	0.836636	0.836072	0.001226	7.046341	0.721265	0.031433	9.309103	1838.484	99.89366	0.000272
57	0.012501	0.008495	0.835579	0.8367	0.001215	7.254696	0.720723	0.030438	9.223218	1833.097	99.90654	0.000267
58	0.012481	0.008425	0.844629	0.83599	0.001225	7.433976	0.714936	0.031412	9.270665	1838.642	99.8712	0.000281
59	0.012495	0.008621	0.817748	0.833731	0.000922	9.308805	0.720223	0.029671	9.137366	1825.699	99.8907	0.000264
60	0.012491	0.008583	0.827124	0.833069	0.000954	8.925324	0.719496	0.030502	9.239832	1829.575	99.88545	0.000267

Table E.3 Parameters and SOH values extracted from the ECM of Cell 3 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
61	0.013062	0.01019	0.945783	0.867146	0.004523	1.889219	0.741176	0.030139	8.563841	1796.381	99.93404	0.000278
62	0.013004	0.010644	0.946281	0.846448	0.003616	2.369183	0.737348	0.028458	8.172015	1790.575	99.95613	0.000232
63	0.01407	0.010453	0.969938	0.850608	0.003975	2.189611	0.736903	0.030295	8.459745	1795.459	99.94686	0.000236
64	0.013693	0.010638	0.880681	0.826467	0.001761	4.51505	0.731749	0.028352	8.215296	1799.978	99.92831	0.000254
65	0.012885	0.00832	0.875581	0.831325	0.001208	7.941801	0.711098	0.031526	9.349097	1824.137	99.87528	0.000275
66	0.012814	0.00811	0.897965	0.828338	0.001209	8.691448	0.704396	0.031056	9.205999	1827.451	99.88809	0.000263
67	0.012594	0.00432	2.013425	0.807059	0.005165	2.509364	0.71261	0.026033	8.230096	1818.465	99.81014	0.000338
68	0.012758	0.00783	0.858214	0.833173	0.001116	10	0.709087	0.028937	8.9954	1814.148	99.89321	0.000251
69	0.012719	0.007721	0.921935	0.830908	0.001126	7.251546	0.701056	0.031975	9.540159	1829.141	99.90747	0.000234
70	0.01334	0.011127	0.912141	0.815492	0.001577	5.458911	0.719913	0.032464	8.565859	1824.365	99.93664	0.00025
71	0.013062	0.01019	0.945783	0.867146	0.004523	1.889219	0.741176	0.030139	8.563841	1796.305	99.93404	0.000278
72	0.013004	0.010644	0.946281	0.846448	0.003616	2.369183	0.737348	0.028458	8.172015	1770.779	99.95613	0.000232
73	0.01407	0.010453	0.969938	0.850608	0.003975	2.189611	0.736903	0.030295	8.459745	1809.839	99.94686	0.000236
74	0.013693	0.010638	0.880681	0.826467	0.001761	4.51505	0.731749	0.028352	8.215296	1798.928	99.92831	0.000254
75	0.012885	0.00832	0.875581	0.831325	0.001208	7.941801	0.711098	0.031526	9.349097	1820.588	99.87528	0.000275
76	0.012814	0.00811	0.897965	0.828338	0.001209	8.691448	0.704396	0.031056	9.205999	1820.645	99.88809	0.000263
77	0.012594	0.00432	2.013425	0.807059	0.005165	2.509364	0.71261	0.026033	8.230096	1815.587	99.81014	0.000338
78	0.012758	0.00783	0.858214	0.833173	0.001116	10	0.709087	0.028937	8.9954	1811.575	99.89321	0.000251
79	0.012719	0.007721	0.921935	0.830908	0.001126	7.251546	0.701056	0.031975	9.540159	1826.848	99.90747	0.000234
80	0.01334	0.011127	0.912141	0.815492	0.001577	5.458911	0.719913	0.032464	8.565859	1812.973	99.93664	0.00025

Table E.3 Parameters and SOH values extracted from the ECM of Cell 3 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
81	0.013129	0.010213	0.956368	0.833469	0.002664	3.211339	0.723025	0.03301	9.406881	1795.985	99.93722	0.000268
82	0.013166	0.010897	0.971102	0.819831	0.002356	3.803758	0.719117	0.034782	9.490448	1798.821	99.94342	0.00024
83	0.013062	0.010366	0.945638	0.825656	0.002159	3.986146	0.717656	0.031502	8.7944	1804.381	99.92446	0.000266
84	0.01259	0.008553	0.919538	0.818864	0.00105	9.999036	0.706073	0.029903	9.177982	1801.249	99.88349	0.00025
85	0.013031	0.010159	0.933256	0.827144	0.002091	3.921109	0.724874	0.031483	9.512875	1777.515	99.92909	0.000255
86	0.012542	0.008452	0.95582	0.816843	0.00112	9.952986	0.693861	0.033667	9.587465	1821.851	99.88555	0.000274
87	0.012297	0.004964	2.323466	0.75831	0.004835	3.208609	0.696609	0.029133	8.93726	1815.598	99.84947	0.000343
88	0.012507	0.008011	0.962774	0.818261	0.001224	9.999965	0.695377	0.030986	9.194565	1814.149	99.88966	0.000251
89	0.012497	0.008022	0.960582	0.819188	0.001178	9.999978	0.691524	0.033198	9.562721	1821.559	99.8858	0.000269
90	0.012501	0.007972	0.950858	0.819489	0.001138	9.999868	0.697184	0.030872	9.34137	1806.793	99.89983	0.00025
91	0.01279	0.009689	0.950215	0.812	0.00123	7.53191	0.710829	0.030399	9.054946	1792.74	99.93488	0.000243
92	0.012528	0.00835	0.968978	0.81604	0.001197	9.999981	0.696141	0.032142	9.367136	1814.412	99.92273	0.00024
93	0.012469	0.008053	0.973318	0.817152	0.001215	9.998881	0.692639	0.031582	9.283467	1812.654	99.8823	0.000258
94	0.01147	0.010825	0.6729	0.915627	0.002262	4.438511	0.621073	0.130247	9.535009	1814.095	98.93537	0.006887
95	0.012452	0.007852	0.982798	0.818157	0.001295	10	0.68797	0.033102	9.573756	1816.454	99.88572	0.000269
96	0.012446	0.007715	0.983648	0.818325	0.001316	10	0.691708	0.030301	9.153507	1806.451	99.9072	0.000242
97	0.012146	0.005425	2.299369	0.740983	0.003845	4.208937	0.683793	0.029187	8.865624	1815.439	99.78525	0.000353
98	0.012392	0.007175	1.012614	0.819595	0.001704	10	0.679919	0.030407	8.726731	1819.626	99.89927	0.000246
99	0.012776	0.009434	0.993459	0.806634	0.001309	8.089996	0.701242	0.030982	8.749675	1803.663	99.93393	0.000226
100	0.012894	0.010176	0.9922	0.803276	0.001283	7.646782	0.702117	0.034047	9.365835	1805.871	99.9361	0.000245

Table E.3 Parameters and SOH values extracted from the ECM of Cell 3 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
101	0.019175	0.007378	1.145302	0.843862	0.002997	2.79694	0.697391	0.031183	9.252613	1794.65	99.92368	0.00021
102	0.020942	0.007434	1.179257	0.827608	0.002474	3.434953	0.68574	0.029786	8.626977	1810.427	99.95064	0.000166
103	0.022994	0.007481	1.163676	0.824743	0.002337	3.681331	0.677937	0.031891	9.139777	1813.123	99.96122	0.000195
104	0.024037	0.00355	2.930772	0.782907	0.00645	2.426553	0.684989	0.027167	8.347194	1798.41	99.89909	0.000232
105	0.023975	0.007501	1.168204	0.820662	0.00219	3.884932	0.677584	0.031868	9.134162	1812.254	99.96172	0.000193
106	0.024188	0.007167	1.13318	0.828251	0.002263	3.566406	0.678257	0.031918	9.58243	1795.952	99.93432	0.000212
107	0.024244	0.007889	1.191142	0.832103	0.003064	2.952079	0.683478	0.035118	9.491272	1807.317	99.94572	0.000214
108	0.024609	0.008721	1.151163	0.853798	0.004273	2.096641	0.702696	0.036637	10	1786.416	99.96417	0.000227
109	0.02315	0.007724	1.232076	0.865405	0.00491	1.795982	0.719376	0.02499	8.042207	1712.556	99.98029	0.000145
110	0.023219	0.008998	1.115451	0.848334	0.003941	2.172569	0.722808	0.024358	7.568737	1187.003	99.97766	0.000137
111	0.012243	0.010134	1.109623	0.809493	0.002263	4.350477	0.704826	0.032088	8.863204	1783.755	99.97156	0.000196
112	0.012258	0.009892	1.115143	0.813896	0.002487	3.858827	0.710368	0.028579	8.284693	1765.931	99.97038	0.000162
113	0.012364	0.00971	1.161087	0.826903	0.003487	2.854538	0.713069	0.033015	9.247567	1766.039	99.9602	0.000193
114	0.012407	0.010262	1.159283	0.817532	0.003187	3.273538	0.704908	0.035954	9.350389	1786.469	99.9511	0.000206
115	0.011668	0.008038	1.093773	0.80489	0.001156	9.977448	0.688956	0.031257	9.481126	1782.04	99.92121	0.000207
116	0.011531	0.007379	1.137543	0.806424	0.00136	10	0.681406	0.029308	8.841859	1791.262	99.94104	0.000193
117	0.011467	0.00736	1.171315	0.804053	0.001293	9.996539	0.671399	0.032604	9.437481	1801.148	99.9126	0.000201
118	0.011442	0.007131	1.188676	0.804208	0.001436	10	0.669317	0.031243	9.132321	1800.301	99.93929	0.000198
119	0.011445	0.007144	1.162644	0.806624	0.001358	9.99984	0.67296	0.031754	9.347598	1797.773	99.93972	0.000212
120	0.011347	0.006629	1.17359	0.811243	0.001393	10	0.668105	0.03224	9.697625	1795.098	99.92078	0.000212

Table E.3 Parameters and SOH values extracted from the ECM of Cell 3 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
121	0.01201	0.009829	1.124094	0.806335	0.002082	4.707133	0.69978	0.031243	8.69938	1770.841	99.94604	0.000184
122	0.01417	0.009716	1.139701	0.815065	0.002567	3.856334	0.707754	0.034689	9.680915	1760.111	99.95186	0.000201
123	0.013722	0.009661	1.08783	0.803709	0.001577	6.151789	0.697072	0.033909	10	1769.618	99.90618	0.00027
124	0.012927	0.007278	1.165052	0.805937	0.001362	10	0.672823	0.033195	9.667921	1791.627	99.9096	0.000208
125	0.012849	0.007096	1.183877	0.80685	0.001408	10	0.669873	0.034105	9.801286	1795.432	99.91115	0.000213
126	0.012798	0.00694	1.190913	0.806898	0.001497	10	0.667892	0.032499	9.460137	1792.055	99.92293	0.000199
127	0.01277	0.006985	1.186285	0.806776	0.001404	10	0.667227	0.032753	9.563593	1790.868	99.92989	0.000198
128	0.012806	0.008322	1.082805	0.786226	0.000001	0.000001	0.665978	0.032987	9.522182	1792.876	99.89427	0.000206
129	0.012736	0.006975	1.200903	0.805303	0.001441	9.999901	0.664969	0.033816	9.789476	1792.688	99.93475	0.000205
130	0.012696	0.006713	1.216172	0.807386	0.001494	10	0.662097	0.033971	9.828759	1794.7	99.91327	0.00021
131	0.012298	0.007135	1.111221	0.793953	0.000001	0.000001	0.653489	0.03339	10	1789.33	99.86922	0.000228
132	0.012281	0.007184	1.155945	0.787016	0.000001	0.000001	0.645655	0.030341	9.147496	1788.257	99.91484	0.000195
133	0.012237	0.005511	1.21278	0.822748	0.001719	10	0.655592	0.030931	9.571715	1781.287	99.90889	0.00021
134	0.01223	0.005158	1.230282	0.829724	0.002204	8.651041	0.652458	0.030155	9.147851	1787.602	99.92019	0.000201
135	0.012229	0.005862	1.234686	0.815397	0.001474	10	0.654283	0.032886	9.947106	1783.539	99.88728	0.00021
136	0.011794	0.001142	6.621409	0.853229	0.006918	2.399501	0.65741	0.028054	8.848746	1779.409	99.82143	0.000292
137	0.012072	0.004964	1.215942	0.832179	0.00164	10	0.649666	0.029942	9.439468	1780.808	99.87029	0.000203
138	0.012004	0.006064	1.161603	0.79866	0.000009	0.000001	0.637601	0.031705	10	1786.449	99.85738	0.000215
139	0.01189	0.004429	1.266873	0.840366	0.00168	10	0.636071	0.031876	10	1790.316	99.89714	0.000223
140	0.01188	0.004419	1.291684	0.838562	0.0017	9.281408	0.633448	0.031567	9.959476	1785.877	99.85249	0.000218

Table E.3 Parameters and SOH values extracted from the ECM of Cell 3 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
141	0.012079	0.006486	1.196233	0.789227	0.000011	0.000001	0.634007	0.032758	10	1784.105	99.89366	0.000215
142	0.012127	0.006574	1.182882	0.790288	0.000001	0.000001	0.640054	0.032759	9.962272	1783.719	99.90848	0.000206
143	0.012082	0.005002	1.248486	0.827445	0.001735	10	0.641198	0.031096	9.591603	1780.239	99.89389	0.000204
144	0.012181	0.006761	1.17431	0.788306	0.000001	0.000001	0.638787	0.032927	9.897885	1782.368	99.88685	0.000204
145	0.012143	0.005098	1.239505	0.825881	0.001792	10	0.64684	0.030644	9.526862	1775.218	99.91928	0.000212
146	0.011602	0.001376	5.958573	0.831106	0.006089	2.924797	0.635277	0.027909	8.850829	1780.154	99.82965	0.00029
147	0.012858	0.007015	1.726306	0.777851	0.004082	4.489475	0.669819	0.033596	8.665281	1779.642	99.94405	0.000224
148	0.013157	0.010493	1.165219	0.78098	0.001348	8.316658	0.687397	0.031996	8.746683	1753.501	99.96408	0.00018
149	0.01327	0.010816	1.173517	0.787132	0.00183	5.912496	0.692379	0.034006	9.286303	1749.436	99.97013	0.000185
150	0.013166	0.010693	1.161741	0.780548	0.001363	8.24602	0.68843	0.03293	8.92777	1749.359	99.95417	0.000182
151	0.012467	0.008274	1.159235	0.776472	0.000001	0.000001	0.651309	0.034975	9.999992	1771.72	99.93445	0.000216
152	0.012331	0.006545	1.297359	0.801695	0.001632	10	0.649341	0.035245	9.980537	1773.869	99.91572	0.000211
153	0.012316	0.006516	1.287484	0.802543	0.001603	10	0.651512	0.034511	9.789771	1774.008	99.88917	0.000216
154	0.012329	0.006281	1.274009	0.806287	0.001806	10	0.652835	0.03299	9.64643	1767.527	99.93394	0.000194
155	0.012317	0.00634	1.265748	0.80558	0.001702	10	0.657599	0.031609	9.315574	1764.066	99.89634	0.000198
156	0.012294	0.006196	1.293255	0.80551	0.001921	10	0.648919	0.033503	9.57843	1771.266	99.91108	0.0002
157	0.01171	0.001329	6.045316	0.841818	0.006892	2.59606	0.646851	0.02888	8.871514	1766.649	99.84209	0.000282
158	0.014102	0.010533	1.193291	0.795573	0.002383	4.542792	0.694575	0.034591	9.43057	1730.259	99.96292	0.000208
159	0.013825	0.010181	1.155083	0.78975	0.001552	6.70305	0.689608	0.030415	8.629401	1735.126	99.9647	0.0002
160	0.013707	0.010228	1.193797	0.780755	0.001386	7.898337	0.681316	0.032275	8.901962	1743.933	99.97164	0.000173

Table E.3 Parameters and SOH values extracted from the ECM of Cell 3 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
161	0.013658	0.011276	1.100197	0.764093	0.000005	0.000001	0.679032	0.037342	9.999998	1749.9	99.95786	0.000209
162	0.013557	0.010837	1.11005	0.765735	0.000002	0.000001	0.673792	0.031223	8.56306	1752.986	99.95702	0.000187
163	0.013254	0.00848	1.223433	0.787776	0.001277	9.987937	0.667359	0.034868	9.903878	1754.994	99.95098	0.000222
164	0.012995	0.008692	1.196319	0.768924	0.00001	0.000001	0.649814	0.034654	9.661597	1765.515	99.93635	0.000189
165	0.012918	0.006775	1.293254	0.797631	0.001798	10	0.655511	0.034	9.755424	1759.525	99.93795	0.000194
166	0.01286	0.006661	1.327546	0.796325	0.001921	10	0.649334	0.034223	9.633639	1765.216	99.93755	0.000193
167	0.012843	0.006677	1.332182	0.795239	0.001856	10	0.651004	0.033157	9.481316	1760.195	99.92965	0.000193
168	0.012727	0.007714	1.225113	0.773313	0.000001	0.000001	0.6422	0.034778	10	1766.163	99.92244	0.000203
169	0.013323	0.00937	1.259277	0.775736	0.001406	9.999608	0.670908	0.034773	9.385571	1748.684	99.94295	0.000194
170	0.013176	0.008853	1.270511	0.779153	0.00134	9.876996	0.666858	0.034032	9.284068	1752.886	99.95058	0.000175
171	0.013295	0.009583	1.262096	0.773618	0.001385	9.974922	0.670729	0.032612	8.999438	1741.533	99.95989	0.00018
172	0.013162	0.009746	1.12554	0.769926	0.000001	0.008301	0.669711	0.033272	9.706901	1738.594	99.95047	0.000199
173	0.012756	0.006526	1.369603	0.795173	0.001842	10	0.642134	0.0356	10	1763.996	99.94293	0.000205
174	0.012741	0.008064	1.226056	0.770495	0.000029	0.000001	0.641058	0.035347	9.958126	1762.497	99.90376	0.000211
175	0.012655	0.006316	1.37089	0.797061	0.001743	10	0.642361	0.034604	9.890834	1760.461	99.91054	0.000203
176	0.012209	0.001503	5.773028	0.839875	0.007129	2.60896	0.644341	0.030552	9.168825	1760.588	99.86814	0.000277
177	0.01264	0.006129	1.365349	0.799748	0.001813	10	0.642011	0.034285	9.907586	1757.599	99.9248	0.0002
178	0.012691	0.007857	1.251327	0.769086	0.000001	0.000001	0.636336	0.035268	10	1761.106	99.92584	0.0002
179	0.013274	0.009164	1.285845	0.774971	0.001493	10	0.665637	0.030986	8.261755	1746.045	99.9484	0.000183
180	0.013413	0.010296	1.235269	0.773527	0.001333	9.093288	0.671758	0.037039	10	1741.8	99.94823	0.000221

