

Final Report



University of
Sheffield

Applying Machine learning methods to model the degradation of lithium based batteries under multi-stage CC charging

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1 Introduction

The global consumption of energy is rising by 4.5×10^{16} Joules every year; 77% of which is from non-renewable sources [1]. With the effects of non-renewables on the environment still not fully realised, coupled with concerns over their finite nature, there is a constant need to increase the usage of renewable sources. However, a large set of renewable generation methods fall under the category of variable renewable energy (VRE) sources [2], thus requiring a robust form of energy storage to solve their intermittent availability. As battery technology improves, the use of batteries as a storage medium for the energy sector is becoming increasingly prominent. There is also a rapid increase in electric vehicle production, with a push to increase the adoption of EVs. In 2024, 17.3 million EVs were produced [3], alongside a recent average year-on-year increase of 20%. Lithium-ion batteries (LIBs) are currently the most widely used batteries due to their desirable characteristics in energy density, ageing behaviour, cost, and more.

EVs and the energy sector now account for 90% of total lithium-ion battery demand, and the total lithium-ion battery demand has increased ten-fold since 2016 [4]. Different sources predict different forecasts for battery growth [5, 6]; regardless, the rate of demand does not appear to be decreasing in the near future.

LIBs decrease in performance and capacity over time [7], until they are deemed unsuitable for their current use. Eventually, all batteries in use today will require disposal. In 2021, 436,000 tonnes of lithium were mined for batteries alone [8], further highlighting the need to reduce reliance on mining while meeting demand. Battery chemistry is still a developing field, and newer batteries may use fewer scarce materials, making long-term sustainability difficult to predict, however, some reports suggest cobalt reserves may be exhausted by 2040 [9]. Recycling methods are being developed to recover battery materials, termed battery metal recycling (BMR) - however, sources vary widely, with estimates of current recycling rates ranging from as low as 5%. Recycling technology is still developing, and many different process routes exist [10]. Since most valuable metals are located in the cathode, hydrometallurgical processes can recover them, at the expense of other metal recovery, although often

with reduced lithium yield [11] - this could continue to become more beneficial however, promising work has shown lithium recovery requiring less than 40% of the energy needed to mine virgin material [12], while still recovering nickel and cobalt.

There is also increasing interest in reusing batteries before recycling. These are referred to as second-life batteries (SLBs). In EV applications, batteries are typically retired when their usable capacity falls below 80% [13], yet they can still perform effectively in less demanding applications such as energy storage systems (ESS) [14]. Re-use has been reported to reduce CO_2 emissions by up to 56% compared with natural gas systems. However, challenges exist, including safety validation, cell sorting based on health, and the lack of automated pack disassembly methods. These additional steps may lead to SLBs being insufficiently cheaper than new batteries, limiting commercial appeal [14].

In summary, several methods are developing to reduce reliance on newly mined materials and lower recycling energy requirements, but extending the usable lifetime of existing batteries remains a direct and impactful way to reduce environmental burden while meeting rising demand. If just one additional life cycle could be added to all EVs currently on the road (60 million [15]), the saved energy would be enough to power the UK for an entire day [16]. With most modern batteries capable of over 1000 cycles, any increase in cycle life can lead to significant benefit.

Modelling and predicting lithium-ion battery degradation is therefore pivotal, as it enables informed decisions on how best to charge and operate batteries to prolong life, as well as optimise usage across their lifetime.

1.1 Project Aims

This project aims first to characterise lithium battery behaviour through parameterisation without ex-situ tests. The obtained data will then be used, in combination with previous work, to develop a charging protocol based on minimising different objective functions. The results from this will be used to form the basis of a machine learning model, with the intention that the model can, over time, provide a simpler method of predicting a battery's

future behaviour. If the model can show how different charging currents affect degradation, a charging protocol derived from minimising such a model will be implemented and tested experimentally. If this is not achieved, the project will still provide value by validating existing charging strategies designed to minimise degradation, and by investigating parameterisation of batteries during degradation using optimisation tools.

Figure 1 highlights the original idealised goal: to develop a purely data-driven model capable of predicting output voltage for any cycle, allowing the derivation of an ideal charging current to maximise lifespan.

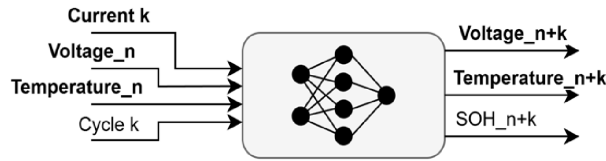


Figure 1: Initial end objective: black-box battery degradation modelling

1.1.1 Objectives

- Analyse ICLOCS2 and other methods for parameterising batteries under real-time use
- Modify previously developed charging methods for laboratory implementation and compare real experimental results
- Examine how adapting the charging profile during degradation influences battery life-time
- Investigate machine learning methods to model the collected data for predicting degradation
- Use the model to develop a new charging strategy and validate experimentally

2 Literature Review

2.1 Lithium based battery backgrounds

Notice: During this research, and given the author does not come from an electrochemical background, it became clear that the terms potential and overpotential are used with slightly different meanings depending on context. There are likely equivalences between definitions, though the author cannot fully state them. For example, [17] describes the commonly used symbol ϕ as the electrical potential, whereas measurements of voltage in practice generally correspond to electrochemical potential difference (specifically of electrons) between two points, expressed as $\Delta\tilde{\mu} = \Delta\mu + \Delta z F \phi$. Overpotential in some instances, such as the Butler-Volmer model for current exchange, is a function of overpotential η and from G. Plett[18] is a difference in the current *electrical potential* and equilibrium potential, yet papers like [19] show overpotential more generally as the difference between any equilibrium potential and current potential. Thus confirmation should be made in regards to what type of potential and overpotential. Assumptions are given that potentials are a measure of energy state, which a difference between two points causing a force, and overpotential representing additional energy required for a process to occur.