Table E.3 Parameters and SOH values extracted from the ECM of Cell 3 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
181	0.013293	0.01075	1.233686	0.772343	0.001365	8.560011	0.681172	0.030942	8.469417	1708.313	99.93969	0.000185
182	0.013049	0.011135	1.156381	0.756995	0.000001	0.000001	0.675719	0.02992	8.408538	1713.385	99.96412	0.00017
183	0.012431	0.007123	1.383095	0.786811	0.001827	10	0.64751	0.0352	9.82647	1741.802	99.93988	0.000194
184	0.012392	0.00689	1.378941	0.788656	0.001811	10	0.64782	0.035152	10	1739.201	99.946	0.000204
185	0.012353	0.006636	1.405875	0.789882	0.002072	10	0.639001	0.034034	9.503746	1743.601	99.90615	0.000199
186	0.012323	0.006605	1.422504	0.789303	0.002059	10	0.633108	0.036305	10	1747.316	99.9348	0.000213
187	0.012319	0.006759	1.424258	0.787517	0.001868	10	0.637363	0.036035	9.95526	1745.344	99.92479	0.000209
188	0.01238	0.008582	1.286972	0.758918	0.000001	0.000001	0.636473	0.036173	9.978916	1746.764	99.93118	0.000195
189	0.012102	0.005762	1.463796	0.797893	0.00198	10	0.629947	0.033449	9.628966	1743.151	99.89324	0.000201
190	0.013241	0.011377	1.303665	0.76761	0.001851	6.810732	0.672191	0.034844	8.797553	1727.49	99.97797	0.000179
191	0.013495	0.0114	1.166999	0.753675	0.000003	0.000001	0.677295	0.028728	8.346906	1698.458	99.95113	0.00018
192	0.013643	0.0112	1.269547	0.767579	0.001541	7.91512	0.676218	0.038006	9.866644	1717.207	99.96835	0.000157
193	0.013349	0.010074	1.305207	0.766688	0.001386	9.999196	0.666505	0.037045	9.852338	1726.53	99.96841	0.000195
194	0.013151	0.009133	1.343206	0.770529	0.001466	9.983598	0.655696	0.035219	9.480563	1731.599	99.96331	0.000205
195	0.013051	0.008634	1.412742	0.767465	0.001758	10	0.653556	0.034069	9.048664	1730.983	99.90935	0.000205
196	0.012277	0.001632	5.569836	0.844182	0.007844	2.526546	0.645744	0.031352	9.162255	1733.038	99.90503	0.00027
197	0.012633	0.006831	1.469379	0.783578	0.001926	10	0.634561	0.036654	10	1744.845	99.94847	0.000203
198	0.012664	0.008605	1.31499	0.756547	0.000012	0.000001	0.634539	0.035984	9.860726	1741.195	99.94818	0.000186
199	0.012599	0.006633	1.47679	0.78392	0.00197	10	0.636253	0.035164	9.820588	1737.537	99.92124	0.000197
200	0.01244	0.005807	1.45688	0.796709	0.002079	10	0.632184	0.034613	10	1736.707	99.91679	0.000217

Table E.4 Parameters and SOH values extracted from the ECM of Cell 4

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
1	0.051615	0.016013	0.607314	0.859994	0.000001	0.000001	0.803509	0.018889	6.671369	1781.577	99.92982	0.0003
2	0.042578	0.01276	0.672779	0.858958	0.000005	0.000001	0.79554	0.021139	7.248898	1821.86	99.87341	0.00031
3	0.099359	0.011997	0.674632	0.859981	0.000002	0.000001	0.789708	0.020038	7.20723	708.7575	99.889	0.000353
4	0.039416	0.011576	0.614083	0.873881	0.000001	0.000001	0.81021	0.015806	6.738237	1490.259	99.83629	0.000312
5	0.054337	0.000016	0.000001	0.549997	0.011619	0.884431	0.803726	0.016051	6.646892	1827.275	99.81547	0.000347
6	0.034421	0.010771	0.724635	0.855683	0.000003	0.000001	0.784634	0.021824	7.840228	1892.625	99.86034	0.000311
7	0.031374	0.007082	0.808085	0.880218	0.000823	9.300804	0.759173	0.026216	8.785506	1889.953	99.77773	0.000277
8	0.030379	0.00755	0.72835	0.875368	0.000001	0.000001	0.765406	0.029402	10	1897.605	99.84212	0.000295
9	0.029983	0.006125	0.791186	0.889388	0.001269	10	0.756031	0.029512	10	1897.411	99.83188	0.000281
10	0.029101	0.000001	0.000034	0.4	0.007878	1.328424	0.756613	0.025861	9.104628	1905.204	99.74414	0.000362
11	0.019736	0.005681	0.847309	0.869734	0.000001	0.000001	0.718561	0.027952	10	1915.999	99.8618	0.000222
12	0.018784	0.005883	0.822007	0.874331	0.000001	0.000001	0.734576	0.026906	9.597023	1912.425	99.82088	0.000238
13	0.018402	0.00276	2.778488	0.813834	0.003584	3.090438	0.731296	0.024887	9.157358	1911.558	99.59849	0.000328
14	0.018726	0.005877	0.808398	0.876715	0.000001	0.000001	0.740058	0.027545	10	1903.52	99.76752	0.000245
15	0.018363	0.001067	6.308017	0.848586	0.005406	1.97647	0.735438	0.023246	8.583276	1909.951	99.68604	0.000317
16	0.018763	0.004562	0.800346	0.909886	0.001361	10	0.741325	0.026706	10	1894.988	99.80168	0.000256
17	0.018573	0.002515	2.833499	0.830559	0.003776	2.764755	0.736768	0.023417	8.875508	1900.176	99.63541	0.000318
18	0.018876	0.0059	0.871732	0.863921	0.000001	0.000001	0.721941	0.027521	10	1903.791	99.80928	0.000222
19	0.018864	0.004657	0.864147	0.900012	0.001213	10	0.735177	0.027253	10	1901.058	99.84986	0.000243
20	0.020019	0.006607	0.838587	0.877871	0.001517	10	0.753704	0.025802	8.846559	1881.173	99.7965	0.000273

Table E.4 Parameters and SOH values extracted from the ECM of Cell 4 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
21	0.020018	0.008104	0.815362	0.855923	0.000003	0.000001	0.753704	0.025966	8.879556	1878.33	99.80112	0.00027
22	0.029691	0.008884	0.814167	0.850692	0.000001	0.000001	0.759581	0.02285	7.889838	1825.389	99.86308	0.000252
23	0.028496	0.008925	0.770581	0.896326	0.001705	3.705243	0.773645	0.01924	5.20957	1840.127	95.1382	0.001656
24	0.04	0.010156	0.784559	0.848537	0.000001	0.000001	0.769518	0.021994	7.907319	1271.049	99.87732	0.000248
25	0.033516	0.00746	0.687808	0.885709	0.000003	0.000001	0.786687	0.018767	7.722982	1890.248	99.79701	0.000272
26	0.030804	0.006438	0.841355	0.865752	0.000001	0.000001	0.741336	0.027447	9.999991	1896.339	99.84572	0.000273
27	0.029965	0.001134	4.616911	0.918294	0.005708	1.827201	0.738551	0.023688	8.697728	1895.201	99.67271	0.000305
28	0.030057	0.006327	0.868763	0.861725	0.000001	0.000001	0.738985	0.023179	8.531671	1894.836	99.82404	0.000242
29	0.030152	0.00622	0.859623	0.865346	0.000001	0.000001	0.736929	0.027682	10	1894.723	99.83187	0.000247
30	0.029408	0.000001	0.000001	0.4	0.00683	1.636381	0.734391	0.025099	9.393236	1903.175	99.74865	0.000336
31	0.029286	0.009756	0.709025	0.866254	0.000019	0.000001	0.792349	0.017349	6.938871	1350.053	99.89239	0.000244
32	0.029883	0.009902	0.812798	0.844309	0.000001	0.000001	0.765171	0.021414	7.665061	1826.538	99.81225	0.000272
33	0.039552	0.001307	3.934162	0.97626	0.008672	1.139382	0.787779	0.018957	7.316815	1293.506	99.83316	0.000308
34	0.036618	0.007618	0.872404	0.850733	0.000002	0.000001	0.743665	0.023233	8.176301	1884.517	99.82579	0.000247
35	0.031624	0.000001	0.000001	0.797043	0.007372	1.555868	0.738451	0.025353	9.424711	1884.413	99.74833	0.000329
36	0.030402	0.00646	0.885465	0.857678	0.000001	0.000001	0.738255	0.024221	8.795302	1893.679	99.84342	0.000248
37	0.029452	0.001245	4.642378	0.904787	0.005732	1.951529	0.730069	0.023617	8.62856	1896.575	99.78021	0.00031
38	0.028698	0.006432	0.876991	0.860129	0.000011	0.000001	0.730328	0.028591	10	1895.42	99.76585	0.000271
39	0.028074	0.005506	1.008755	0.871647	0.00093	9.991379	0.723566	0.028468	10	1896.839	99.82947	0.000251
40	0.028162	0.006328	0.897152	0.856994	0.000001	0.000001	0.729978	0.027508	10	1888.22	99.83604	0.000253

Table E.4 Parameters and SOH values extracted from the ECM of Cell 4 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
41	0.028679	0.009055	0.860308	0.84202	0.000002	0.000001	0.752919	0.027396	9.217705	1867.691	99.90494	0.000283
42	0.028425	0.009254	0.859228	0.84022	0.000002	0.000001	0.755388	0.023603	8.178447	1862.706	99.86908	0.000269
43	0.028661	0.00729	0.858454	0.866486	0.001924	10	0.756931	0.022063	7.869555	1856.842	99.86892	0.000268
44	0.028693	0.009349	0.873648	0.837738	0.000004	0.000001	0.75373	0.022936	8.027698	1861.363	99.88886	0.000259
45	0.030003	0.006671	0.905169	0.854542	0.000001	0.000001	0.736571	0.023704	8.605418	1882.695	99.82304	0.000237
46	0.033047	0.008275	0.86022	0.847531	0.000001	0.000001	0.751505	0.027567	10	1852.044	99.90955	0.000285
47	0.029474	0.001351	4.652956	0.889974	0.00581	2.023349	0.727217	0.023442	8.55133	1889.994	99.79794	0.000305
48	0.029727	0.006537	0.928214	0.851381	0.000001	0.000001	0.724271	0.028864	10	1894.051	99.84312	0.000267
49	0.02981	0.006451	0.915208	0.853744	0.000002	0.000001	0.729355	0.027683	10	1880.485	99.86285	0.000242
50	0.029453	0.000002	0.008414	0.4	0.007098	1.721933	0.726569	0.022731	8.464076	1887.187	99.7438	0.000319
51	0.032933	0.008869	0.906887	0.835303	0.000001	0.000001	0.746405	0.021962	7.764369	1858.048	99.88303	0.00025
52	0.032665	0.009146	0.889768	0.837027	0.000001	0.000001	0.753489	0.02116	7.5332	1851.135	99.90101	0.000236
53	0.042789	0.000913	5.992106	0.967564	0.008567	1.202137	0.777111	0.02186	8.149809	1202.572	99.82148	0.000334
54	0.035863	0.009418	0.741727	0.864529	0.000001	0.000001	0.779218	0.02017	7.495961	1283.764	99.87715	0.000254
55	0.035742	0.008658	0.754124	0.865281	0.000004	0.000001	0.776535	0.021296	8.173368	1308.053	99.84535	0.00027
56	0.032786	0.006953	0.908136	0.850703	0.000001	0.000001	0.737863	0.027721	9.999997	1869.418	99.86216	0.00025
57	0.030379	0.0015	3.7583	0.913386	0.005669	2.060276	0.726936	0.024905	8.945601	1886.555	99.77705	0.000299
58	0.030346	0.006505	0.951042	0.848678	0.000001	0.000001	0.720498	0.028479	10	1884.75	99.79473	0.000264
59	0.03009	0.006489	0.940227	0.849712	0.000002	0.000001	0.728413	0.028719	10	1889.966	99.88664	0.000245
60	0.02949	0.000002	0.000001	1	0.007081	1.789245	0.721588	0.024137	8.915999	1885.365	99.74299	0.000325

Table E.4 Parameters and SOH values extracted from the ECM of Cell 4 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
61	0.03187	0.008666	0.896177	0.838991	0.000001	0.000001	0.751511	0.023369	8.328804	1842.946	99.85015	0.000275
62	0.033901	0.009594	0.88973	0.834178	0.000003	0.000001	0.751631	0.025628	8.603253	1845.18	99.79409	0.000284
63	0.036106	0.009273	0.965826	0.839186	0.000987	9.987871	0.749031	0.02428	8.240116	1843.711	99.92204	0.000268
64	0.038325	0.009347	0.874524	0.838346	0.000002	0.000001	0.765151	0.021898	8.232821	1821.788	99.88017	0.000278
65	0.031824	0.006738	0.931668	0.847856	0.000001	0.000001	0.733404	0.027995	9.999958	1873.403	99.86842	0.000256
66	0.030213	0.006593	0.976643	0.844487	0.000001	0.000001	0.718142	0.028504	10	1881.619	99.85871	0.000245
67	0.029605	0.001299	4.493095	0.904498	0.005686	2.089553	0.722755	0.025164	8.997468	1885.463	99.68686	0.000321
68	0.029895	0.006403	1.005263	0.842943	0.000001	0.000001	0.724182	0.021418	8.053116	1871.37	99.83343	0.000235
69	0.029724	0.006345	0.980099	0.846347	0.000004	0.000001	0.717301	0.029117	10	1887.68	99.77252	0.000253
70	0.029064	0.000001	0.000001	0.4	0.006979	1.894642	0.712729	0.028338	10	1886.785	99.66215	0.000339
71	0.029567	0.008376	0.959725	0.832664	0.000001	0.000001	0.731092	0.031051	10	1880.239	99.90238	0.000247
72	0.028853	0.009578	0.932471	0.828798	0.000001	0.000001	0.743969	0.026461	8.732666	1857.778	99.91777	0.000252
73	0.031179	0.007078	0.955485	0.857806	0.00197	10	0.734997	0.030283	10	1856.048	99.84295	0.000259
74	0.031477	0.008928	0.936932	0.831107	0.000003	0.000001	0.744398	0.025208	8.89181	1841.279	99.91883	0.000266
75	0.031457	0.006784	0.961651	0.84577	0.000001	0.000001	0.725111	0.028357	9.999994	1870.536	99.86739	0.000262
76	0.031191	0.006645	1.000427	0.843848	0.000001	0.000001	0.717878	0.029064	9.999997	1881.946	99.87425	0.000236
77	0.030663	0.001271	4.742649	0.902351	0.005751	2.085376	0.723205	0.023984	8.78578	1871.119	99.67383	0.000312
78	0.030823	0.006486	1.028737	0.839242	0.000001	0.000001	0.708507	0.028715	10	1880.613	99.87391	0.000244
79	0.030774	0.006447	0.999186	0.842195	0.000003	0.000001	0.713535	0.029243	10	1883.679	99.78131	0.000257
80	0.030019	0.000055	0.000001	0.549982	0.007026	1.860298	0.716553	0.024714	9.260316	1868.817	99.74128	0.000321