Lithium-ion batteries are favourable largely due to the highly reductive nature of lithium. Taking the potential relative to the standard hydrogen electrode (SHE), the half-reaction of metallic lithium is approximately $-3.01V$ [18]. The cells potential difference is the difference in potentials of the negative and positive solid state electrodes $V_t = \phi_s^+(t) - \phi_s^-(t) - IR_{cc}$ where R_{cc} is the current collector or tabs ohmic resistance [20], having a large negative reduction potential allows for a variety of positive electrodes, yielding a high battery voltage. Coupled with Lithium's low molecular weight, a high energy density cell can be achieved too.

All lithium-ion batteries follow the same basic principle of operation. They consist of a positive electrode, a negative electrode, an electrolyte, a separator, and current collectors. Unlike many battery chemistries where active materials undergo conversion reactions that change the electrode's chemical composition, lithium-ion electrodes typically store lithium

through intercalation and de-intercalation — the lithium is inserted into or extracted from [18]. The negative electrode is usually graphite, able to store up to one lithium atom per six carbon atoms. The positive electrode can vary greatly, the most common are often composed of transitional metal oxides such as LCO, LMO, NMC, NCA [21]. The electrochemical state of lithium in graphite is similar to that of metallic lithium, so the negative electrode potential lies close to -3.0 V vs. SHE. Positive-electrode lithium is in a lower electrochemical energy state, giving typical reaction potentials of roughly 0-1.3 V vs. SHE, overall there is a large potential difference created. The negative electrode is often the key limiting factor in degradation as discussed later. The positive electrode materials vary greatly in material, but since this electrode has the biggest electrode potential, it has a largest impact on the overall cell voltage, and thus energy density of the cell, in addition since per volume it holds less lithium, electrode material with higher lithium capacity will be of greater affect than improving the negative electrodes capacity. The two reactions with lithium with the battery electrodes chosen for this project are shown below (during discharge, the reactions proceed from left to right, for the charging process, it's right to left):



The electrolyte is a medium that allows lithium ions to travel between the electrodes; however, it does not allow electrons to flow, which instead travel via the external circuit. The separator acts as a structural barrier to prevent the opposite electrodes from touching, allowing only ions to pass and thus preventing uncontrolled reactions that could cause major fire risks. During the discharging process, an external electrical path is provided between the collectors. The lithium stored within the negative electrode deintercalates, releasing lithium ions into the electrolyte, while the electrons leave the negative electrode, traveling across the external circuit to the positive electrode, where the lithium ions recombine with electrons and intercalate into the positive electrode structure. During charging, the applied voltage at the terminals is above the difference of the equilibrium electrode potentials. This

applied overpotential drives lithium ions to deintercalate from the positive electrode, travel across the electrolyte, and intercalate into the negative electrode, where they combine with electrons. The speed at which the ions flow is much slower than the electron transfer, which contributes to the characteristic behavior of lithium batteries [18].

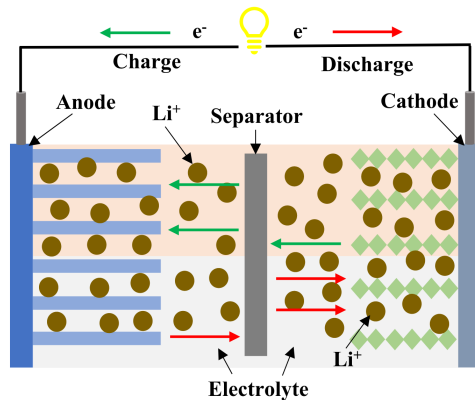


Figure 2: Visual structure of Lithium Battery [11]

2.2 Lithium based battery degradation modes

J'O. Kane et al. [22] summarises the key 3 modes of degradation caused within lithium-ion batteries described below. Calendar aging is neglected in this discussion.

Lithium plating - Under certain charging conditions, the lithium ions within the electrolyte will join with the electrons outside the negative electrode, producing pure lithium metal — which can grow forming dendrites, depicted in figure 3. The most understood causes which accelerate this is when the negative electrode potential falls below that of lithium's own electrode potential [23, 24], becoming the most thermodynamically viable reaction. From electrochemical models, the potential at the electrodes is the sum of their open circuit potentials and overpotential. The overpotential is largely due to the kinetic overpotential at the interface between the electrolyte and electrode [25]; the Butler-Volmer equation shows as the current density j increases, overpotential η increases (figure 9 shows the potentials changing during charge). Low temperatures and high SoC also increase lithium plating, since

it becomes harder for the lithium to intercalate within the carbon.

$$j = a_s i_0 \left[\exp\left(\frac{\alpha_a F}{RT} \eta\right) - \exp\left(-\frac{\alpha_c F}{RT} \eta\right) \right]$$

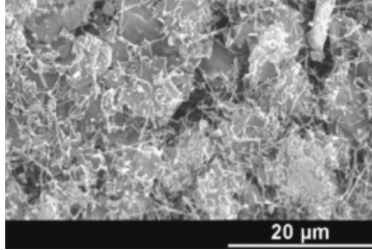


Figure 3: Lithium deposits shown in lighter grey on the graphite electrode [26]

SEI Layer growth - A layer known as solid electrolyte interphase [27] is formed as soon as the electrolyte solution comes into contact with the negative electrode causing salts like Li_2CO_3 to produce acids, followed by further reactions; this barrier acts to prevent electrons further reducing and using up more of the electrolyte, whilst allowing passage of the lithium ions to intercalate [27]. If this SEI breaks apart, new SEI will form, taking more lithium up, losing material for charging (LLI). Having the battery at high and low SoC can cause the SEI layer to thicken also [28]. SEI formation also takes up electrons within its reaction, thus reducing battery capacity.

Particle fracture - The physical volume of the electrodes can change during the intercalation and deintercalation, this is a degradation feature that can't be avoided in order to charge and discharge a battery; some electrodes exhibit more contraction than others, silicon significantly greater than graphite [18]. Concentration gradients, caused by high currents, within the electrode can also cause internal stress. This can over time cause the electrodes to break down, either resulting in more SEI growth, reducing more lithium; inability for areas of lithium intercalation, reducing charge capacity; and separation from the binder causing either increased ohmic resistance or loss in capacity.

In summary, high charging currents, extreme temperatures and extreme states of charge can accelerate degradation, thus to reduce this, charging and discharging at infinitesimally small rates and at optimal temperatures is best, however this neglects considerations such as charge

times, thus a balance between these constraints should always be taken into account and the charging strategies used in this project attempt to do so. The impact on degradation can change between charging and discharging, for example diffusion differences between charge and discharge are shown by J. Lain *et al.* [24].

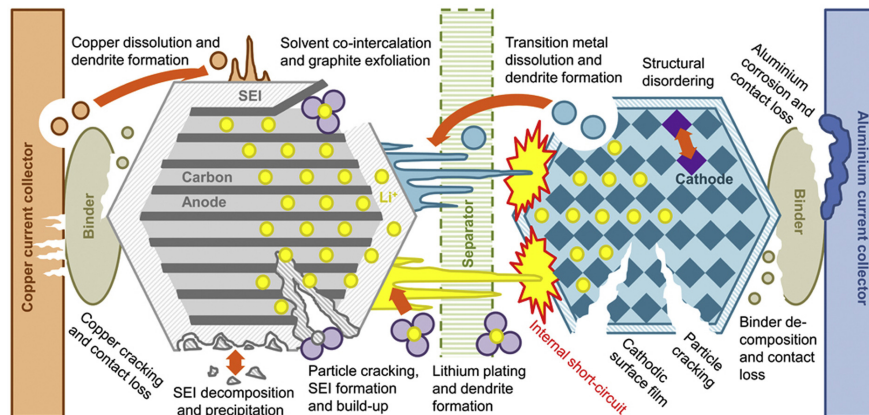


Figure 4: Visual impact of common degradation mechanisms [29]

2.3 Equivalent Circuit Model

There are many ways a lithium battery can be modeled, depending on the accuracy required, parameters available and computational power available. The two main categories are equivalent circuit models and physics-based models [18]. The physics-based models integrate conservation laws as well as dynamical behaviour which leads to a set of PDEs with both scalar and gradient-based boundary conditions. These require discretisation within the physical dimensions of the model to yield a set of ODEs which can be solved for. PyBaMM is a popular framework for such modeling, and its process is shown in figure 5. Popular physics-based models in order of computational complexity [30] are the Doyle-Fuller-Newman model [31], Single-Particle Model with electrolyte (SPMe) and SPM. The key problem of PBM's is that some require over 30 parameters to fully describe the properties, and errors in such can accumulate over time; depending on accuracy needed, the discretisation can yield hundreds of ODEs.

Equivalent circuit models use standard lumped electrical elements to match the behaviour

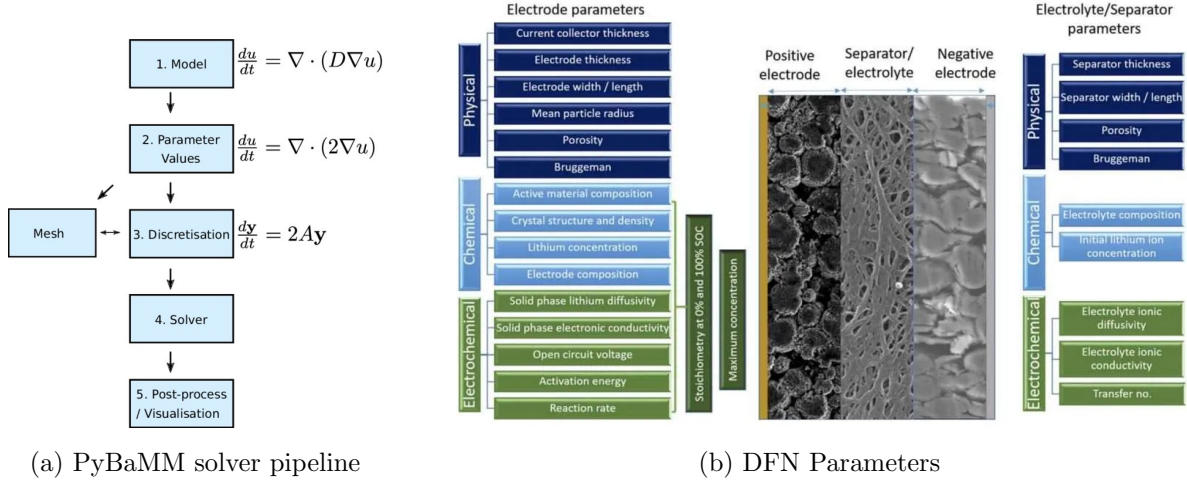


Figure 5: Parameters and solution steps for physics-based modeling

of a real lithium battery's dynamics. It is this type of model most common in BMS systems today. T. Kalogiannis *et al.* [32] provides common methods for obtaining the parameter values used in ECMs. The most common version is shown in figure 6, which is static in its dynamics. The key component is the V_{oc} ideal voltage source; this value becomes a function (when neglecting temperature, degradation, charging-discharging hysteresis) of the battery state of charge SoC, given by

$$SoC(t) = z(t)/Q = (z(t_0) + \int_{t_0}^t \eta(\tau)i(\tau) d\tau)/Q$$

where Q is the battery's nominal maximum capacity and z is the current charge capacity. The R_0 and R_1C_1 branch are used to model the difference in terminal voltage compared to that of the V_{ocv} for a given instantaneous SoC, and η here is the coulombic efficiency, usually ≈ 0.99 for lithium batteries, since some current will be used in irreversible chemical reactions within the cell [18].