Table E.4 Parameters and SOH values extracted from the ECM of Cell 4 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
81	0.030745	0.008156	1.00255	0.826163	0.000001	0.000001	0.729824	0.021549	7.52967	1847.286	99.85474	0.000254
82	0.092722	0.00781	0.898739	0.842984	0.000001	0.000001	0.76008	0.014386	6.67132	1670.456	99.83976	0.000258
83	0.040871	0.001234	5.001502	0.932238	0.007774	1.642978	0.740045	0.021582	7.951269	1833.57	99.83799	0.000298
84	0.037974	0.004588	0.51709	0.961221	0.003874	10	0.732401	0.01781	6.472277	1832.138	99.13707	0.000527
85	0.033987	0.006703	1.019156	0.837444	0.000001	0.000001	0.720192	0.028579	9.999976	1873.46	99.88732	0.000239
86	0.031352	0.006499	1.025317	0.839035	0.000001	0.000001	0.714743	0.028204	9.999919	1871.52	99.89772	0.000249
87	0.030733	0.005294	1.199674	0.85308	0.001243	10	0.703514	0.028966	10	1883.083	99.86091	0.000243
88	0.030351	0.006395	1.089098	0.831931	0.000001	0.000001	0.702548	0.02512	8.772121	1883.651	99.84899	0.000231
89	0.029748	0.006355	1.071016	0.834986	0.000004	0.000001	0.711426	0.024666	8.691349	1881.77	99.85348	0.000225
90	0.028984	0.000012	0.000001	0.999999	0.006962	2.005058	0.706698	0.025605	9.187682	1883.987	99.75749	0.000316
91	0.034417	0.00992	0.740438	0.864017	0.000003	0.000001	0.783693	0.020321	8.562312	437.2188	99.80721	0.00031
92	0.035402	0.009724	0.966777	0.821976	0.000001	0.000001	0.745404	0.022923	7.975477	1818.791	99.87071	0.000268
93	0.035585	0.009379	0.93305	0.854997	0.00128	5.661849	0.777816	0.01533	6.475976	741.1795	99.89201	0.000238
94	0.033143	0.009301	0.998156	0.819415	0.000007	0.000001	0.735658	0.021708	7.612309	1837.253	99.90702	0.000234
95	0.03214	0.008488	0.970227	0.829605	0.000016	0.000001	0.73569	0.028525	10	1835.434	99.90481	0.000258
96	0.030852	0.007242	1.071636	0.824188	0.000001	0.000001	0.706974	0.028483	10	1863.075	99.85816	0.00026
97	0.029633	0.005416	1.214868	0.852001	0.001227	10	0.705188	0.029239	10	1878.611	99.87612	0.00024
98	0.030221	0.006518	1.083787	0.831272	0.000001	0.000001	0.702879	0.029778	10	1881.429	99.79683	0.000252
99	0.030128	0.006506	1.109358	0.827289	0.000002	0.000001	0.695786	0.029465	10	1880.069	99.85293	0.000255
100	0.029707	0.000001	0.000001	0.999999	0.007197	2.061477	0.697621	0.026696	9.345785	1882.153	99.79967	0.00033

Table E.4 Parameters and SOH values extracted from the ECM of Cell 4 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
101	0.038674	0.009262	0.768678	0.863885	0.000001	0.000001	0.786541	0.013182	5.643596	663.2933	99.82917	0.000284
102	0.056745	0.00855	0.834063	0.85103	0.000002	0.000001	0.776417	0.013656	6.256511	756.4133	99.86018	0.000236
103	0.038706	0.00141	3.311293	0.951061	0.005708	1.620987	0.759547	0.021965	8.554236	1273.67	99.80533	0.000311
104	0.053852	0.006537	1.058447	0.831093	0.000003	0.000001	0.723242	0.019775	7.907599	1841.704	99.82226	0.000255
105	0.038175	0.006333	1.066743	0.836953	0.000001	0.000001	0.709788	0.028516	10	1869.501	99.78878	0.000249
106	0.038269	0.006337	1.103253	0.830779	0.000001	0.000001	0.710856	0.024459	8.799616	1866.291	99.75731	0.000236
107	0.035538	0.004878	1.186929	0.862618	0.001451	10	0.703598	0.028378	10	1872.156	99.89368	0.000255
108	0.036906	0.006201	1.176634	0.822196	0.000001	0.000001	0.698259	0.022497	8.232692	1871.879	99.84664	0.000228
109	0.036738	0.005645	0.496783	0.994877	0.00108	3.65128	0.746056	0.029139	2.906566	1663.562	82.03835	0.007266
110	0.033137	0.007487	1.053987	0.878371	0.002328	2.959053	0.778874	0.014954	6.608509	575.8104	99.86773	0.00024
111	0.040573	0.009532	0.815152	0.850479	0.000001	0.000001	0.764228	0.015251	6.674587	724.0289	99.74173	0.000295
112	0.039963	0.009544	0.884319	0.838205	0.000001	0.000001	0.770018	0.015754	6.575601	783.6944	99.90014	0.000218
113	0.060623	0.009047	0.868683	0.843405	0.000004	0.000001	0.766146	0.019215	8.292952	840.6052	99.83323	0.000287
114	0.043004	0.009034	0.878401	0.840808	0.000001	0.000001	0.765728	0.01474	6.263093	800.8998	99.8658	0.000235
115	0.0402	0.006905	1.082095	0.82582	0.000009	0.000001	0.711808	0.028045	10	1848.548	99.90493	0.000254
116	0.043991	0.00656	0.864585	0.860633	0.000001	0.000001	0.750661	0.017985	7.262249	1146.894	99.80819	0.000244
117	0.042088	0.006516	0.885625	0.857777	0.000001	0.000001	0.747958	0.018561	7.484297	1167.975	99.79378	0.000246
118	0.038864	0.006539	1.143411	0.820604	0.000001	0.000001	0.706896	0.019633	7.512123	1843.075	99.83992	0.000221
119	0.039164	0.006376	0.883109	0.859793	0.000001	0.000001	0.74424	0.020116	7.968807	1186.506	99.70876	0.000272
120	0.03953	0.000046	0.000001	0.4	0.00699	1.519631	0.746466	0.018501	7.608742	1168.104	99.69129	0.000307

Table E.4 Parameters and SOH values extracted from the ECM of Cell 4 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
121	0.037325	0.010761	0.880695	0.830836	0.000001	0.000001	0.76655	0.015935	6.640599	729.1956	99.89694	0.000239
122	0.039334	0.01161	0.87471	0.829746	0.000001	0.000001	0.772775	0.016629	6.619094	751.2299	99.92461	0.000224
123	0.043368	0.007695	1.034996	0.919997	0.004249	1.765144	0.778699	0.021712	8.584416	476.3721	99.88014	0.000277
124	0.042204	0.011619	0.863879	0.830614	0.000006	0.000001	0.771159	0.016395	6.614968	722.5418	99.91386	0.00025
125	0.03952	0.008445	1.04948	0.817537	0.000001	0.000001	0.724933	0.028461	10	1831.924	99.90905	0.00025
126	0.031715	0.006875	1.137468	0.821242	0.000001	0.000001	0.702507	0.02902	10	1857.753	99.8965	0.000255
127	0.030676	0.005304	1.295669	0.843814	0.001459	10	0.694208	0.02927	10	1865.033	99.86569	0.000235
128	0.030139	0.006665	1.159573	0.819202	0.000001	0.000001	0.689622	0.029168	9.999997	1865.494	99.88144	0.000238
129	0.029785	0.00659	1.137608	0.824349	0.000002	0.000001	0.693719	0.029254	10	1864.712	99.91061	0.000241
130	0.027859	0.000024	0.000001	0.54962	0.007373	2.111105	0.693706	0.025891	9.1325	1867.027	99.7722	0.000317
131	0.037325	0.010761	0.880695	0.830836	0.000001	0.000001	0.76655	0.015935	6.640599	1849.238	99.89694	0.000239
132	0.039334	0.01161	0.87471	0.829746	0.000001	0.000001	0.772775	0.016629	6.619094	1846.958	99.92461	0.000224
133	0.043368	0.007695	1.034996	0.919997	0.004249	1.765144	0.778699	0.021712	8.584416	1848.731	99.88014	0.000277
134	0.042204	0.011619	0.863879	0.830614	0.000006	0.000001	0.771159	0.016395	6.614968	1832.095	99.91386	0.00025
135	0.03952	0.008445	1.04948	0.817537	0.000001	0.000001	0.724933	0.028461	10	1840.494	99.90905	0.00025
136	0.031715	0.006875	1.137468	0.821242	0.000001	0.000001	0.702507	0.02902	10	1864.647	99.8965	0.000255
137	0.030676	0.005304	1.295669	0.843814	0.001459	10	0.694208	0.02927	10	1859.472	99.86569	0.000235
138	0.030139	0.006665	1.159573	0.819202	0.000001	0.000001	0.689622	0.029168	9.999997	1859.902	99.88144	0.000238
139	0.029785	0.00659	1.137608	0.824349	0.000002	0.000001	0.693719	0.029254	10	1848.112	99.91061	0.000241
140	0.027859	0.000024	0.000001	0.54962	0.007373	2.111105	0.693706	0.025891	9.1325	1852.623	99.7722	0.000317

Table E.4 Parameters and SOH values extracted from the ECM of Cell 4 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
141	0.038632	0.009575	0.911694	0.833371	0.000001	0.000001	0.751577	0.020359	7.337888	1003.524	99.89159	0.000245
142	0.038129	0.007811	0.92593	0.842694	0.000014	0.000001	0.741912	0.022031	8.026424	1253.747	99.86566	0.000246
143	0.038593	0.00572	1.194841	0.84467	0.002223	10	0.702957	0.022529	7.803383	1825.798	99.87976	0.000227
144	0.038215	0.008195	1.192499	0.801587	0.000003	0.000001	0.707074	0.021753	7.667156	1816.515	99.88753	0.000235
145	0.038441	0.006916	1.291683	0.80258	0.000001	0.000001	0.686772	0.023033	8.128743	1838.135	99.86879	0.000234
146	0.038673	0.006414	1.207057	0.820421	0.000001	0.000001	0.694308	0.029755	10	1844.455	99.80348	0.000248
147	0.039149	0.004955	1.393903	0.844395	0.001435	10	0.68241	0.02918	10	1843.123	99.82971	0.000261
148	0.039698	0.006278	1.247928	0.815784	0.000001	0.000001	0.686247	0.028667	10	1839.8	99.89991	0.000251
149	0.040279	0.006339	1.287507	0.809916	0.000001	0.000001	0.686549	0.023362	8.397692	1840.541	99.85604	0.000236
150	0.041179	0.006262	1.25273	0.815636	0.000004	0.000001	0.684129	0.029107	10	1844.834	99.90218	0.000254
151	0.04495	0.008674	1.171342	0.800744	0.000001	0.000001	0.707803	0.023758	8.267934	1805.924	99.91338	0.000249
152	0.039381	0.008342	0.990186	0.826279	0.000004	0.000001	0.744135	0.015515	6.715146	1418.798	99.91017	0.000205
153	0.043532	0.007989	1.055512	0.838456	0.00094	9.854416	0.753514	0.016129	6.866287	808.2365	99.85398	0.000258
154	0.042506	0.007909	1.161459	0.808599	0.000004	0.000001	0.710517	0.019603	7.412823	1786.723	99.89566	0.000221
155	0.041732	0.006898	1.189674	0.812472	0.000006	0.000001	0.689171	0.024421	8.458287	1830.92	99.78886	0.000247
156	0.040416	0.006683	1.345008	0.800698	0.000015	0.000001	0.691535	0.0226	8.027259	1833.864	99.8135	0.000236
157	0.041037	0.006685	1.30185	0.804151	0.000001	0.000001	0.687687	0.023571	8.338349	1838.35	99.85978	0.000246
158	0.042141	0.006624	1.260351	0.810693	0.000023	0.000001	0.685688	0.028082	9.463133	1838.395	99.77033	0.00024
159	0.042493	0.006716	1.317619	0.797853	0.000001	0.000001	0.662458	0.029156	10	1836.328	99.8875	0.000253
160	0.04305	0.007264	1.239087	0.807214	0.000001	0.000001	0.688532	0.031027	9.999982	1838.634	99.81811	0.000245

Table E.4 Parameters and SOH values extracted from the ECM of Cell 4 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
161	0.044361	0.009111	1.162149	0.800368	0.000002	0.000001	0.713965	0.021346	7.487629	1538.532	99.91798	0.000217
162	0.054485	0.008493	1.077056	0.812813	0.000001	0.000001	0.731718	0.014956	6.459381	1797.806	99.89591	0.000213
163	0.045737	0.006229	1.2686	0.829744	0.002163	10	0.698622	0.023254	8.150005	976.3595	99.82948	0.000247
164	0.066415	0.007206	0.914278	0.852057	0.000001	0.000001	0.729305	0.028373	9.589891	1504.925	99.73406	0.000317
165	0.042372	0.006798	1.32654	0.801012	0.000003	0.000001	0.673545	0.029295	10	1813.572	99.84505	0.000281
166	0.042009	0.00666	1.251519	0.810756	0.000003	0.000001	0.690003	0.028509	10	1834.37	99.87164	0.000256
167	0.042066	0.006761	1.278005	0.807403	0.000005	0.000001	0.684505	0.029573	10	1835.361	99.91393	0.000256
168	0.04201	0.006822	1.306549	0.803885	0.000191	0.000001	0.67708	0.030104	10	1831.132	99.82929	0.000261
169	0.041762	0.006926	1.321296	0.797765	0.000001	0.000001	0.682222	0.02111	7.641757	1828.674	99.8675	0.000229
170	0.042548	0.007346	1.299579	0.797779	0.000004	0.000001	0.684244	0.028082	9.469874	1806.749	99.91897	0.000255
171	0.041449	0.008911	1.213146	0.793697	0.000001	0.000001	0.700406	0.029902	10	1786.801	99.91333	0.00026
172	0.039816	0.008896	1.228228	0.794049	0.000001	0.000001	0.710891	0.02184	7.576376	1569.017	99.89402	0.000232
173	0.064285	0.008546	1.20318	0.7981	0.000001	0.000001	0.70732	0.021009	7.116634	1796.02	99.86775	0.000242
174	0.050455	0.007184	1.217382	0.808321	0.000003	0.000001	0.708397	0.020152	7.870673	1262.546	99.71303	0.00027
175	0.057408	0.006752	1.267183	0.807627	0.000001	0.000001	0.699039	0.018211	7.128191	1824.417	99.83112	0.00022
176	0.047783	0.00666	1.27772	0.807354	0.000001	0.000001	0.685402	0.028704	10	1815.739	99.83885	0.000261
177	0.04284	0.006739	1.347758	0.800018	0.000005	0.000001	0.687651	0.023461	8.330108	1829.456	99.88742	0.000251
178	0.043046	0.006768	1.356214	0.79688	0.000007	0.000001	0.685992	0.023704	8.427216	1831.623	99.88212	0.000246
179	0.042035	0.006659	1.27753	0.810433	0.000001	0.000001	0.693662	0.028508	10	1818.483	99.87008	0.00026
180	0.041403	0.006756	1.394547	0.794212	0.000051	0.000001	0.679793	0.021765	7.797246	1825.788	99.87367	0.000218

Table E.4 Parameters and SOH values extracted from the ECM of Cell 4 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
181	0.041449	0.008911	1.213146	0.793697	0.000001	0.000001	0.700406	0.029902	10	1789.302	99.91333	0.00026
182	0.039816	0.008896	1.228228	0.794049	0.000001	0.000001	0.710891	0.02184	7.576376	1791.3	99.89402	0.000232
183	0.064285	0.008546	1.20318	0.7981	0.000001	0.000001	0.70732	0.021009	7.116634	1793.444	99.86775	0.000242
184	0.050455	0.007184	1.217382	0.808321	0.000003	0.000001	0.708397	0.020152	7.870673	1750.584	99.71303	0.00027
185	0.057408	0.006752	1.267183	0.807627	0.000001	0.000001	0.699039	0.018211	7.128191	1779.059	99.83112	0.00022
186	0.047783	0.00666	1.27772	0.807354	0.000001	0.000001	0.685402	0.028704	10	1811.465	99.83885	0.000261
187	0.04284	0.006739	1.347758	0.800018	0.000005	0.000001	0.687651	0.023461	8.330108	1818.791	99.88742	0.000251
188	0.043046	0.006768	1.356214	0.79688	0.000007	0.000001	0.685992	0.023704	8.427216	1817.3	99.88212	0.000246
189	0.042035	0.006659	1.27753	0.810433	0.000001	0.000001	0.693662	0.028508	10	1808.039	99.87008	0.00026
190	0.041403	0.006756	1.394547	0.794212	0.000051	0.000001	0.679793	0.021765	7.797246	1819.735	99.87367	0.000218
191	0.040787	0.007692	1.238091	0.802536	0.000001	0.000001	0.695272	0.029852	10	1799.894	99.85164	0.000252
192	0.040962	0.007727	1.25758	0.799023	0.000001	0.000001	0.700491	0.022501	8.194742	1779.131	99.86155	0.000263
193	0.040049	0.001071	7.083927	0.889925	0.00686	2.34906	0.695487	0.024628	8.613944	1813.198	99.86863	0.000287
194	0.040583	0.006531	1.398962	0.795409	0.000034	0.000001	0.679348	0.020915	7.68918	1811.85	99.8671	0.000222
195	0.040599	0.006423	1.371768	0.801728	0.000009	0.000001	0.673634	0.029488	10	1826.079	99.87128	0.000252
196	0.040173	0.006476	1.385789	0.79982	0.000001	0.000001	0.673932	0.029544	10	1828.233	99.9164	0.000248
197	0.04002	0.004251	1.393332	0.856502	0.00237	10	0.67371	0.023998	8.236855	1827.951	99.82157	0.00023
198	0.040311	0.006568	1.463283	0.788661	0.000015	0.000001	0.653525	0.02724	9.340214	1825.292	99.91503	0.000216
199	0.040647	0.0062	1.443798	0.794888	0.000001	0.000006	0.651516	0.028845	10	1822.863	99.89587	0.000232
200	0.037012	0.00796	1.396483	0.804737	0.001633	10	0.704458	0.028568	9.018735	1792.681	99.85594	0.000266

Table E.5 Parameters and SOH values extracted from the ECM of Cell 5

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
1	0.012931	0.011036	0.867465	0.884849	0.003617	2.180567	0.786299	0.027775	8.621488	1826.388867	99.952739	0.000234
2	0.012353	0.008715	0.736629	0.860720	0.000009	0.000001	0.763451	0.027594	9.157674	1916.788375	99.870441	0.000267
3	0.021461	0.008984	1.096881	0.835549	0.002045	4.203657	0.730390	0.027236	8.237327	1918.057665	99.913798	0.000208
4	0.022036	0.008533	1.100806	0.844020	0.002186	3.858692	0.728035	0.032793	9.972690	1912.631288	99.941939	0.000224
5	0.021549	0.008349	0.994923	0.815283	0.000001	0.000001	0.710353	0.030972	9.745591	1923.040153	99.911516	0.000241
6	0.021649	0.007006	1.107312	0.836439	0.001128	7.678856	0.701991	0.030206	9.486791	1924.987818	99.926245	0.000228
7	0.021716	0.007093	1.081576	0.831598	0.000863	9.598388	0.703205	0.029586	9.425001	1922.816186	99.898152	0.000208
8	0.021845	0.007843	1.032595	0.813010	0.000034	0.000001	0.694680	0.030813	9.548098	1916.251264	99.860905	0.000226
9	0.021947	0.006763	1.144125	0.831741	0.001122	8.207268	0.695253	0.030452	9.590471	1917.464039	99.911920	0.000215
10	0.022037	0.006658	1.114771	0.832288	0.000968	9.583489	0.697531	0.028402	9.289357	1889.049411	99.913370	0.000209
11	0.012740	0.010154	0.872835	0.871459	0.002441	3.056585	0.775018	0.030745	9.645590	1881.399359	99.943006	0.000254
12	0.012423	0.008943	0.756906	0.854717	0.000009	0.000001	0.761810	0.026997	9.165109	1898.309102	99.868744	0.000252
13	0.012347	0.007658	0.821682	0.868549	0.000820	8.453103	0.752773	0.028841	9.515626	1911.693866	99.856698	0.000272
14	0.012344	0.008367	0.783793	0.852791	0.000014	0.000001	0.750839	0.026872	8.866930	1915.036079	99.894886	0.000243
15	0.012328	0.007396	0.842997	0.868633	0.000951	7.840761	0.750745	0.026953	8.933685	1914.354198	99.901682	0.000246
16	0.012336	0.007241	0.855686	0.870259	0.001064	6.931952	0.753525	0.025295	8.606175	1905.573102	99.894814	0.000232
17	0.012024	0.001074	5.524127	0.921585	0.007780	1.471868	0.749047	0.026643	8.838549	1916.816451	99.813511	0.000329
18	0.012347	0.007304	0.840716	0.870872	0.000927	7.774877	0.749537	0.028780	9.473476	1910.400332	99.838691	0.000267
19	0.012315	0.007042	0.863353	0.870084	0.001018	7.486543	0.746061	0.027038	8.958604	1911.622632	99.868717	0.000244
20	0.012308	0.006993	0.855881	0.867459	0.000803	9.616330	0.741768	0.028604	9.437041	1916.753875	99.871548	0.000257

Table E.5 Parameters and SOH values extracted from the ECM of Cell 5 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
21	0.012887	0.009971	0.926616	0.884025	0.003509	2.256915	0.774555	0.027780	8.798191	1860.944906	99.935610	0.000250
22	0.012839	0.009812	0.908764	0.880567	0.003051	2.529921	0.770508	0.027204	8.648713	1871.719918	99.922750	0.000261
23	0.012760	0.010252	0.879298	0.857864	0.001750	4.368667	0.763321	0.032885	9.928042	1890.457332	99.932333	0.000241
24	0.012674	0.008171	0.864972	0.862834	0.001118	6.491133	0.756049	0.026797	9.066955	1891.295406	99.915084	0.000249
25	0.012518	0.007485	0.902548	0.861993	0.001116	7.357603	0.742717	0.028105	9.028081	1911.594900	99.904893	0.000245
26	0.012374	0.004356	1.515901	0.875622	0.004316	2.609938	0.741364	0.027393	8.917926	1913.423009	99.890718	0.000269
27	0.012182	0.001176	5.074931	0.923670	0.007622	1.538462	0.743696	0.026715	8.964525	1906.422830	99.782173	0.000339
28	0.012530	0.008269	0.833242	0.845194	0.000002	0.000001	0.739712	0.027967	9.065619	1910.640047	99.898898	0.000242
29	0.012487	0.007240	0.902278	0.861983	0.001010	8.232018	0.736115	0.029673	9.516745	1910.500313	99.882790	0.000258
30	0.012482	0.007178	0.878929	0.862456	0.000833	9.044496	0.742839	0.027396	9.190152	1901.328411	99.875635	0.000237
31	0.013028	0.010431	0.925955	0.863740	0.002639	3.074697	0.763354	0.030242	9.057283	1873.776276	99.917286	0.000252
32	0.012990	0.010805	0.891981	0.852154	0.001814	4.376464	0.761980	0.026420	8.095781	1872.426065	99.945300	0.000213
33	0.013018	0.010542	0.944066	0.857609	0.002509	3.289379	0.763280	0.026854	8.136556	1874.163613	99.952208	0.000214
34	0.012714	0.008996	0.892568	0.853589	0.001200	6.352777	0.752618	0.029080	9.168033	1889.395679	99.888342	0.000244
35	0.012507	0.007603	0.913325	0.856730	0.001076	7.276240	0.741986	0.027302	9.124827	1890.044557	99.891192	0.000240
36	0.012532	0.007475	0.906408	0.857815	0.000987	8.387572	0.743553	0.026943	8.921451	1897.093373	99.919311	0.000235
37	0.012231	0.002156	4.802199	0.794408	0.006750	1.941304	0.735654	0.027159	8.995119	1900.830093	99.747596	0.000359
38	0.012544	0.008266	0.851178	0.841824	0.000001	0.000001	0.736844	0.029455	9.528950	1900.129962	99.868704	0.000248
39	0.012525	0.007411	0.922634	0.855754	0.000906	9.278341	0.733038	0.030709	9.630830	1907.131001	99.869523	0.000258
40	0.012526	0.007370	0.891349	0.858207	0.000869	9.538016	0.741985	0.030617	9.754492	1902.970003	99.866985	0.000264

Table E.5 Parameters and SOH values extracted from the ECM of Cell 5 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
41	0.012937	0.010017	0.907514	0.849535	0.001527	5.063315	0.755624	0.031595	9.743220	1872.643185	99.936487	0.000235
42	0.013049	0.010274	0.958044	0.858469	0.002568	3.243339	0.757893	0.033728	9.863356	1878.835970	99.942334	0.000252
43	0.013110	0.010553	0.962398	0.858901	0.002838	2.953662	0.762876	0.028065	8.757305	1846.198112	99.941706	0.000235
44	0.012957	0.009972	0.911355	0.853510	0.001742	4.427398	0.757463	0.028248	9.053760	1861.440746	99.938830	0.000250
45	0.012719	0.008519	0.900386	0.850599	0.000971	7.980629	0.746135	0.029338	9.818483	1871.318386	99.913670	0.000241
46	0.012533	0.007133	0.957682	0.855107	0.001150	7.974741	0.732882	0.028177	9.219928	1892.713057	99.901459	0.000236
47	0.012325	0.004341	2.259332	0.794334	0.004101	3.177015	0.731470	0.027061	9.009602	1895.265077	99.803672	0.000312
48	0.012531	0.007911	0.877313	0.839193	0.000011	0.000001	0.727513	0.027710	9.058873	1893.177095	99.876168	0.000230
49	0.012508	0.006902	0.951054	0.855912	0.001009	8.596245	0.731031	0.028599	9.478930	1888.134452	99.869633	0.000235
50	0.012518	0.007031	0.959734	0.852432	0.000892	9.948124	0.725026	0.029889	9.528688	1899.183730	99.877625	0.000242
51	0.012988	0.009833	0.959057	0.849985	0.001933	4.183407	0.749189	0.031385	9.550500	1867.071590	99.952815	0.000209
52	0.013352	0.010019	0.910284	0.851839	0.001800	4.061632	0.774021	0.018451	7.283336	1655.661149	99.907996	0.000211
53	0.013493	0.010245	0.969573	0.847239	0.002054	4.074754	0.750896	0.028770	8.715363	1864.538702	99.944581	0.000220
54	0.013503	0.010537	0.964647	0.842152	0.001852	4.536781	0.751384	0.028517	8.592128	1865.639107	99.951328	0.000206
55	0.012966	0.007206	0.985713	0.851026	0.001121	8.302557	0.724074	0.030921	9.743084	1894.761973	99.892451	0.000260
56	0.012942	0.007028	0.979640	0.850428	0.000993	9.160741	0.726423	0.029306	9.510270	1890.148239	99.898204	0.000248
57	0.012561	0.000982	6.446031	0.907373	0.007547	1.746567	0.721822	0.025757	8.682137	1890.021648	99.830880	0.000322
58	0.012961	0.007928	0.933946	0.829277	0.000001	0.000001	0.720840	0.027513	8.926181	1889.903425	99.900943	0.000226
59	0.012937	0.006940	1.001603	0.846634	0.001038	9.998449	0.718159	0.028368	9.148838	1891.002480	99.907935	0.000231
60	0.012917	0.006956	0.967705	0.850683	0.000898	9.862379	0.725560	0.029149	9.545292	1882.897531	99.854063	0.000242

Table E.5 Parameters and SOH values extracted from the ECM of Cell 5 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
61	0.012939	0.007876	0.915697	0.834003	0.000001	0.000001	0.723260	0.030041	9.674996	1885.409684	99.879783	0.000238
62	0.012928	0.007896	0.929477	0.830141	0.000001	0.000001	0.721296	0.026678	8.839836	1880.444358	99.910746	0.000214
63	0.012886	0.006902	0.984017	0.849485	0.000940	9.826478	0.720868	0.029722	9.686274	1883.576359	99.875664	0.000246
64	0.012873	0.007785	0.921759	0.833399	0.000075	0.000001	0.719125	0.030548	9.763369	1887.137106	99.864694	0.000249
65	0.012956	0.006854	1.015025	0.846555	0.000986	9.760747	0.716664	0.029788	9.415185	1890.490053	99.863760	0.000240
66	0.012966	0.006782	1.036965	0.844148	0.001047	9.998273	0.712377	0.028409	9.041108	1890.894468	99.908100	0.000221
67	0.012732	0.004529	2.399315	0.771907	0.003491	3.832204	0.720467	0.025612	8.808713	1878.351783	99.816380	0.000295
68	0.013090	0.008624	0.943710	0.823404	0.000001	0.000001	0.721385	0.028299	8.625623	1887.285726	99.930375	0.000206
69	0.013480	0.010550	0.982198	0.831409	0.001428	6.130014	0.738731	0.031876	9.181790	1873.020279	99.946200	0.000223
70	0.013475	0.010387	0.975207	0.834628	0.001507	5.627602	0.744469	0.027770	8.384639	1857.437932	99.955697	0.000200
71	0.013287	0.009484	0.993393	0.831438	0.001136	7.702003	0.734583	0.029411	8.935363	1867.323284	99.935460	0.000222
72	0.013356	0.009611	0.977988	0.835525	0.001251	6.623331	0.738863	0.027798	8.468804	1863.162684	99.923115	0.000218
73	0.013474	0.009950	0.996438	0.841747	0.001884	4.473932	0.743674	0.029081	8.872217	1853.662985	99.931710	0.000226
74	0.013471	0.010171	0.986294	0.836803	0.001709	4.859306	0.750083	0.030928	10.000000	1826.188118	99.957723	0.000222
75	0.012953	0.006917	1.044126	0.840932	0.001040	9.998634	0.717704	0.029110	9.320388	1877.151418	99.874815	0.000229
76	0.012926	0.006703	1.056214	0.844181	0.001105	9.221606	0.711074	0.030612	9.768077	1880.109228	99.881540	0.000238
77	0.012549	0.001163	5.853516	0.897220	0.007134	1.974672	0.706316	0.028877	9.319882	1885.826071	99.796374	0.000333
78	0.012952	0.007579	0.973759	0.825822	0.000001	0.000001	0.712440	0.027064	9.028954	1870.699096	99.906351	0.000217
79	0.012902	0.006592	1.086674	0.840214	0.001071	9.997670	0.703559	0.029583	9.376038	1886.288941	99.915324	0.000235
80	0.012910	0.006461	1.063428	0.842880	0.001116	9.999996	0.710255	0.027518	9.068243	1875.327500	99.918855	0.000220

Table E.5 Parameters and SOH values extracted from the ECM of Cell 5 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
81	0.013467	0.009683	1.023872	0.847799	0.002272	3.799840	0.738840	0.031943	9.648484	1853.440507	99.905886	0.000286
82	0.013581	0.010315	1.057189	0.844592	0.002755	3.314491	0.744526	0.031188	9.118132	1844.942782	99.945915	0.000223
83	0.013654	0.010732	1.027614	0.832880	0.002006	4.551420	0.740665	0.029102	8.566906	1846.357691	99.962831	0.000195
84	0.013268	0.008515	0.993934	0.838812	0.001247	6.905157	0.737471	0.029800	9.965596	1833.908712	99.912852	0.000226
85	0.013374	0.009582	1.002445	0.828091	0.001142	7.828687	0.733103	0.032298	10.000000	1848.278449	99.934154	0.000219
86	0.012986	0.007099	1.110278	0.832247	0.001100	9.999585	0.709639	0.029739	9.409566	1872.400815	99.914758	0.000224
87	0.012618	0.001131	6.096661	0.897798	0.007415	1.958686	0.705988	0.028458	9.121956	1876.891893	99.829423	0.000311
88	0.012980	0.007825	0.992288	0.822120	0.000029	0.000001	0.707258	0.031111	9.793743	1874.275508	99.895160	0.000229
89	0.012950	0.006674	1.092130	0.836546	0.001155	10.000000	0.708356	0.028821	9.170574	1871.299108	99.888076	0.000218
90	0.012947	0.006654	1.136933	0.833751	0.001184	9.999998	0.699362	0.029608	9.263360	1877.638138	99.916060	0.000220
91	0.021435	0.011733	0.843219	0.820046	0.000013	0.000001	0.755113	0.020250	7.329591	1371.313234	99.952988	0.000216
92	0.021765	0.011340	0.909532	0.810912	0.000001	0.000001	0.733581	0.028581	8.703734	1844.884062	99.937871	0.000243
93	0.021473	0.009878	1.015190	0.822266	0.001145	7.671232	0.730390	0.027216	8.235577	1838.516067	99.910734	0.000238
94	0.022051	0.009160	1.040536	0.832815	0.001548	5.729777	0.728035	0.032641	9.934752	1852.654818	99.935777	0.000252
95	0.021549	0.008349	0.994923	0.815283	0.000001	0.000001	0.710353	0.030972	9.745591	1864.512026	99.911516	0.000241
96	0.021649	0.007006	1.107312	0.836439	0.001128	7.678856	0.701991	0.030206	9.486791	1869.753599	99.926245	0.000228
97	0.021716	0.007093	1.081576	0.831598	0.000863	9.598388	0.703205	0.029586	9.425001	1864.718403	99.898152	0.000208
98	0.021845	0.007843	1.032595	0.813010	0.000034	0.000001	0.694680	0.030813	9.548098	1870.695900	99.860905	0.000226
99	0.021947	0.006763	1.144125	0.831741	0.001122	8.207268	0.695253	0.030452	9.590471	1868.989587	99.911920	0.000215
100	0.022037	0.006658	1.114771	0.832288	0.000968	9.583489	0.697531	0.028402	9.289357	1861.635841	99.913370	0.000209

Table E.5 Parameters and SOH values extracted from the ECM of Cell 5 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
101	0.024715	0.010434	0.929153	0.813950	0.000001	0.000001	0.726477	0.029167	8.599576	1785.067986	99.922015	0.000229
102	0.022003	0.009021	0.959535	0.818151	0.000001	0.000001	0.711880	0.032379	9.528278	1802.573325	99.902666	0.000238
103	0.020025	0.006468	0.996657	0.852575	0.002270	10.000000	0.701048	0.031547	9.142864	1814.249853	99.919309	0.000240
104	0.018807	0.006335	1.010724	0.851965	0.002179	10.000000	0.698838	0.031558	9.132535	1815.282989	99.888590	0.000243
105	0.018179	0.006065	0.985208	0.857984	0.002365	10.000000	0.696666	0.029538	8.748074	1815.434234	99.914224	0.000227
106	0.017723	0.006102	0.997846	0.855816	0.002113	10.000000	0.699359	0.029868	8.912329	1810.800552	99.889383	0.000242
107	0.018798	0.006638	1.027850	0.845307	0.002335	10.000000	0.697918	0.032115	9.006325	1818.720433	99.906751	0.000240
108	0.018731	0.010155	0.966066	0.808958	0.000001	0.000001	0.715110	0.031459	9.070715	1800.000467	99.930118	0.000228
109	0.019797	0.009066	1.084695	0.818319	0.001296	9.999999	0.708591	0.034912	9.613912	1810.520956	99.919005	0.000244
110	0.018953	0.007788	1.002506	0.834752	0.002312	10.000000	0.712074	0.029969	8.780985	1799.389345	99.935826	0.000231
111	0.018648	0.008745	0.980227	0.816910	0.000015	0.000001	0.709090	0.030069	9.107338	1796.132338	99.882872	0.000237
112	0.018172	0.008257	1.048829	0.810834	0.000001	0.000001	0.693885	0.030638	9.155440	1812.023018	99.906200	0.000240
113	0.017818	0.005939	1.058426	0.851211	0.002206	10.000000	0.688436	0.032814	9.680179	1816.435712	99.898327	0.000256
114	0.017576	0.005922	1.074661	0.849727	0.002104	10.000000	0.689624	0.032336	9.660070	1814.842946	99.888807	0.000257
115	0.017382	0.005975	1.106389	0.846430	0.001998	10.000000	0.687853	0.032901	9.737075	1817.503961	99.884144	0.000259
116	0.016805	0.001092	6.912969	0.880380	0.007409	2.141597	0.689797	0.029765	9.161956	1813.769494	99.827678	0.000330
117	0.016777	0.002852	4.149703	0.771340	0.005325	3.139131	0.685212	0.029547	9.082610	1815.748412	99.819214	0.000320
118	0.018285	0.010203	1.020087	0.801161	0.000002	0.000001	0.704891	0.030903	8.759808	1804.966796	99.941296	0.000220
119	0.018274	0.008818	1.094538	0.818389	0.001464	10.000000	0.709093	0.034157	9.637779	1802.886341	99.933297	0.000254
120	0.018106	0.008066	1.069295	0.823917	0.002226	10.000000	0.704685	0.033545	9.480052	1804.298178	99.941756	0.000252