The common state space form of this system is given below

$$\begin{bmatrix} \dot{v}_1(t) \\ \dot{z}(t) \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_1C_1} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_1(t) \\ z(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{C_1} \\ \frac{1}{Q} \end{bmatrix} i(t) \quad (3)$$

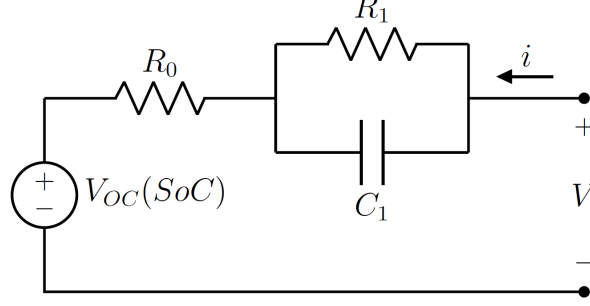


Figure 6: ECM model with 1st-order polarizing dynamics

$$V_{batt}(t) = V_{oc}(z) + i(t)R_0 + v_1(t) \quad (4)$$

W. Appiah et al. [19] provide the equation for the total overpotential within the battery derived from the Fuller–Newman electrochemical model. Here, the total overpotential η_{batt} is equal to the difference between the equilibrium battery potential U_{batt} and the terminal voltage potential V_{batt} , i.e. $V_{batt} = U_{batt} - \eta_{batt}$. This is analogous to the ECM model given above, whereby the overpotential (dynamical behaviour) is modelled by $i(t)R_0 + v_1(t)$, where the equilibrium potential is $V_{oc}(z)$.

$$\eta_{batt} = \left[\underbrace{\left(\Phi_{2,p}|_{x=L_p} - \Phi_{2,n}|_{x=0} \right)}_{\text{Electrolyte overpotential } (\eta_2)} + \underbrace{\left[\left(U_p(c_{1,p}^s)|_{x=L_p} - U_p(\bar{c}_p)|_{x=L_p} \right) - \left(U_n(c_{1,n}^s)|_{x=0} - U_n(\bar{c}_n)|_{x=0} \right) \right]}_{\text{Li concentration overpotential } (\eta_1^c)} + \underbrace{\left(\eta_p^{ct}|_{x=L_p} - \eta_n^{ct}|_{x=0} \right)}_{\text{Kinetic overpotential } (\eta^{ct})} - \underbrace{R_f I_{app}}_{\text{Electrode ohmic overpotential } (\eta_1^\Omega)} \right] \quad (5)$$

Whilst the voltage dynamics of lithium batteries do depend on temperature, this project keeps the ambient temperature at 30°C, thus real-time effects on the electrical dynamics are minimal. However, modelling of the temperature is vital since temperature directly affects degradation. L. Mattia et al. [14] explain the various thermal modelling approaches and

show which contributions are key in heat production, with the main equation given below. Reversible heat generation cannot be directly inferred by the basic ECM model shown in figure 6. J. Xu et al. equated it to being proportional to $\partial U/\partial T$, where U is the OCV and T is the temperature. This value changes over the SoC of the battery, and the paper calculates the curve for a battery similar to the one used in this project, shown in figure 7.

$$mCp \frac{dT}{dt} = \underbrace{I^2 R_0 + IV_1}_{\text{irreversible}} - \underbrace{IT \frac{\partial U}{\partial T}}_{\text{reversible}} - \underbrace{hAT}_{\text{dissipation}} \quad (6)$$

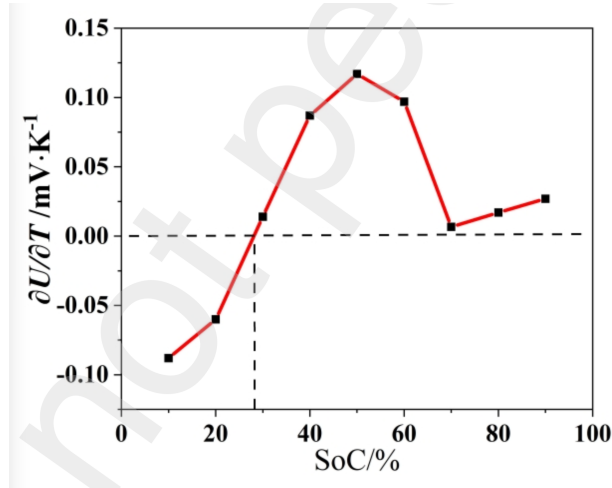


Figure 7: Charging segment extracted from the UoS dataset

A. Farman et al. [33] shows that the OCV of lithium batteries can change throughout degradation, Lithium phosphate batteries showed a 20 mV difference in regions of the SoC after aging of 500 cycles at 1C of charge and discharge. Additionally, while there exists methods of extracting an accurate OCV curve, it can take hours to accurately obtain to minimise overpotentials [32]. This is where numerical methods could be utilised to obtain the OCV curve and the other ECM parameters by fitting against a grey-box model of the dynamics, ICLOCS2 [34], will be used heavily throughout this project to see its ability to parameterise the battery dynamics. A.A. Mohamed et al. [35] shows the many methods to obtain ECM parameters with methods ranging from analytical approaches based on various current inputs, to meta-heuristic optimisation algorithms.

2.4 Charging methods

There exist many techniques to charge batteries with a graphical summary of the common methods shown in figure 10. Q. Lin et al. [36] highlights the different methods described below. The most common method is known as CC-CV charge. This is where the bulk charge is done such that the applied overpotential to the battery causes a constant current to flow, the voltage potential of the battery rises to a defined maximum point, the charging device then switches to a constant voltage charging mode, this fixed voltage is held until the charge current decays to a negligible or fixed amount - current still flows during this stage as there is still an overpotential between the battery's equilibrium state and the applied constant voltage. This is the simplest to implement without the need for an accurate SoC reading to risk overcharging (like would be with pure CC charging).