Table E.5 Parameters and SOH values extracted from the ECM of Cell 5 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
121	0.017752	0.009493	1.004591	0.807104	0.000045	0.000001	0.703007	0.031183	9.115614	1794.627928	99.882588	0.000249
122	0.017666	0.009340	0.994734	0.810905	0.000042	0.000001	0.709358	0.028841	8.593786	1795.993564	99.922656	0.000220
123	0.017289	0.006496	1.085621	0.840235	0.002157	10.000000	0.694854	0.031919	9.483502	1807.672899	99.898172	0.000250
124	0.017007	0.006050	1.121875	0.844012	0.002100	10.000000	0.686593	0.030774	9.071654	1812.718377	99.886582	0.000247
125	0.016873	0.005811	1.107897	0.848233	0.002152	10.000000	0.685135	0.030560	9.147407	1813.768105	99.916715	0.000241
126	0.016325	0.001119	7.053583	0.873372	0.007395	2.256914	0.683142	0.029282	8.901937	1816.750300	99.859822	0.000326
127	0.016445	0.004246	2.622105	0.779566	0.003822	4.366745	0.679984	0.029794	9.093176	1816.621699	99.809115	0.000313
128	0.017230	0.009570	1.066567	0.798064	0.000001	0.000001	0.696002	0.029866	8.639770	1803.377591	99.940507	0.000214
129	0.017239	0.007900	1.092978	0.824262	0.002115	10.000000	0.701272	0.033398	9.472493	1802.211335	99.913614	0.000260
130	0.017894	0.007529	1.080042	0.828346	0.002321	10.000000	0.700940	0.029692	8.683824	1799.584058	99.926316	0.000231
131	0.017555	0.002292	0.476790	1.000000	0.005588	2.008967	0.841815	0.028607	8.841517	1807.713050	99.786030	0.000234
132	0.017336	0.005011	2.138827	0.854160	0.002468	0.452813	1.000000	0.026391	8.384171	1807.128167	99.769568	0.000236
133	0.017027	0.007180	1.473939	0.780199	0.000478	4.483843	0.891322	0.026015	8.335132	1808.614838	99.690057	0.000271
134	0.017246	0.002516	0.443036	1.000000	0.004810	2.267940	0.856363	0.027288	8.543381	1811.576023	99.764067	0.000237
135	0.016917	0.000005	0.000001	0.549837	0.007622	1.337280	0.775184	0.027028	8.661228	1809.286512	99.621641	0.000299
136	0.017178	0.004719	2.215870	0.859914	0.002479	0.447844	1.000000	0.025997	8.416299	1805.909233	99.712858	0.000256
137	0.016484	0.003905	0.379660	1.000000	0.005947	1.314690	1.000000	0.093596	8.934440	1804.238405	78.083519	0.007333
138	0.017048	0.004399	2.343130	0.862768	0.002469	0.441867	1.000000	0.026531	8.653873	1805.383494	99.718279	0.000247
139	0.016736	0.000029	0.000001	0.400000	0.006801	1.439381	0.773004	0.026410	8.744879	1810.201331	99.577772	0.000293
140	0.016928	0.002623	0.414282	1.000000	0.003802	2.668041	0.879760	0.028291	9.051616	1815.187372	99.682577	0.000256

Table E.5 Parameters and SOH values extracted from the ECM of Cell 5 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
141	0.018261	0.009007	1.038214	0.806311	0.000042	0.000001	0.704477	0.029725	9.079387	1783.072317	99.876683	0.000242
142	0.017791	0.009075	1.081789	0.800543	0.000009	0.000001	0.693786	0.032002	9.315046	1801.083936	99.909793	0.000236
143	0.017653	0.006169	1.103646	0.843066	0.002335	10.000000	0.687869	0.031119	9.233964	1804.504897	99.898511	0.000241
144	0.017133	0.006014	1.082707	0.846176	0.002372	10.000000	0.682224	0.030011	9.122368	1804.016850	99.918755	0.000247
145	0.016961	0.007563	1.145532	0.803763	0.000001	0.000001	0.677991	0.029703	9.230931	1803.141820	99.891294	0.000238
146	0.016484	0.001463	5.155830	0.867244	0.006464	2.504909	0.680009	0.026768	8.664179	1800.827654	99.860175	0.000293
147	0.016767	0.005054	1.156373	0.855813	0.002275	10.000000	0.671069	0.028888	8.932402	1808.459709	99.896730	0.000230
148	0.016681	0.007185	1.161374	0.806679	0.000001	0.000001	0.672802	0.028586	8.899429	1806.641855	99.900760	0.000226
149	0.016552	0.004881	1.170423	0.856478	0.002086	10.000000	0.671715	0.030655	9.717281	1805.310968	99.897881	0.000247
150	0.017035	0.005745	1.202664	0.838103	0.002335	10.000000	0.673949	0.030392	8.807292	1811.657444	99.887758	0.000246
151	0.017657	0.011141	1.006387	0.798415	0.000001	0.000001	0.710638	0.032713	9.386038	1785.119132	99.924844	0.000243
152	0.017777	0.012103	0.982480	0.796526	0.000001	0.000001	0.718638	0.034318	9.999999	1766.487224	99.936206	0.000243
153	0.017005	0.006987	0.849291	0.861183	0.002334	10.000000	0.736378	0.018579	7.272889	1469.389774	99.929912	0.000195
154	0.017020	0.006930	1.081676	0.835556	0.002514	10.000000	0.696718	0.031465	9.193963	1794.188037	99.909275	0.000247
155	0.016912	0.006853	1.111533	0.833265	0.002394	10.000000	0.692365	0.030792	9.075013	1791.307498	99.892389	0.000243
156	0.016271	0.001372	6.050985	0.868661	0.007396	2.373110	0.678185	0.028920	8.831856	1803.941358	99.873752	0.000300
157	0.016651	0.005207	1.145861	0.853170	0.002251	10.000000	0.679351	0.029274	9.208602	1797.282387	99.890983	0.000255
158	0.016659	0.007189	1.171849	0.806363	0.000001	0.000001	0.674327	0.028678	9.031492	1799.575529	99.910873	0.000238
159	0.016617	0.005061	1.272306	0.845573	0.002161	10.000000	0.665140	0.030189	9.236848	1808.491286	99.905300	0.000245
160	0.016603	0.004892	1.188168	0.855768	0.002168	10.000000	0.672424	0.028629	9.061339	1801.614281	99.907483	0.000241

Table E.5 Parameters and SOH values extracted from the ECM of Cell 5 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
161	0.016850	0.008356	1.146465	0.797328	0.000047	0.000001	0.677964	0.031267	9.226202	1796.949777	99.897426	0.000239
162	0.017044	0.009442	1.137922	0.791192	0.000021	0.000001	0.688279	0.030140	8.779579	1793.027941	99.932288	0.000209
163	0.017023	0.007223	1.169626	0.823945	0.002280	10.000000	0.690736	0.033622	9.570530	1792.502765	99.898273	0.000253
164	0.016855	0.006733	1.185966	0.827319	0.002343	10.000000	0.684730	0.032383	9.317450	1798.012914	99.906709	0.000247
165	0.016790	0.006689	1.192901	0.828015	0.002302	10.000000	0.682171	0.033573	9.686172	1797.354589	99.903170	0.000252
166	0.016128	0.001263	6.614876	0.868130	0.007372	2.375447	0.678711	0.028592	8.937050	1795.220964	99.843532	0.000313
167	0.016289	0.005128	1.219019	0.848679	0.002335	10.000000	0.667157	0.030357	9.221876	1804.839077	99.910912	0.000243
168	0.016140	0.007174	1.237023	0.799349	0.000001	0.000001	0.663314	0.032271	9.815978	1804.181105	99.885283	0.000239
169	0.016046	0.004914	1.265476	0.849277	0.002264	10.000000	0.660215	0.033014	9.973623	1805.600991	99.860275	0.000259
170	0.016053	0.004648	1.139602	0.863521	0.002373	10.000000	0.670295	0.029460	9.376642	1795.430028	99.868855	0.000239
171	0.016878	0.010170	1.093699	0.790044	0.000001	0.000001	0.698344	0.029995	8.787479	1773.382626	99.919395	0.000230
172	0.016818	0.009921	1.069708	0.795364	0.000001	0.000001	0.700453	0.031207	9.345366	1772.855405	99.915135	0.000243
173	0.016794	0.007115	1.087296	0.831497	0.002680	10.000000	0.694978	0.029782	8.722658	1780.354514	99.933040	0.000223
174	0.016739	0.007420	1.140608	0.823334	0.002471	10.000000	0.691679	0.031636	9.318709	1783.483625	99.927185	0.000226
175	0.016118	0.005498	1.218779	0.842709	0.002416	10.000000	0.670714	0.031545	9.426535	1799.724220	99.913764	0.000240
176	0.015545	0.001215	7.008542	0.855338	0.006745	2.693025	0.662924	0.029668	9.297700	1801.173672	99.858023	0.000318
177	0.015767	0.003762	2.966648	0.772883	0.003731	4.845082	0.664953	0.027744	8.911876	1793.792607	99.845864	0.000282
178	0.016021	0.006968	1.244739	0.800665	0.000001	0.000001	0.661313	0.032316	9.907021	1800.386402	99.902965	0.000244
179	0.015957	0.004633	1.233683	0.858799	0.002406	10.000000	0.658673	0.031176	9.498154	1802.477062	99.862304	0.000244
180	0.015880	0.004376	1.241795	0.861404	0.002395	10.000000	0.656056	0.031077	9.705645	1801.974580	99.878500	0.000244

Table E.5 Parameters and SOH values extracted from the ECM of Cell 5 (Continued)

Cycle	R_0	R_s	Q_s	α_s	R_{ct}	Q_{dl}	α_{dl}	R_w	σ	Capacity	R^2	RMSE
181	0.016886	0.010882	1.084610	0.787459	0.000003	0.000001	0.695682	0.032406	9.263934	1772.016517	99.938074	0.000250
182	0.016793	0.010590	1.106049	0.786532	0.000009	0.000001	0.692206	0.031162	8.982937	1776.681937	99.926131	0.000243
183	0.019912	0.006954	1.102835	0.829956	0.002719	10.000000	0.691407	0.028396	8.497251	1769.416890	99.915188	0.000218
184	0.019130	0.001603	5.945210	0.841529	0.007128	2.541576	0.672672	0.029861	9.204235	1790.054423	99.858922	0.000307
185	0.018957	0.005225	1.385574	0.833410	0.002073	10.000000	0.658648	0.031134	9.377228	1800.364339	99.883286	0.000248
186	0.018364	0.001032	8.240885	0.857512	0.006629	2.679676	0.664289	0.027187	8.728912	1791.549749	99.789363	0.000322
187	0.018693	0.006995	1.290881	0.794998	0.000001	0.000001	0.660756	0.030272	9.414118	1794.618223	99.897844	0.000225
188	0.018521	0.007062	1.313432	0.791506	0.000001	0.000001	0.654041	0.032032	9.719640	1793.661602	99.891213	0.000234
189	0.018471	0.004915	1.390449	0.837334	0.002242	10.000000	0.654041	0.031596	9.635405	1798.615193	99.886217	0.000241
190	0.018332	0.004608	1.390866	0.845131	0.002138	10.000000	0.649381	0.029684	9.261200	1799.520250	99.897852	0.000248
191	0.019032	0.010949	1.112537	0.783306	0.000007	0.000001	0.694897	0.033152	9.345769	1766.238379	99.938328	0.000237
192	0.018811	0.010381	1.157731	0.781520	0.000001	0.000001	0.689668	0.029543	8.443784	1774.908472	99.952048	0.000199
193	0.018180	0.007349	1.171632	0.819384	0.002867	10.000000	0.684468	0.030671	8.777198	1776.690938	99.933366	0.000222
194	0.017602	0.005447	1.192860	0.842877	0.002713	10.000000	0.670288	0.029491	8.983475	1786.713284	99.920089	0.000223
195	0.017422	0.007259	1.305341	0.791719	0.000023	0.000001	0.655815	0.031756	9.477559	1797.666945	99.909985	0.000229
196	0.016912	0.001129	8.299292	0.843513	0.006673	2.915103	0.651327	0.030539	9.437654	1797.715767	99.828794	0.000315
197	0.017339	0.004546	1.310755	0.852181	0.002498	10.000000	0.649764	0.030154	9.268304	1796.059223	99.896833	0.000257
198	0.017371	0.006898	1.330747	0.792686	0.000001	0.000001	0.651099	0.031458	9.498874	1796.318999	99.880822	0.000226
199	0.017312	0.004641	1.356423	0.846112	0.002357	10.000000	0.652644	0.029821	9.140856	1795.235259	99.892130	0.000228
200	0.017300	0.004569	1.358054	0.847224	0.002440	10.000000	0.651349	0.032277	9.836685	1796.081423	99.877350	0.000244

Table E.6 Linear -Kramars Kronig Validation of cell 1

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
1	1.2654	1.0105	0.5938	0.4386
2	1.1414	1.0607	0.5866	0.431
3	44.1545	10.3111	10.7882	3.9086
4	1.5664	1.1557	0.5171	0.4783
5	1.2651	0.7947	0.5827	0.3782
6	0.9329	0.8038	0.4763	0.3814
7	2.8517	1.0009	0.7005	0.4526
8	1.8468	1.7201	0.7083	0.6856
9	1.4951	1.4618	0.6758	0.6671
10	1.4372	1.6783	0.648	0.7038
11	1.7707	0.8504	0.6486	0.4428
12	1.2315	0.8011	0.5562	0.3996
13	1.8628	1.0519	0.5808	0.4929
14	1.4133	1.0369	0.5815	0.4712
15	0.6734	0.69	0.3122	0.2844
16	0.7645	0.2792	0.3331	0.1424
17	1.1011	0.6789	0.352	0.2406
18	3.0629	1.9849	1.1787	0.8224
19	2.5648	2.2387	1.1406	0.9188
20	2.3572	2.4189	1.1096	1.0489
21	2.0617	1.2078	0.7971	0.5954
22	1.2854	1.7578	0.6715	0.6652
23	1.7686	1.8286	0.7344	0.6791
24	1.5103	1.5627	0.6534	0.6274
25	1.809	1.3411	0.7187	0.621
26	1.2042	1.7063	0.5583	0.6341
27	1.4082	1.3954	0.664	0.6055
28	1.2109	1.858	0.6296	0.6936
29	1.279	1.5869	0.629	0.6317
30	0.7803	1.2256	0.4305	0.4867
31	0.7938	1.4806	0.4304	0.5253
32	1.4137	0.915	0.5441	0.398
33	1.4157	1.0785	0.5271	0.4242
34	1.3212	1.091	0.51	0.4324
35	1.0734	0.682	0.5528	0.3371

Table E.6 Linear -Kramars Kronig Validation of cell 1 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
36	1.0653	1.2826	0.4425	0.4754
37	0.9444	1.0132	0.447	0.4465
38	1.0291	0.9853	0.4793	0.4429
39	1.4289	1.1492	0.578	0.4536
40	1.3956	1.3354	0.5398	0.4857
41	0.7473	0.7726	0.3312	0.3321
42	1.2622	0.9121	0.4275	0.3478
43	1.4124	0.8841	0.4454	0.3403
44	0.9561	0.89	0.356	0.3829
45	0.6976	0.8441	0.3414	0.3766
46	0.8555	1.1216	0.3689	0.4043
47	0.7824	0.6904	0.3929	0.299
48	0.6659	0.9112	0.3312	0.3876
49	0.6111	1.2292	0.3353	0.4503
50	0.8556	0.7907	0.4026	0.3486
51	0.8844	0.7236	0.4225	0.3137
52	1.0733	0.4603	0.4971	0.2623
53	1.2361	1.2537	0.4226	0.4291
54	0.8547	0.9242	0.3608	0.4018
55	0.9285	1.1502	0.3887	0.4253
56	0.9257	0.5858	0.4407	0.2754
57	1.1514	1.1576	0.4428	0.4128
58	0.7221	1.0215	0.3639	0.3798
59	1.2413	1.3846	0.4439	0.4795
60	0.6487	1.0081	0.3711	0.4273
61	1.3768	0.7729	0.5099	0.3292
62	0.8921	1.1297	0.3566	0.411
63	0.7932	0.6781	0.3985	0.2953
64	0.7773	1.1666	0.388	0.438
65	0.8837	0.5708	0.425	0.2858
66	0.952	1.3142	0.3976	0.4577
67	0.8377	1.0739	0.4205	0.4191
68	0.9364	0.8465	0.456	0.3644
69	0.901	1.3527	0.4158	0.4645
70	0.7527	1.0343	0.3805	0.4164