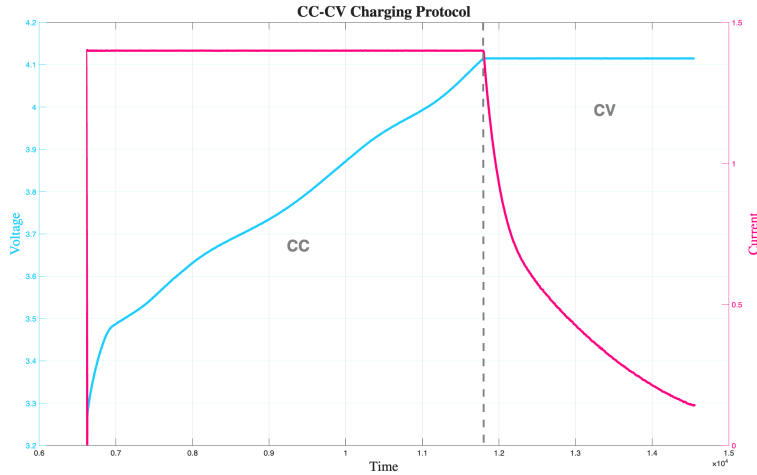


Figure 8: Charging segment extracted from the UoS dataset

CV is another method such that the voltage applied is the battery's maximum at full SoC, but since lithium batteries have low internal resistances, this can lead to a very high current draw at low SoC (where the equilibrium voltage is low), hence can cause accelerated degradation, Q. Lin et al. mentions 40% capacity decrease after only 160 cycles. Boost charging provides a high current increase at low SoC, but only for brief periods and can significantly reduce degradation rate compared to CV.

AC charging is another method which aims to minimise the frequency dependent impedance

of the battery, effectively allowing charging the battery with a lower effective overpotential, however as Q. Lin et al. mentions, there are disputes on the effectiveness of this method; coupled with the fact EIS (electrochemical impedance spectroscopy) is required to find the frequency points of interest to target, this method won't be further researched within the project.

Multistage CC is a popular method in research as it allows for the customisation of the charging throughout the cycle, this means various models can be used to optimise for a specific goal. G. Tucker et al. [37] for example, simulates various functions to minimise based on the ECM model provided in the section above, showing that the physics optimisation correlates closely to optimised degradation obtained through purely data-driven methods. Electrochemical-based models allow for a finer level of optimisation, such as ensuring the negative electrode does not reach a potential to cause lithium plating, [20] models an observer to estimate the potentials, which could be used within optimisation as one of the constraints, figure 9 shows their predicted potential voltages.

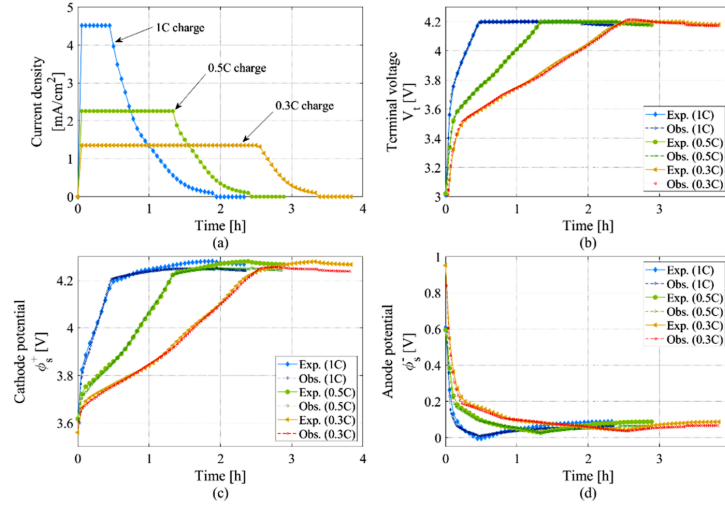


Figure 9: Estimated potentials in response to charge currents

The multistage CC charging method provides a good framework to trial different charging methods, its balance of ease of implamentation and adjustability means it is this method which will be used in the project to optimise for degradedadition.

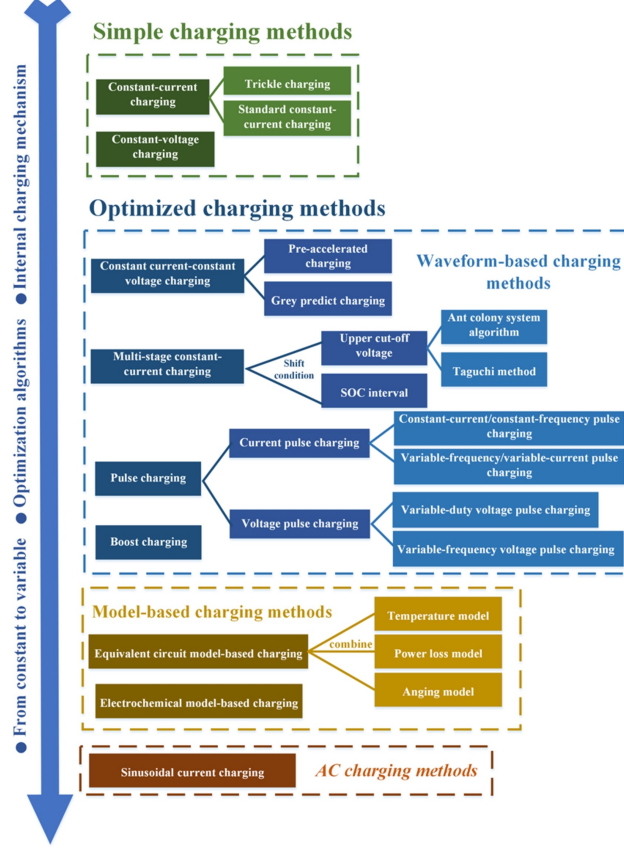


Figure 10: Common charge techniques summarised

2.5 Modelling degradation

There are three main categorical methods to predict the degradation of lithium-ion batteries: Purely data-driven methods, physics-based models and a hybrid (physics informed). F. Wang et al. [38] highlights the advantages of the hybrid approach, stating issues and advantages with pure data-driven and pure physics model, they also present a means of categorising the common hybrid approaches.

Papers focusing on the physics based modeling usually focus on a subset of degradation modes, such as SEI thickness growth from N.Kamyab *et al.*[39]. Most models start with the Doyle-Fuller-Newman model [31] to describe the transport of lithium within the battery (including potentials), then further sub-modules representing degradation mechanisms are integrated to yield the required models. For example J. Okane et al. [22] adds SEI, electrode cracking and loss of active material (LAM) as the degradation models. These approaches

can model intricate parts within the battery, but require a lot of parameters about each battery under test, additionally, the discretised solutions are only ever as accurate as the models used.

Kuzhiyil et al. [40] represent the electrochemical dynamics as $\frac{dx}{dt} = f(\mathbf{x}, \mathbf{z}, \mathbf{u}, t; \alpha)$ and coupling to degradation dynamics $\frac{dz}{dt} = f(\mathbf{z}, \mathbf{x}, \mathbf{u}, t; \theta)$ where $\mathbf{x} \in \mathbb{R}^{n_1}$ and $\mathbf{z} \in \mathbb{R}^{m_1}$ (once the SPM is discretised), representing the battery electrochemical and degradation state variables respectively. They use neural nets in place of some common degradation equations to improve the PBM's accuracy, in the report's case, to improve accuracy of calendar aging with good results, however complications can arise in parameterisation and obtaining parameters to train against.

Severson et al. [41], provides one of the largest available datasets for battery charging. This paper uses a purely data driven approach in modeling, but uses engineered features such as the change in discharge voltage curves between cycle 0 and cycle 100. Using a linear regression model, they predict the cycle-to-failure (defined when the capacity drops to 80% of original), it shows up to a 9.2% error. Attia et al. [26] takes the work of Severson et al. to great use, using the model to predict how well different charge cycles last by cycling the batteries under random multistage CC cycles, predicting the degradation and using a Bayesian optimisation strategy [42] to find the next appropriate charging protocol - in a closed loop feedback shown in figure 11

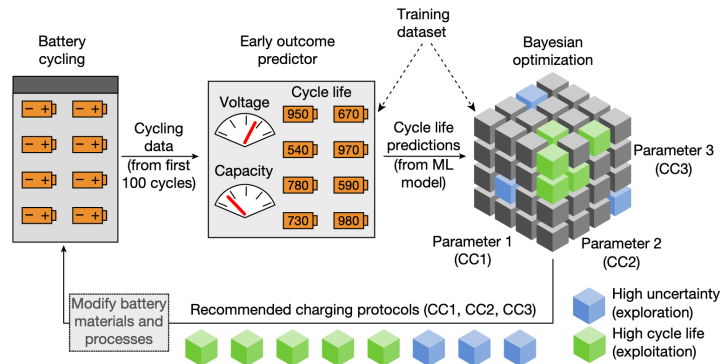


Figure 11: Closed loop workflow for finding optimal CC charging

3 Methodology

3.1 Thermal Modeling

It's most common to consider the 1d Lumped thermal model of small batteries, such as 18650's. Tucker shows that using this approach, yields a charge profile close to that of the optimum profile found from Attia, its thought that if this model could somehow be improved to help give a more true measurement of the battery's temperature during use. [cite thermal paper], shows there are many methods to this with varying levels of complexity, usually with a higher order approach means more parameters needed. Given this project aims for actual use in the field, an approach with obtainable parameters. The most popular approach is using the 0-d lumped element model, this requires only...

Matlabs Partial Differential Equation Toolbox allows for finding solutions in the form

$$\mathbf{m} \frac{\partial^2 \mathbf{u}}{\partial t^2} + d \frac{\partial \mathbf{u}}{\partial t} - \nabla \cdot (\mathbf{c} \nabla \mathbf{u}) + \mathbf{a} \mathbf{u} = \mathbf{f} \quad (7)$$

Subject to the boundary conditions in either the Dirichlet form $\mathbf{h} \mathbf{u} = \mathbf{r}$ or Neumann form $\vec{\mathbf{n}} \cdot (\mathbf{c} \nabla \mathbf{u}) + \mathbf{q} \mathbf{u} = g$. All bold terms can be matrix type and the associated documentation for each coefficient was used to determine what type of information can be passed to the solver as described below.