Table E.6 Linear -Kramars Kronig Validation of cell 1 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
71	0.9097	0.5431	0.4346	0.2809
72	0.7057	0.8305	0.344	0.3535
73	1.1357	0.5032	0.4808	0.2798
74	0.8659	0.9156	0.401	0.3717
75	0.7236	0.9138	0.3757	0.4011
76	1.0393	1.2965	0.4131	0.4402
77	0.9982	1.1555	0.3875	0.4305
78	0.9694	0.8229	0.4393	0.3573
79	1.0276	0.867	0.4948	0.3707
80	0.9246	0.8868	0.4244	0.4049
81	0.9548	1.3272	0.4119	0.4863
82	0.9935	0.8109	0.4158	0.3659
83	0.8514	0.5538	0.4572	0.2951
84	0.9896	0.8137	0.4414	0.3522
85	0.8478	1.3698	0.4187	0.4803
86	0.8856	0.9776	0.4049	0.4338
87	0.7571	1.3344	0.4207	0.4931
88	0.9126	1.2989	0.4299	0.4894
89	0.9929	0.6589	0.5377	0.3411
90	0.97	1.522	0.4567	0.5236
91	0.766	1.1449	0.3643	0.4257
92	0.884	0.6579	0.4214	0.292
93	0.9474	0.779	0.3985	0.3459
94	1.429	0.7788	0.5419	0.3209
95	0.7983	0.9051	0.3901	0.3971
96	1.0461	1.3117	0.4512	0.4531
97	1.2435	0.6141	0.5345	0.3103
98	1.3619	1.3284	0.5027	0.4635
99	0.7727	1.2744	0.371	0.4671
100	0.8069	1.3	0.393	0.4752
101	2.456	1.5814	0.8778	0.6361
102	2.1064	1.6956	0.8046	0.6954
103	1.365	1.3921	0.7713	0.5685
104	2.1913	1.5242	0.8033	0.6944
105	2.2517	1.5816	0.8395	0.7147

Table E.6 Linear -Kramars Kronig Validation of cell 1 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
106	1.7563	2.028	0.773	0.7378
107	1.5866	2.083	0.7076	0.7443
108	1.873	1.4646	0.8157	0.599
109	2.5316	1.7385	0.8352	0.7501
110	2.2365	1.1654	0.9574	0.623
111	1.9902	1.6535	0.7911	0.7178
112	2.3932	1.6309	0.836	0.725
113	1.8392	2.1825	0.7859	0.7684
114	2.1636	1.7041	0.8681	0.7586
115	2.3303	1.2335	0.936	0.6378
116	1.9272	1.5735	0.8256	0.6279
117	2.108	1.9561	0.8091	0.7485
118	1.6105	2.1662	0.7651	0.7743
119	1.9404	2.1222	0.8524	0.7683
120	2.4323	1.8612	0.8802	0.8121
121	1.9259	1.246	1.0343	0.6524
122	1.8939	1.1992	1.0056	0.6218
123	1.7979	1.8427	0.8483	0.7891
124	2.2466	1.7634	0.964	0.7443
125	1.7896	2.4067	0.7999	0.8585
126	1.8208	2.1675	0.8755	0.8315
127	1.8314	1.6835	0.8718	0.7221
128	1.7399	2.6404	0.8499	0.9177
129	1.6581	1.8911	0.8345	0.7451
130	1.8086	2.1064	0.8505	0.9124
131	1.541	1.0756	0.8396	0.5634
132	1.814	2.3214	0.7429	0.8054
133	1.6889	1.7581	0.785	0.7619
134	1.3625	1.693	0.7744	0.7715
135	1.7215	1.6258	0.7941	0.6772
136	1.4687	2.3733	0.8141	0.8305
137	1.6595	2.3303	0.796	0.8247
138	1.8086	1.9887	0.972	0.8331
139	1.8999	1.7122	0.9547	0.738
140	1.7596	2.7007	0.8245	0.9645

Table E.6 Linear -Kramars Kronig Validation of cell 1 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
141	1.7478	2.2236	0.8244	0.8011
142	1.4722	2.0588	0.7516	0.78
143	1.2853	1.8274	0.82	0.7889
144	1.5556	1.4963	0.8058	0.6533
145	1.8954	1.7238	0.9819	0.6958
146	1.8928	1.8427	0.9077	0.7646
147	1.8042	1.6161	0.9777	0.7571
148	1.9452	2.6391	0.8984	0.9549
149	1.7078	1.8034	0.8772	0.8908
150	1.5239	1.9378	0.7788	0.7945
151	1.7479	1.8992	0.9434	0.7361
152	1.8607	1.7961	0.8037	0.7462
153	1.7168	2.2926	0.8239	0.8986
154	1.9399	1.7807	0.9518	0.6992
155	1.3274	1.7779	0.8247	0.7932
156	1.9839	1.2	1.0623	0.7209
157	1.8072	2.089	0.9214	0.8794
158	2.0132	1.8895	1.1827	0.8279
159	1.7878	1.6996	1.0301	0.7915
160	1.7271	2.5086	0.8261	0.911
161	1.8359	1.7204	0.9023	0.8656
162	1.7199	1.7795	0.9822	0.7774
163	1.9697	1.8389	0.9047	0.8113
164	1.7952	2.278	0.8438	0.8814
165	1.8928	1.7065	0.9338	0.7527
166	1.7159	2.393	0.888	0.9235
167	1.702	1.711	0.92	0.8976
168	2.1211	3.006	1.0319	1.0369
169	1.7391	2.4761	0.8214	0.9488
170	1.6838	1.8033	0.8932	0.8728
171	1.9431	2.4128	0.8799	0.9283
172	1.8285	1.7625	0.9125	0.7148
173	1.8056	1.4402	1.0197	0.7344
174	2.0185	2.5796	0.9372	0.9113
175	1.6915	2.1591	0.8513	0.8635

Table E.6 Linear -Kramars Kronig Validation of cell 1 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
176	1.611	2.0605	0.8431	0.8506
177	1.8791	2.2779	0.8099	0.8913
178	1.5186	2.1219	0.8089	0.8544
179	2.0208	2.6755	1.0263	1.0261
180	1.6196	2.7578	0.8828	0.916
181	2.0313	2.1095	1.0119	0.8768
182	2.1203	2.3942	0.9741	0.9035
183	1.9188	2.0361	0.9068	0.8071
184	2.177	2.2076	1.3057	0.9967
185	2.7545	1.5913	1.0346	0.6734
186	2.468	2.309	1.0338	0.9041
187	2.1902	2.6761	0.9588	0.938
188	2.5323	2.2292	1.111	0.9153
189	2.0074	1.7588	0.9769	0.8864
190	2.2713	2.4235	0.9785	0.8873
191	2.3442	1.4451	1.2572	0.8367
192	1.7826	1.9691	0.9228	0.7582
193	1.8439	2.4701	0.8926	0.9342
194	2.3666	1.9252	1.0387	0.8104
195	2.1129	2.9498	0.9707	1.0296
196	2.1969	2.7372	1.053	1.0223
197	2.1841	3.294	1.0525	1.143
198	1.8626	2.038	0.9484	0.87
199	2.6752	2.6651	1.2432	1.075
200	1.6592	2.0953	0.8931	0.8663

Table E.7 Linear -Kramars Kronig Validation of cell 2

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
1	1.9914	2.4811	1.2565	1.0892
2	1.5094	2.3763	0.7877	0.8651
3	2.2327	3.4649	1.2762	1.2547
4	1.199	1.9666	0.5719	0.5577
5	2.2996	3.4739	1.2958	1.2457
6	1.1855	2.3419	0.5775	0.7768
7	1.5819	3.3194	0.9097	0.9954
8	1.5096	2.5154	0.634	0.75
9	3.1721	3.5002	1.0956	1.1284
10	1.2077	3.0256	0.6948	0.8227
11	1.0602	1.5245	0.4909	0.567
12	1.3255	1.9713	0.6308	0.702
13	2.2016	3.3431	1.1801	1.2571
14	2.1466	3.3795	1.1734	1.2105
15	2.0329	3.3093	1.1596	1.172
16	1.3608	2.1333	0.613	0.7541
17	1.2919	2.2971	0.6218	0.6709
18	1.268	2.069	0.5413	0.639
19	1.8141	3.0033	1.0007	1.1404
20	1.2158	1.6381	0.5216	0.5462
21	1.3001	2.3345	0.6152	0.7393
22	1.1673	2.3661	0.6512	0.747
23	1.4768	2.3932	0.638	0.7835
24	1.3275	2.8954	0.6693	0.8348
25	1.6451	2.6017	0.7217	0.734
26	1.2441	2.3751	0.5995	0.7689
27	1.0878	2.1267	0.5114	0.7531
28	1.3397	1.7331	0.5306	0.5286
29	1.1502	1.934	0.6138	0.5436
30	1.3055	2.0663	0.5175	0.7285
31	0.9647	1.502	0.4571	0.4517
32	0.894	1.787	0.4735	0.606
33	1.2484	1.8678	0.5413	0.6269
34	1.2166	2.1226	0.6691	0.5896
35	1.2691	2.1319	0.6411	0.6719

Table E.7 Linear -Kramars Kronig Validation of cell 2 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
36	1.169	2.1278	0.5449	0.6911
37	1.2623	1.1524	0.5022	0.5274
38	1.0155	2.3979	0.5419	0.7454
39	2.6498	3.1258	1.0814	1.1525
40	1.3597	1.5108	0.4929	0.5595
41	1.3336	2.1067	0.5559	0.7502
42	1.1204	2.0985	0.508	0.7296
43	1.2893	2.1116	0.6289	0.6151
44	1.2225	2.1387	0.5626	0.6722
45	1.1397	2.1712	0.5345	0.6435
46	1.3277	2.3336	0.6544	0.6873
47	1.9896	3.4308	1.0968	1.2098
48	1.3148	2.287	0.5616	0.7278
49	1.1822	2.2403	0.5734	0.7566
50	1.1037	1.9761	0.4717	0.6946
51	1.2851	2.276	0.5469	0.7614
52	1.3571	2.3525	0.5848	0.7809
53	1.3168	2.336	0.5407	0.7942
54	1.3666	2.418	0.629	0.7228
55	1.439	2.345	0.5833	0.8223
56	1.2555	2.7526	0.6514	0.8764
57	1.4478	3.4308	0.8948	1.0317
58	1.5582	2.6709	0.6194	0.7875
59	1.4227	2.8142	0.5682	0.8399
60	1.665	3.5053	0.8217	0.9985
61	1.5348	2.7022	0.7099	0.7507
62	1.7193	2.7271	0.732	0.7553
63	1.5999	2.8636	0.6975	0.7997
64	1.5981	2.7943	0.7171	0.7715
65	1.7892	3.8846	1.1268	1.1801
66	2.1447	4.0944	1.2782	1.277
67	1.3317	2.7742	0.6011	0.8873
68	1.6538	2.795	0.7594	0.8056
69	1.7732	2.5204	0.6302	0.7075
70	1.5343	3.2608	0.8501	0.943

Table E.7 Linear -Kramars Kronig Validation of cell 2 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
71	1.4625	2.6142	0.6333	0.8016
72	1.4763	3.4106	0.8552	0.9958
73	2.1894	3.768	1.0968	1.0729
74	1.4702	2.6431	0.6339	0.8024
75	1.5012	2.6764	0.6661	0.7781
76	1.5165	2.495	0.756	0.7648
77	1.5875	2.1463	0.5965	0.759
78	1.5709	2.6916	0.6429	0.7722
79	1.2696	2.5798	0.6284	0.779
80	1.3806	2.6606	0.6419	0.8177
81	1.5672	2.8254	0.6775	0.7658
82	1.482	2.7603	0.6695	0.7365
83	1.5292	2.7709	0.6303	0.7867
84	1.6355	2.7624	0.6799	0.8265
85	1.5048	2.6946	0.7089	0.7725
86	1.9514	2.3176	0.5927	0.794
87	1.7092	2.7474	0.6998	0.7794
88	1.6007	2.6959	0.6594	0.8616
89	1.5885	2.3544	0.6386	0.7104
90	1.7055	2.73	0.6633	0.8172
91	0.8204	1.4822	0.3986	0.4224
92	0.9868	1.6667	0.4253	0.5303
93	0.905	1.733	0.4095	0.4983
94	0.9584	1.7102	0.4443	0.5415
95	1.1918	1.8461	0.5044	0.5252
96	0.9723	1.8533	0.4147	0.5826
97	1.1251	1.4684	0.4852	0.5149
98	1.225	1.7712	0.5475	0.5316
99	1.2868	2.1862	0.5568	0.6648
100	1.2229	2.245	0.5067	0.7058
101	3.3	5.3234	0.9201	1.206
102	4.1675	9.201	2.1089	2.5089
103	3.2725	5.3024	0.9483	1.2181
104	3.3783	5.404	1.0162	1.2447
105	3.1966	6.7028	1.086	1.5793

Table E.7 Linear -Kramars Kronig Validation of cell 2 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
106	3.2083	6.8105	1.0745	1.5831
107	3.0714	6.6993	1.0428	1.5211
108	3.1645	6.7441	1.0218	1.6041
109	3.4131	5.6376	0.9676	1.3679
110	3.1818	6.8063	1.0957	1.609
111	3.4336	5.277	0.9533	1.1582
112	2.4778	8.1176	1.457	1.9989
113	2.9739	6.4415	0.9983	1.3977
114	2.3943	7.9365	1.4158	1.9754
115	2.91	6.7218	1.0259	1.5371
116	2.9165	8.1606	1.4805	1.9373
117	2.7988	7.8928	1.3248	1.8416
118	2.4057	3.5115	0.8892	1.0573
119	3.4197	5.6757	0.9591	1.343
120	3.2218	6.6622	1.0264	1.6013
121	2.4801	7.8387	1.322	1.8702
122	3.3018	8.591	1.7735	2.1751
123	3.3042	5.2856	0.9199	1.2455
124	3.1925	6.7315	1.0774	1.6101
125	3.1375	6.3491	1.0694	1.4982
126	2.4694	3.4653	0.9197	0.9494
127	2.4076	2.3605	0.767	0.8657
128	2.4539	3.5556	0.8574	1.0052
129	2.3558	3.5506	0.8559	1.0528
130	2.6622	6.7533	1.0063	1.5126
131	2.47	7.9884	1.4412	1.9512
132	2.8445	7.9473	1.4039	1.8961
133	3.2664	6.5718	1.1312	1.5267
134	2.3777	2.3419	0.8001	0.7382
135	2.5004	3.384	0.8319	1.0485
136	2.3275	3.4134	0.8682	0.9552
137	2.4219	3.4002	0.85	1.0431
138	2.3401	4.6675	1.284	1.3918
139	2.4487	2.4172	0.8045	0.8942
140	3.2756	5.2231	0.9172	1.2557

Table E.7 Linear -Kramars Kronig Validation of cell 2 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
141	2.9705	5.0516	0.9319	1.124
142	3.179	8.0469	1.7632	2.1789
143	2.7518	7.3006	1.2682	1.7271
144	3.531	6.397	1.1037	1.509
145	3.1987	5.1594	0.8834	1.2853
146	2.1632	3.722	0.8715	1.0807
147	2.2027	3.167	0.8053	1.0285
148	2.317	4.5773	1.2707	1.2899
149	2.3195	4.1446	1.0537	1.1921
150	3.0216	4.9029	0.9511	1.1351
151	3.1319	4.7848	0.9514	1.0646
152	3.1674	4.8421	0.9575	1.1085
153	3.175	4.8663	0.963	1.0965
154	3.272	5.179	0.946	1.2313
155	2.2849	3.2284	0.8253	0.8996
156	2.2169	2.2815	0.6361	0.8771
157	2.2521	3.2253	0.8257	1.0045
158	2.2246	3.2022	0.7916	0.999
159	2.0984	2.1462	0.743	0.7672
160	2.2985	2.2125	0.7097	0.7895
161	2.8173	6.4693	1.0446	1.5112
162	2.8034	6.111	1.0345	1.385
163	3.0264	4.8487	0.9493	1.1282
164	2.9346	6.2576	1.0365	1.4541
165	3.222	5.1284	0.9857	1.1428
166	3.3576	5.1421	0.9026	1.2494
167	3.1063	6.1437	1.0419	1.4617
168	3.1085	5.0568	0.8859	1.1817
169	2.2248	2.1308	0.7078	0.7498
170	2.2589	4.0143	1.1037	1.1656
171	2.3367	2.4159	0.7739	0.718
172	2.4316	3.2141	0.9925	0.9957
173	2.2446	3.0709	0.8856	1.0229
174	2.3919	3.9491	1.0647	1.0561
175	2.0569	2.1492	0.7546	0.7394

Table E.7 Linear -Kramars Kronig Validation of cell 2 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
176	2.2547	2.2044	0.7223	0.7533
177	2.2184	3.0263	0.8986	0.935
178	2.262	2.2164	0.7037	0.8283
179	2.3328	3.1916	0.9371	0.9161
180	2.168	2.5485	0.7613	0.9064
181	2.1551	2.1873	0.7098	0.8271
182	2.1677	2.3388	0.7373	0.8249
183	2.3037	2.3663	0.8586	0.7445
184	2.2808	2.2376	0.7159	0.8005
185	2.3725	3.1071	0.9189	1.0165
186	2.4083	3.0306	0.8246	1.0009
187	2.4499	3.2903	0.9729	0.9935
188	2.2311	2.3588	0.6866	0.9018
189	2.2164	2.1438	0.7357	0.7278
190	2.4397	3.1063	0.9314	0.8656
191	2.886	4.626	0.82	1.1849
192	2.6877	4.5642	0.7699	1.1236
193	3.2042	4.7471	0.9546	1.0706
194	2.1338	2.0577	0.7464	0.6948
195	2.0477	2.2122	0.7754	0.8063
196	2.412	3.0863	0.8363	1.0077
197	2.1325	2.2513	0.7396	0.8054
198	1.9741	2.0902	0.6261	0.7741
199	2.1354	2.1186	0.7537	0.7223
200	2.164	2.2001	0.6975	0.8252

Table E.8 Linear -Kramars Kronig Validation of cell 3

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
1	3.2355	6.845	1.6766	1.982
2	2.9933	5.0906	1.086	1.2344
3	3.0522	5.0674	1.0228	1.2227
4	3.0358	5.0432	1.0242	1.23
5	3.1874	4.9488	1.0467	1.2797
6	2.8597	5.0137	1.1295	1.2488
7	2.7616	6.4175	1.4793	1.8329
8	2.9536	5.0845	1.0209	1.2594
9	3.9701	7.3011	2.0524	2.3176
10	2.7432	5.5155	1.0494	1.3154
11	2.3332	5.2122	1.2653	1.4772
12	2.7488	4.2352	0.9681	1.0087
13	2.7509	4.2148	0.9324	1.0967
14	2.7278	5.0586	1.0831	1.2661
15	2.303	5.7406	1.2091	1.5931
16	3.1069	4.8301	1.0096	1.2369
17	4.4321	7.3772	2.0806	2.3361
18	3.0957	4.899	0.972	1.2615
19	4.6618	7.4969	2.2105	2.4616
20	2.941	5.9344	1.2129	1.5447
21	2.3019	4.6743	0.9994	1.1977
22	3.1766	4.064	0.9269	0.9649
23	2.8533	3.3844	0.825	0.9438
24	2.915	3.5295	0.7628	0.9419
25	3.7895	6.3562	1.8351	2.0238
26	3.4551	5.0008	1.0452	1.1853
27	3.8944	7.1009	1.8692	2.1036
28	3.2386	4.2608	0.9142	1.0353
29	2.8958	7.0061	1.4905	1.9226
30	2.7478	4.9619	1.0284	1.1849
31	2.4483	4.9023	0.9104	1.2303
32	2.4594	5.0479	1.0574	1.3309
33	2.5984	5.6636	1.1468	1.4888
34	3.1556	4.2773	0.96	0.9927
35	3.1129	5.0208	0.9543	1.231

Table E.8 Linear -Kramars Kronig Validation of cell 3 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
36	2.7611	5.9578	1.0774	1.4583
37	2.5976	6.2858	1.244	1.5911
38	2.4851	6.6255	1.3342	1.7697
39	2.6047	6.0176	1.1366	1.4667
40	2.7586	5.6649	0.9864	1.3265
41	2.5641	4.9835	1.0638	1.2861
42	3.0994	5.8778	1.443	1.7681
43	3.131	3.8055	0.8235	0.9208
44	3.3697	4.3726	0.9778	1.0403
45	3.1951	5.1306	0.9584	1.1761
46	3.2007	5.0531	0.995	1.1899
47	3.0813	5.1165	0.9187	1.1986
48	3.7538	5.3175	1.0221	1.2411
49	2.8618	6.643	1.4697	1.8559
50	3.0999	5.0556	1.0165	1.2185
51	2.8961	4.4529	0.9581	1.0763
52	2.7628	4.3807	0.867	1.0543
53	2.6867	5.2298	1.0481	1.3329
54	3.0604	4.3546	0.932	1.0034
55	2.5953	6.1116	1.2468	1.6284
56	3.3888	4.2311	0.8942	0.9965
57	3.14	5.0454	0.944	1.1905
58	3.0675	6.7829	1.6088	1.9187
59	3.117	5.0574	0.9566	1.1654
60	2.5639	6.3852	1.342	1.6927
61	2.9964	4.2583	1.0299	1.0363
62	3.1772	4.2177	0.8481	0.9426
63	2.318	4.5559	1.0573	1.2409
64	2.5833	4.0543	0.793	0.9426
65	3.0191	4.9042	0.9389	1.1385
66	2.6202	4.9068	0.93	1.1154
67	3.0392	4.9437	0.9483	1.1331
68	2.7796	5.0052	0.8929	1.12
69	2.0839	3.592	1.1144	1.2141
70	3.1523	3.4823	0.7685	0.8322

Table E.8 Linear -Kramars Kronig Validation of cell 3 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
71	3.1151	3.801	0.8409	0.925
72	2.8228	3.5899	0.7623	0.8775
73	2.7018	4.3092	0.8085	0.9885
74	3.1599	4.4835	0.9164	1.0525
75	2.8198	4.9386	0.8828	1.1255
76	3.0986	4.1089	0.8426	0.9667
77	3.4276	6.8506	1.6987	1.9904
78	2.2599	5.6131	0.957	1.3085
79	2.6865	4.9229	0.9134	1.1952
80	3.2926	5.0906	0.9445	1.1511
81	2.7816	4.0364	0.8948	0.9715
82	2.8929	4.2066	0.8453	0.9479
83	2.9648	4.1353	0.9633	0.9505
84	2.7909	5.7185	1.0705	1.3436
85	2.8159	5.6693	1.4049	1.6596
86	3.0273	4.8768	0.9505	1.1314
87	3.0339	4.1039	0.7877	0.9878
88	3.1382	6.0056	1.186	1.4773
89	3.4807	4.1917	0.9506	1.0076
90	3.3831	4.1915	0.861	0.9817
91	2.3387	5.3719	0.9914	1.3513
92	3.0173	3.7248	0.8151	0.8802
93	3.1102	5.1199	0.9612	1.1523
94	2.6808	5.4647	0.8718	1.2684
95	2.5988	5.9918	1.1128	1.4758
96	2.9986	4.9449	0.8587	1.097
97	3.2756	4.3071	0.9084	1.0031
98	3.308	5.1279	0.9464	1.1465
99	2.8663	3.7654	0.7537	0.8394
100	2.9986	4.3241	0.8543	0.981
101	1.7561	1.8543	0.5701	0.5963
102	1.2788	2.1305	0.5706	0.5925
103	1.1919	1.5921	0.4139	0.5352
104	1.3616	1.5301	0.4564	0.4217
105	1.3898	1.4013	0.4273	0.5065

Table E.8 Linear -Kramars Kronig Validation of cell 3 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
106	2.2225	2.6869	1.1119	1.1097
107	1.3112	1.7807	0.5793	0.6437
108	1.1936	1.5778	0.3456	0.4652
109	1.2259	1.0691	0.3255	0.3643
110	1.3869	1.3892	0.3732	0.3611
111	2.6526	4.9273	0.8167	1.1064
112	3.5015	4.2144	0.7915	0.9159
113	3.1072	4.7036	0.8451	1.0341
114	3.3743	4.7177	0.9055	1.0462
115	3.7616	5.0616	1.767	1.7854
116	2.3616	2.2365	0.6477	0.6832
117	2.2537	2.9207	0.7471	0.74
118	1.7346	3.9243	0.9572	1.1196
119	1.974	2.822	0.6252	0.8373
120	2.5458	3.1417	0.7887	0.8732
121	3.2834	5.0795	0.908	1.0612
122	3.1931	3.7669	0.7477	0.8805
123	2.5003	5.7812	1.1157	1.4808
124	2.1953	2.0409	0.6602	0.6138
125	1.6944	2.1783	0.6151	0.6395
126	2.0856	2.7543	0.681	0.7066
127	1.8779	2.7064	0.6143	0.7189
128	2.4793	2.9239	0.7621	0.7313
129	2.4387	2.7781	0.687	0.7724
130	2.0208	3.5683	0.7908	0.9145
131	2.1113	3.7685	0.8522	0.9985
132	2.2093	2.3225	0.6495	0.65
133	2.0462	3.9552	0.903	1.071
134	2.3245	2.3092	0.6264	0.6827
135	2.3203	2.9893	0.7409	0.7904
136	2.3985	2.42	0.731	0.6627
137	2.5086	4.5551	1.2155	1.2377
138	2.3094	2.4761	0.7074	0.7342
139	2.6166	2.5199	0.7423	0.8149
140	2.7175	3.5	0.8882	0.9083

Table E.8 Linear -Kramars Kronig Validation of cell 3 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
141	2.238	2.2517	0.6846	0.7337
142	2.4474	2.3589	0.6765	0.7421
143	2.7234	2.2986	0.712	0.6721
144	2.2578	2.2258	0.7137	0.6556
145	2.3587	2.2895	0.6222	0.7675
146	1.8761	3.1935	0.6805	0.8575
147	2.7301	4.3285	0.7537	0.9963
148	2.8231	5.5292	0.8032	1.2037
149	2.8903	4.7273	0.7969	1.02
150	4.252	7.2573	1.9178	2.2014
151	2.2768	3.9837	0.9568	1.1407
152	1.9443	2.9205	0.7073	0.7903
153	2.2919	3.3321	0.8007	0.8342
154	2.5363	2.1267	0.6465	0.6321
155	2.1777	3.2312	0.7519	0.7723
156	2.2527	2.1727	0.6654	0.6046
157	2.1072	3.1243	0.766	0.7614
158	2.8056	3.7459	0.6777	0.8989
159	2.9596	4.0359	0.7415	0.9236
160	2.9352	4.1998	0.7271	0.9181
161	2.9168	5.0189	0.7716	1.1249
162	2.7117	5.0261	0.7823	1.0713
163	3.0739	4.4726	0.787	1.0424
164	2.0074	1.9105	0.5672	0.5748
165	1.8187	1.8866	0.5527	0.5869
166	3.1311	4.8481	1.5816	1.6279
167	2.0293	1.9728	0.5884	0.5712
168	2.0895	2.9942	0.6823	0.7884
169	2.5345	6.3326	1.1272	1.556
170	2.9089	4.2997	0.7423	0.9082
171	2.7937	5.1552	0.7765	1.1089
172	2.9047	4.3259	0.7993	0.9959
173	2.1043	1.9561	0.5777	0.6598
174	2.424	1.963	0.6716	0.6438
175	2.0422	3.3994	0.7468	0.8504

Table E.8 Linear -Kramars Kronig Validation of cell 3 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
176	2.1203	2.8364	0.6586	0.7545
177	2.0574	2.939	0.6355	0.7659
178	1.8276	3.5063	0.7167	0.8909
179	2.3508	5.7548	0.8975	1.2913
180	3.0785	4.0177	0.7921	0.9412
181	3.0157	4.0402	0.7805	0.869
182	3.1432	4.264	0.7703	0.9499
183	1.9186	4.0835	1.0259	1.1481
184	1.9799	1.9868	0.5555	0.6655
185	2.1971	2.0348	0.6863	0.5735
186	2.1723	3.0683	0.6856	0.834
187	2.0449	1.8942	0.5801	0.6393
188	2.1681	2.8624	0.6694	0.7495
189	2.637	3.1373	0.7919	0.7515
190	2.8713	3.9552	0.6872	0.9006
191	2.7987	4.0729	0.709	0.9005
192	2.7571	3.7436	0.6838	0.7923
193	2.5814	4.935	0.7063	1.0979
194	3.4709	4.3008	0.7921	0.9905
195	2.9778	4.5097	0.7895	0.973
196	1.954	1.8864	0.5196	0.626
197	2.1375	1.9469	0.5737	0.6613
198	2.0297	1.9151	0.5581	0.5861
199	1.9874	1.8032	0.5927	0.569
200	2.4808	3.7842	0.8802	0.96

Table E.9 Linear -Kramars Kronig Validation of cell 4

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
1	0.6418	1.2151	0.3038	0.3576
2	0.9952	1.3626	0.3666	0.4171
3	0.6521	0.719	0.3042	0.286
4	1.1764	1.4684	0.4344	0.4652
5	0.6538	1.1112	0.3077	0.3175
6	1.1426	1.715	0.4255	0.561
7	1.1509	1.9087	0.5103	0.4947
8	1.3055	2.5854	0.7937	0.9332
9	1.003	1.9198	0.4599	0.5956
10	0.9027	1.9549	0.4501	0.6047
11	1.3463	2.2616	0.7858	0.874
12	1.4536	2.9962	0.6314	0.7935
13	1.4189	2.9561	0.6728	0.8233
14	1.258	2.6607	0.6253	0.692
15	1.7857	3.9761	1.0401	1.1275
16	1.4293	2.9563	0.6108	0.8378
17	1.2463	2.6219	0.5638	0.7608
18	0.9804	1.5171	0.5587	0.6203
19	1.4828	2.9933	0.6257	0.8288
20	1.4669	3.3622	0.8006	0.897
21	1.5065	2.8154	0.6917	0.7358
22	0.9784	1.536	0.4205	0.4138
23	10.8876	3.3301	2.8543	1.312
24	1.348	2.0582	0.7503	0.6989
25	0.9565	1.6081	0.4483	0.5123
26	0.9615	1.8793	0.3802	0.6142
27	1.0805	1.7858	0.4793	0.4741
28	0.8968	1.8539	0.4383	0.5217
29	0.9083	1.4964	0.3698	0.4764
30	1.9684	3.8604	0.6739	0.9606
31	2.0372	2.8178	1.0479	1.0233
32	1.2765	1.5065	0.4795	0.3793
33	1.4953	1.9239	0.7328	0.7024
34	1.0389	1.4574	0.3851	0.3654
35	0.8969	1.7376	0.3804	0.5294

Table E.9 Linear -Kramars Kronig Validation of cell 4 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
36	0.993	2.0204	0.4304	0.5703
37	0.7981	1.7576	0.387	0.5558
38	1.04	2.0327	0.4886	0.595
39	0.9071	1.9667	0.4373	0.5746
40	1.0258	1.9617	0.4532	0.5936
41	0.81	1.9962	0.3778	0.6461
42	1.0029	2.0905	0.4569	0.5838
43	1.0373	2.0962	0.434	0.5876
44	1.0082	1.571	0.392	0.4908
45	1.0277	1.846	0.4203	0.4907
46	0.8656	1.7289	0.3518	0.6009
47	0.8765	1.8122	0.4161	0.5617
48	0.8789	1.5854	0.3513	0.5513
49	0.9363	1.5123	0.3659	0.4846
50	0.822	1.8243	0.4218	0.5407
51	1.3831	2.4237	0.7349	0.8152
52	1.7613	2.5945	0.9341	0.9206
53	0.7083	1.2162	0.3424	0.4251
54	0.8009	1.458	0.3982	0.4411
55	0.8161	1.5123	0.3905	0.4709
56	0.9223	1.7483	0.3858	0.5204
57	0.8786	1.8138	0.4297	0.5257
58	0.9334	1.7598	0.4465	0.5511
59	1.0517	1.8087	0.3689	0.5692
60	1.0277	1.8962	0.4277	0.5634
61	0.8327	1.4457	0.3497	0.4929
62	1.2954	1.7164	0.4783	0.4489
63	0.854	1.8828	0.316	0.5185
64	0.7234	1.3935	0.3271	0.4788
65	0.8007	1.7596	0.3656	0.5523
66	1.1586	1.5513	0.3818	0.4806
67	0.9502	1.8227	0.4675	0.5586
68	0.8344	1.7805	0.4116	0.5048
69	0.9501	1.7938	0.4752	0.5179
70	1.0246	1.5279	0.4524	0.4529

Table E.9 Linear -Kramars Kronig Validation of cell 4 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
71	0.7901	1.8052	0.3802	0.5418
72	0.7985	1.9058	0.3812	0.5632
73	1.7563	2.7373	0.9458	0.9776
74	0.8487	1.4162	0.3057	0.5168
75	0.8477	1.8151	0.373	0.5822
76	0.8115	1.663	0.386	0.5123
77	0.7955	1.7924	0.4186	0.5165
78	0.8852	1.8129	0.4071	0.5436
79	0.9977	1.8495	0.4639	0.5251
80	0.8706	1.8222	0.3956	0.5332
81	0.8755	2.1323	0.4611	0.61
82	0.5131	0.5389	0.2256	0.2028
83	0.9544	1.4073	0.3397	0.4184
84	1.7913	1.8957	0.9746	0.6526
85	0.729	1.5723	0.3371	0.486
86	0.935	1.8065	0.3533	0.5651
87	0.9957	1.7633	0.4076	0.5242
88	1.002	1.898	0.4277	0.4974
89	0.9411	1.8719	0.3982	0.4925
90	0.9985	1.9269	0.4394	0.551
91	0.8335	1.4656	0.4642	0.5208
92	0.9605	1.4451	0.3618	0.4705
93	0.9559	1.4687	0.354	0.403
94	0.881	1.2859	0.3374	0.388
95	0.9347	1.9796	0.4859	0.6486
96	1.0191	1.4988	0.3722	0.5047
97	0.7911	1.9741	0.3996	0.5464
98	0.8988	1.8882	0.4475	0.5214
99	0.9626	1.3971	0.357	0.5026
100	0.9566	1.3737	0.2853	0.5094
101	1.1484	1.6376	0.5977	0.5317
102	0.7017	1.028	0.2486	0.279
103	0.7798	1.339	0.3164	0.5053
104	0.6555	0.7934	0.2334	0.3192
105	0.8227	1.1932	0.3436	0.3711

Table E.9 Linear -Kramars Kronig Validation of cell 4 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
106	1.1196	1.1454	0.3897	0.2906
107	0.9263	1.2884	0.2701	0.4724
108	0.6904	1.5477	0.3485	0.4188
109	29.9546	16.6065	8.1205	6.2751
110	1.1164	1.5162	0.4388	0.4217
111	0.9635	1.226	0.4766	0.3714
112	0.745	0.8911	0.2856	0.2732
113	0.541	0.9934	0.2313	0.2987
114	0.8055	1.1765	0.3145	0.3295
115	0.6636	1.21	0.2737	0.4582
116	0.8373	1.0664	0.3163	0.3662
117	0.8934	1.1944	0.3339	0.3811
118	0.8362	1.3074	0.3437	0.3599
119	0.9268	1.4187	0.4096	0.4288
120	0.9717	1.2593	0.3562	0.3803
121	1.0562	1.296	0.3448	0.3884
122	0.8528	0.8643	0.2808	0.2931
123	0.6588	0.9786	0.3257	0.3127
124	0.9719	1.035	0.2931	0.3228
125	0.5663	1.4274	0.2716	0.4387
126	0.8697	1.5966	0.3413	0.5621
127	0.8983	1.7037	0.3984	0.4983
128	1.0391	1.4229	0.3681	0.484
129	0.8477	1.7075	0.3446	0.5687
130	1.0528	2.3169	0.5825	0.6933
131	1.0427	2.6241	0.4931	0.6351
132	1.2486	2.4959	0.5229	0.6517
133	1.1344	2.6179	0.6636	0.8347
134	1.012	2.0612	0.419	0.5687
135	1.1315	2.1408	0.4678	0.6072
136	1.0761	2.117	0.3837	0.6497
137	1.1073	2.2775	0.4382	0.6096
138	1.0869	2.1632	0.4371	0.6211
139	1.3279	1.7083	0.423	0.5303
140	1.2442	2.2229	0.5322	0.5356