Since the RS battery under review is an 18650, it's a cylindrical battery,

3.2 Bayesian Optimization

As this project aims to find the optimal charging profile for degradation,

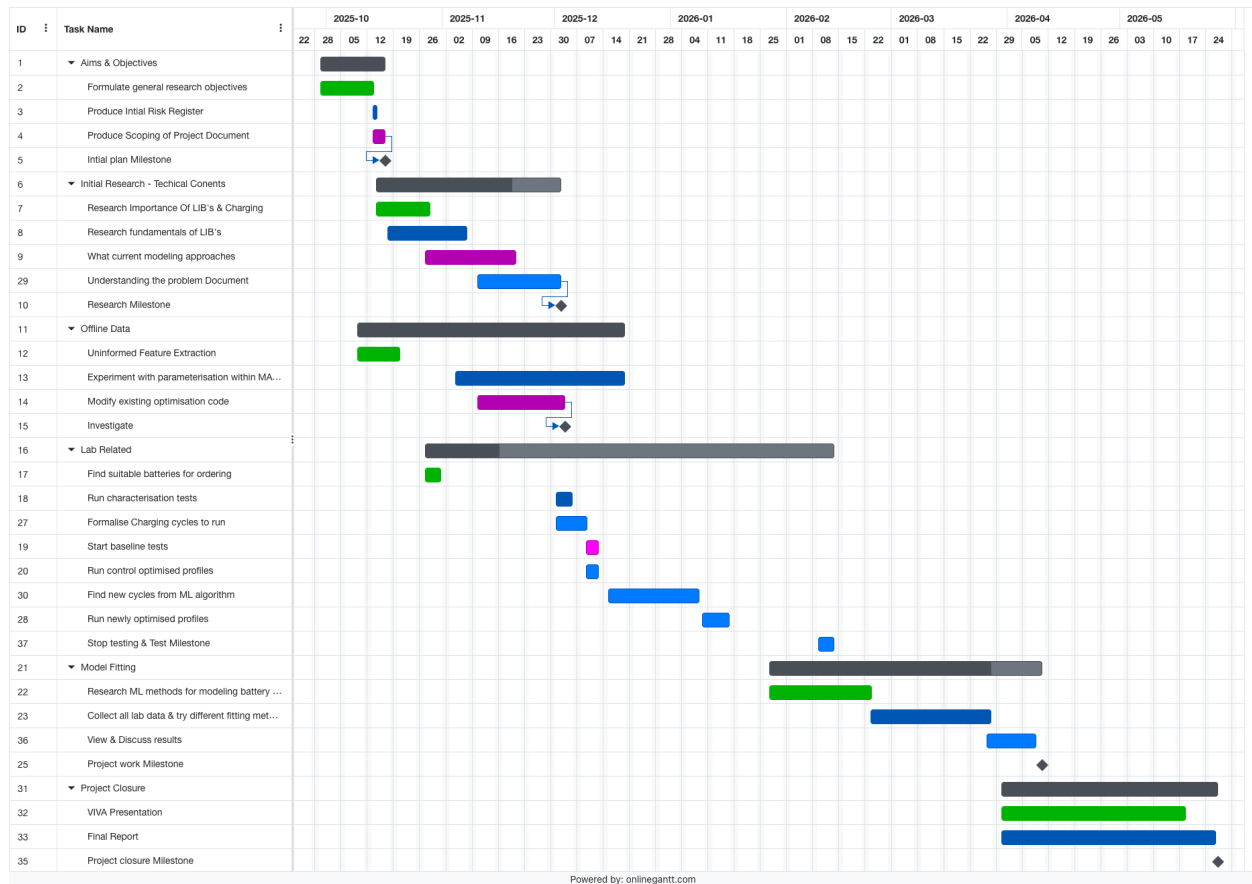
4 Self Review

Choosing this final year project has, and will continue to, be a big personal undertaking. I knew nothing about batteries other than the very basics when starting, I also knew very little within systems & control other than simple LTI systems. Research has also been a struggle for me as many papers incorporate control methods or electrochemical background of which i dont have, a high amount of papers regarding the use of AI in modeling degradedadtion are also behind paywalls. I understand this document does not have indepth explanations of the use of AI within the modeling and may be vauge in the project steps, the project is very much in the sense adapting to what can be done. Work in general AI was done early in the project, I was able to learn the basics in pure nural-nets and produced a basic image classifer within pytorch but took a pause to work on other aspects of the project and univeristy modules.

A large amount of time has been spent of narrowing down the focus of the project, as well as preparing the opmitised controll desgins for the lab testing. As of 01/12/2025, the first two batteries are undergoing characterisation tests and the softwear side is nearly done. Focus will now be spent on researching more about the machine learning and ways to optimise charging from the modeling of the battery.

5 Project Plan

6 Risk Register



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Figure 12: Gantt Chart of current project plan

Risk Assessment Table - Refer to risk Grid on tab 2. R=L*S								
Risk and Opportunities	Pre Mitigation			Mitigation Methods	Residual			Risk Owner (should be the best person to manage the risk!)
	L	S	R		L	S	R	
Data availability issues: Being unable to find adequate data to add to learning set & analysis	3	4	12	There is relatively limited data available for the required data set. The university have tested & collected significant data which should be enough for atleast a form of modeling. Being flexible and communicating with suprvisor should mean there will be an outcome in modeling regardless	2	2	4	Student
Lab Data breach	2	1	2	Data recorded is not sensitive nor contain any information about people. However ensuring the basics of data saftey are utilised should help reduce the chance any data breach does occur. By ensuring computers holding the information are pasword protected and not left opend when unnatained.	1	1	1	Student
Data loss	2	4	8	Data from the univerity is held locally and few people have the data locally, thus there should atleast an option to recover data - although the chance of needing to do this should be minimised to reduce any delays. Data collected online should be downloaded (respecting any IP rights) incase of changes out of our controll. Data from the lab experiments should be held in more than one place. For all the data, having atleast one location locally, and another in the google drive cloud should provide enough redundancy	1	3	3	Student
Lab testing issues: For the testing and recording of data needed in order to test the charging protocols and gather data from, there may be no room in the cyclers	3	5	15	Plan the time allocated for the lab as early as possible. Ensure basic training & understanding of the battery cyler has already been obtained to ensure time is best spent in the lab. If data can not be obtained, look into the electrochemical models to provide data, such as PyBaMM	2	2	4	Student / Lab leader
Lab saftey: Dealing with charging & discharging of batteries to their near complete lifecycle pose a health and saftey risk	2	5	10	Ensure all required healt and saftey preperation is done before entering the labs and ensure they are practised during the lab testing	1	3	3	Lab leader
Tests not started in time for degradedition to immerge	4	5	20	Ensure the charging protocols are provided as soon as possible, plan the general lab plan in advance such that the lab tecnitians are well prepared	2	5	10	Student
Data such as temperature reading may be corrupted during cycling	2	4	8	Run more than one battery for key cycles for redundancy	2	2	4	Student
Faliure to adapt existing code for optimisation charging to work with existing data and ready for the lab	3	4		Spend as much time as possible to analysie the code, atleast modify in stages so atleast a working form can be provided whith the tested batteries	2	2	4	Student
Overcomplex / inability to learn the ML skills for neural networks	3	4	12	Reasearch as much as possible to gather information. Break down steps bit by bit and understand when enough is enough in order to atleast perform the tasks. MATLAB offers many AI tools in digestible usable forms	2	2	4	Student