Table E.9 Linear -Kramars Kronig Validation of cell 4 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
141	0.8567	1.1731	0.3232	0.3446
142	0.736	1.4466	0.3422	0.4282
143	1.0234	1.9565	0.6018	0.6056
144	0.7895	1.4441	0.3124	0.4043
145	0.6688	1.4231	0.3219	0.413
146	0.7998	1.472	0.3696	0.4187
147	0.7042	1.4253	0.3188	0.4533
148	0.7101	1.1264	0.2442	0.4237
149	0.6568	1.1125	0.277	0.3699
150	0.8586	1.4148	0.275	0.4643
151	0.6207	1.2267	0.2675	0.3913
152	0.6331	1.4458	0.2662	0.3544
153	1.046	1.1762	0.3007	0.3837
154	0.6795	1.3423	0.2782	0.358
155	0.9266	1.3764	0.3675	0.3605
156	0.7435	1.1302	0.3274	0.3235
157	0.7768	1.1302	0.28	0.3743
158	1.0067	1.2865	0.3802	0.3211
159	0.9467	1.0454	0.2749	0.4239
160	0.8186	1.0012	0.3102	0.2892
161	0.9646	0.9624	0.299	0.2645
162	0.8098	1.257	0.2768	0.3445
163	0.6883	0.8865	0.2767	0.2604
164	0.7551	1.3001	0.2857	0.3172
165	0.9227	1.3806	0.3632	0.3243
166	0.7367	1.2837	0.2794	0.3602
167	0.9641	1.5069	0.3116	0.4761
168	0.6144	1.5477	0.3131	0.4241
169	0.7421	1.5538	0.3195	0.4158
170	0.8581	1.4428	0.3538	0.4233
171	0.6259	1.3109	0.2628	0.3313
172	0.6744	1.0069	0.2292	0.2693
173	0.8702	1.2207	0.3458	0.3113
174	0.538	0.8515	0.2783	0.3212
175	0.6616	1.4551	0.3186	0.4902

Table E.9 Linear -Kramars Kronig Validation of cell 4 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
176	0.6782	1.2859	0.2715	0.4372
177	0.6771	1.1292	0.2259	0.4108
178	0.6911	1.3101	0.3206	0.4196
179	0.6888	1.4366	0.3113	0.3756
180	0.6192	1.4951	0.2645	0.4628
181	0.6825	1.3363	0.2673	0.4353
182	0.8275	1.5982	0.3211	0.4152
183	0.7025	0.8033	0.2409	0.2269
184	0.9103	1.0969	0.3341	0.3179
185	0.5382	0.921	0.2453	0.2386
186	0.5894	1.1608	0.2777	0.3829
187	0.8217	1.1497	0.2592	0.3902
188	0.5876	1.3412	0.2603	0.4155
189	0.7202	1.2441	0.2591	0.4092
190	0.6536	1.325	0.2967	0.3568
191	0.769	1.0095	0.3103	0.3521
192	0.8517	1.0832	0.2891	0.3959
193	0.6908	1.4196	0.2885	0.4282
194	0.7963	1.0824	0.2914	0.3234
195	0.6974	1.4186	0.2937	0.4484
196	0.665	1.3607	0.2446	0.4614
197	0.958	1.1826	0.3426	0.2901
198	0.6811	0.964	0.2136	0.3272
199	0.595	1.1005	0.2385	0.4012
200	1.4068	2.1603	0.7265	0.7314

Table E.10 Linear -Kramars Kronig Validation of cell 5

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
1	2.2901	2.4467	0.6402	0.674
2	3.5129	5.5422	1.7301	1.9445
3	2.4225	3.5688	0.8664	1.0074
4	3.4424	5.5096	1.6645	1.8451
5	2.062	3.5984	0.85	0.9795
6	2.0845	3.4728	0.8501	1.0288
7	2.1185	3.4679	0.9029	1.0003
8	3.3244	5.3497	1.6552	1.8271
9	2.3942	3.3141	0.7588	0.9201
10	2.2567	3.0847	0.8085	0.8863
11	1.6282	3.11	0.6865	0.8854
12	2.1078	2.7443	0.7529	0.8045
13	2.017	3.3493	0.8667	1.0097
14	2.3481	3.5908	0.8023	0.9961
15	1.5799	4.3777	1.0307	1.2993
16	1.9657	3.5245	0.7856	0.9242
17	2.2346	4.8449	1.3124	1.5055
18	1.9553	3.328	0.8995	0.9592
19	2.4125	3.4451	0.8715	0.9186
20	2.3091	3.4751	0.8585	1.0117
21	2.2048	2.8893	0.7833	0.8155
22	1.6848	2.8836	0.8093	0.8048
23	1.7155	3.1328	0.6908	0.8366
24	2.1449	3.2711	0.776	0.9512
25	1.8973	3.381	0.7812	0.9413
26	1.7552	3.3017	0.7619	0.9342
27	2.1975	3.4821	0.8394	0.9837
28	3.6262	5.5827	1.8381	1.9572
29	2.2551	4.6972	1.2239	1.4285
30	2.1744	3.4167	0.8427	0.9139
31	1.671	2.7896	0.7449	0.7733
32	3.2853	4.7274	1.461	1.607
33	3.8413	4.9123	1.7996	1.9
34	1.7523	3.1769	0.7837	0.8283
35	1.8289	4.2397	1.0138	1.2064

Table E.10 Linear -Kramars Kronig Validation of cell 5 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
36	1.8474	3.2672	0.7008	0.9377
37	1.937	4.2916	1.0654	1.2367
38	2.2326	4.3399	1.0686	1.2463
39	1.893	3.2745	0.8111	0.9138
40	1.8388	3.1841	0.8098	0.9597
41	2.1404	2.9325	0.6943	0.8146
42	1.8479	2.8368	0.7092	0.8423
43	1.5138	2.8004	0.6559	0.7742
44	1.6371	2.9039	0.7136	0.8585
45	1.8678	2.3549	0.6765	0.7407
46	2.268	4.7352	1.2206	1.4503
47	1.8755	3.312	0.8031	0.8922
48	1.9074	3.2258	0.8103	0.8632
49	1.8638	3.2981	0.7747	0.8887
50	2.5678	4.6456	1.3668	1.4754
51	1.9914	2.4813	0.6272	0.6926
52	2.1037	2.8625	0.6943	0.6894
53	2.0823	2.7989	0.6998	0.7531
54	1.7227	3.2824	0.7486	0.8912
55	2.3894	2.5028	0.7179	0.8334
56	1.8824	2.4889	0.6402	0.83
57	1.7086	4.1179	0.9974	1.2391
58	1.8521	4.5136	1.1217	1.3125
59	1.5866	4.0604	0.897	1.1214
60	1.8783	2.4524	0.6997	0.7354
61	1.8807	2.4814	0.6856	0.7482
62	1.6194	4.038	0.8967	1.1289
63	2.4026	2.5667	0.7141	0.8144
64	1.8471	3.1255	0.7892	0.9122
65	2.1567	3.7699	0.9076	1.0315
66	2.1925	3.1943	0.752	0.8505
67	1.6589	3.9629	0.8821	1.1351
68	1.5188	3.2539	0.6362	0.841
69	2.0413	2.075	0.6037	0.6171
70	2.0087	2.8145	0.6889	0.7113

Table E.10 Linear -Kramars Kronig Validation of cell 5 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
71	2.5674	4.3586	1.2485	1.4508
72	1.7035	2.7651	0.7122	0.7216
73	1.9786	2.7206	0.7051	0.7202
74	1.9144	2.6405	0.5819	0.7796
75	2.2296	3.1139	0.8108	0.8315
76	1.9229	4.2746	1.0718	1.2586
77	1.843	3.1498	0.7655	0.9371
78	1.8136	3.1699	0.6931	0.8779
79	1.7982	3.13	0.7249	0.9291
80	1.8147	3.1848	0.68	0.9042
81	2.0105	2.5159	0.8773	0.7923
82	1.6184	2.3979	0.6615	0.6876
83	1.8766	2.4896	0.6051	0.6482
84	1.6196	2.8231	0.6791	0.7838
85	1.94	2.706	0.6439	0.7404
86	1.5962	3.5272	0.719	0.9454
87	1.7267	3.1311	0.745	0.8475
88	1.725	3.1015	0.7168	0.8526
89	1.5082	3.4468	0.7625	0.8763
90	1.6979	3.1349	0.7231	0.8505
91	1.2436	1.4097	0.442	0.456
92	1.3944	1.5646	0.5485	0.5634
93	1.4234	2.0289	0.7316	0.7409
94	0.8621	1.5655	0.4849	0.5079
95	1.2581	1.7667	0.4248	0.5496
96	1.0529	1.5588	0.3918	0.5305
97	1.0321	1.0533	0.4262	0.4044
98	1.4324	1.9308	0.6588	0.6279
99	1.1412	1.5433	0.4803	0.5234
100	0.9602	1.9808	0.5413	0.6428
101	1.4607	1.9054	0.4321	0.4836
102	1.5721	2.153	0.508	0.5586
103	1.8248	2.4451	0.4815	0.6317
104	2.5504	4.7682	1.4143	1.5021
105	2.1443	2.7604	0.5917	0.6536

Table E.10 Linear -Kramars Kronig Validation of cell 5 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
106	1.9516	3.4462	0.656	0.8113
107	1.8374	2.6117	0.5789	0.6347
108	1.5897	3.1189	0.5961	0.7424
109	1.6224	3.7495	0.8264	1.0154
110	1.9236	4.0838	0.9215	1.1487
111	2.0509	2.6871	0.6321	0.6339
112	1.7809	2.6057	0.576	0.6652
113	1.9117	3.3717	0.6264	0.8694
114	1.9206	2.7906	0.5947	0.7363
115	1.645	4.2748	0.9253	1.1603
116	2.0528	3.4397	0.6949	0.8566
117	1.9052	3.6067	0.6698	0.8516
118	1.9595	2.539	0.537	0.6146
119	2.2394	4.3825	1.167	1.3778
120	1.6758	2.5394	0.4918	0.6975
121	1.9776	2.5846	0.6081	0.6419
122	2.0123	2.6846	0.5829	0.6173
123	1.9071	3.4389	0.6363	0.8402
124	2.1636	2.826	0.6275	0.6788
125	1.9702	2.8543	0.5868	0.7263
126	1.7505	4.058	0.725	0.999
127	2.0161	2.8708	0.6332	0.7512
128	1.7533	3.2903	0.5513	0.7744
129	1.5984	4.0966	0.8082	1.1059
130	2.0357	2.5343	0.5632	0.6402
131	1.7654	4.1811	0.853	1.0986
132	1.9464	2.8243	0.5679	0.6983
133	2.151	2.8813	0.5776	0.7057
134	1.8807	2.8048	0.6121	0.7236
135	2.2019	2.8636	0.642	0.6949
136	2.0377	3.5385	0.6217	0.9034
137	2.1972	2.9325	0.5995	0.7485
138	1.6078	3.9873	0.7217	0.9446
139	2.2508	2.9507	0.6495	0.7525
140	2.3061	3.0176	0.6648	0.7679

Table E.10 Linear -Kramars Kronig Validation of cell 5 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
141	1.9227	2.5763	0.6147	0.6239
142	2.0054	2.549	0.5769	0.6417
143	1.835	2.6096	0.5858	0.6544
144	1.7615	2.7741	0.584	0.7508
145	1.672	3.5428	0.65	0.8695
146	1.9303	3.6035	0.6671	0.8727
147	1.8291	2.8653	0.5649	0.6896
148	1.7354	3.6239	0.6707	0.8663
149	2.2228	3.6317	0.6802	0.9367
150	1.7736	3.4477	0.6634	0.8361
151	1.9647	3.0544	0.6409	0.7305
152	1.7188	3.8486	0.8332	1.0378
153	1.6606	3.5702	0.5674	0.7796
154	2.0919	3.9076	0.7145	0.9047
155	2.1838	2.8118	0.6407	0.6664
156	2.1945	2.8473	0.5959	0.6732
157	2.1259	3.6368	0.6336	0.9452
158	2.2831	2.921	0.5901	0.7851
159	2.2277	3.6694	0.6892	0.9156
160	2.1549	3.6985	0.6557	0.917
161	2.1515	2.8589	0.6357	0.701
162	2.0035	3.2862	0.6201	0.7606
163	1.8162	2.6202	0.5992	0.6863
164	1.939	3.5135	0.6461	0.8359
165	2.2112	2.6809	0.6278	0.7024
166	1.8812	3.7986	0.6684	0.8978
167	2.1376	3.7456	0.6697	0.9186
168	2.2205	3.7464	0.6963	0.9245
169	1.8911	3.7771	0.7034	0.9508
170	2.1499	4.5208	0.8821	1.1158
171	1.891	3.932	0.7449	0.968
172	1.7503	3.3599	0.6225	0.8229
173	1.9702	3.4691	0.6111	0.8248
174	2.0273	4.5193	1.0403	1.2354
175	2.0338	4.7542	1.0489	1.2783

Table E.10 Linear -Kramars Kronig Validation of cell 5 (Continued)

Cycle	Max_Abs_Res_Re (%)	Max_Abs_Res_Im (%)	RMSE_Re (%)	RMSE_Im (%)
176	2.0412	3.8691	0.6726	0.962
177	2.1654	4.078	0.6948	0.9501
178	2.036	3.846	0.7135	0.9707
179	1.8728	3.7341	0.7339	0.8901
180	2.0085	3.0797	0.6152	0.7891
181	1.6862	3.2699	0.601	0.8286
182	1.8615	3.2155	0.6259	0.7829
183	1.3958	2.8647	0.5369	0.6624
184	1.72	3.907	0.9191	1.0907
185	1.8169	4.0262	0.959	1.1155
186	1.9252	3.1741	0.64	0.7677
187	1.8138	2.5662	0.5298	0.6464
188	1.8186	2.5342	0.5672	0.6442
189	1.8135	3.8347	0.7322	0.9605
190	1.6327	3.2398	0.5704	0.8431
191	1.8663	2.2984	0.5093	0.6415
192	1.6807	2.8841	0.508	0.6565
193	1.8144	3.5808	0.5781	0.8291
194	20.399	26.2325	6.0361	6.6689
195	1.9483	3.9585	0.7283	0.9878
196	2.0178	3.4931	0.6511	0.8347
197	1.6925	3.4652	0.5994	0.9186
198	1.661	3.4589	0.6611	0.8115
199	2.1153	3.5137	0.6541	0.8249
200	2.0769	3.5674	0.6667	0.8611

Appendix F.
Analysis Outlier capacity

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Analysis of Capacity Data Anomalies Caused by Current Interruptions

Degradation testing of Cell 4 revealed sudden, anomalous capacity drops (outliers). To determine the cause, the current profiles of the highest capacity (normal) and lowest capacity (abnormal) cycles were compared (Figure F.1).

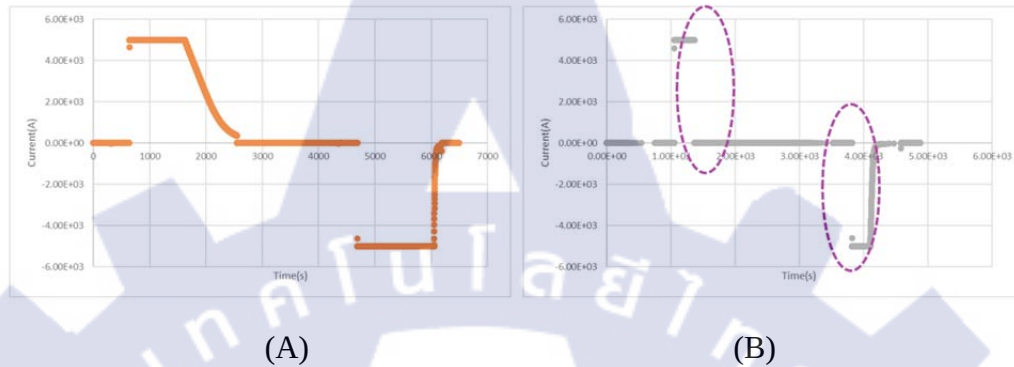


Figure F 1.1 the comparison between normal current profile and anomalous profile (A) the normal profile and (B) the anomaly, The dashed-line areas indicate periods when the testing current dropped to zero during the experiment.

The normal profile (orange graph) demonstrates a complete CC-CV charging sequence, maintaining a 5A constant current followed by a typical CV decay. Conversely, the abnormal profile (gray graph) shows an abruptly terminated CC phase and a completely absent CV phase.

This anomaly is hypothesized to result from a brief power outage. A sudden drop to zero current caused the battery tester to misinterpret the event as an "End Condition" rather than aborting the program. Consequently, the tester skipped the remainder of the charging phase and proceeded directly to the next step (rest or discharge).

Because the battery was not fully charged, the subsequent discharge capacity was artificially low. Therefore, these outliers in Cell 4 are external measurement artifacts rather than true electrochemical degradation, justifying their removal during data preprocessing prior to AI model training.