Figure 13: Current risk register

Note: The following references may have duplicates and unused references, this should hopefully be fixed for the final report

References

- [1] “Renewable electricity – Renewables 2025 – Analysis.” [Online]. Available: <https://www.iea.org/reports/renewables-2025/renewable-electricity>
- [2] Q. Guo, S. Liu, J. Zhang, Z. Huang, and D. Han, “Effects of charging rates on heat and gas generation in lithium-ion battery thermal runaway triggered by high temperature coupled with overcharge,” *Journal of Power Sources*, vol. 600, p. 234237, Apr. 2024. [Online]. Available: <https://linkinghub.elsevier.com/retrieve/pii/S0378775324001885>
- [3] Y. Li, W. Guo, D.-I. Stroe, H. Zhao, P. Kjær Kristensen, L. Rosgaard Jensen, K. Pedersen, and L. Gurevich, “Evolution of aging mechanisms and performance degradation of lithium-ion battery from moderate to severe capacity loss scenarios,” *Chemical Engineering Journal*, vol. 498, p. 155588, Oct. 2024. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1385894724070797>
- [4] “Executive summary – Batteries and Secure Energy Transitions – Analysis.” [Online]. Available: <https://www.iea.org/reports/batteries-and-secure-energy-transitions/executive-summary>
- [5] P. R. Chinnam, A. M. Colclasure, B.-R. Chen, T. R. Tanim, E. J. Dufek, K. Smith, M. C. Evans, A. R. Dunlop, S. E. Trask, B. J. Polzin, and A. N. Jansen, “Fast-Charging Aging Considerations: Incorporation and Alignment of Cell Design and Material Degradation Pathways,” *ACS Applied Energy Materials*, vol. 4, no. 9, pp. 9133–9143, Sep. 2021, publisher: American Chemical Society. [Online]. Available: <https://doi.org/10.1021/acsaem.1c01398>
- [6] M. Lucu, E. Martinez-Laserna, I. Gandiaga, K. Liu, H. Camblong, W. Widanage, and J. Marco, “Data-driven nonparametric Li-ion battery ageing model aiming at learning

- from real operation data – Part A: Storage operation,” *Journal of Energy Storage*, vol. 30, p. 101409, Aug. 2020.
- [7] M. R. Palacín and A. de Guibert, “Why do batteries fail?” *Science*, vol. 351, no. 6273, p. 1253292, Feb. 2016, publisher: American Association for the Advancement of Science. [Online]. Available: <https://www.science.org/doi/abs/10.1126/science.1253292>
- [8] “Battery Metals Report 2023/03 - Everything you need to know about the battery metals lithium, nickel, cobalt and copper!” Mar. 2023. [Online]. Available: <https://www.resource-capital.ch/en/reports/view/battery-metals-report-2023-03/>
- [9] S. Gifford, “Lithium, Cobalt and Nickel: The Gold Rush of the 21st Century,” no. 6.
- [10] P. Das, K. Hewage, R. Kotagodahetti, S. Wanniarachchi, and R. Sadiq, “Lithium-ion battery recycling: a critical review of techno-economical and socio-environmental impacts,” *Separation and Purification Technology*, vol. 382, p. 135847, Feb. 2026. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1383586625044442>
- [11] M. M. Hasan, R. Haque, M. I. Jahirul, M. G. Rasul, I. M. R. Fattah, N. M. S. Hassan, and M. Mofijur, “Advancing energy storage: The future trajectory of lithium-ion battery technologies,” *Journal of Energy Storage*, vol. 120, p. 116511, Jun. 2025. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352152X25012241>
- [12] E. Yoo, U. Lee, J. C. Kelly, and M. Wang, “Life-cycle analysis of battery metal recycling with lithium recovery from a spent lithium-ion battery,” *Resources, Conservation and Recycling*, vol. 196, p. 107040, Sep. 2023. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0921344923001763>
- [13] W. Wang and Y. Wu, “An overview of recycling and treatment of spent LiFePO₄ batteries in China,” *Resources, Conservation and Recycling*, vol. 127, pp. 233–243, Dec. 2017. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0921344917302677>

- [14] L. Mattia, H. Beiranvand, W. Zamboni, and M. Liserre, “Lithium-ion battery thermal modelling and characterisation: A comprehensive review,” *Journal of Energy Storage*, vol. 129, p. 117114, Sep. 2025. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352152X25018274>
- [15] “Trends in electric car markets – Global EV Outlook 2025 – Analysis.” [Online]. Available: <https://www.iea.org/reports/global-ev-outlook-2025/trends-in-electric-car-markets-2>
- [16] “Energy consumption in the UK 2024.” [Online]. Available: <https://www.gov.uk/government/statistics/energy-consumption-in-the-uk-2024>
- [17] S. W. Boettcher, S. Z. Oener, M. C. Lonergan, Y. Surendranath, S. Ardo, C. Brozek, and P. A. Kempler, “Potentially Confusing: Potentials in Electrochemistry,” *ACS Energy Letters*, vol. 6, no. 1, pp. 261–266, Jan. 2021, publisher: American Chemical Society. [Online]. Available: <https://doi.org/10.1021/acsenergylett.0c02443>
- [18] “Battery Management Systems, Volume 1: Battery Modeling.” [Online]. Available: <http://mocha-java.uccs.edu/BMS1/>
- [19] W. A. Appiah, L. H. Rieger, E. Flores, T. Vegge, and A. Bhowmik, “Unravelling degradation mechanisms and overpotential sources in aged and non-aged batteries: A non-invasive diagnosis,” *Journal of Energy Storage*, vol. 84, p. 111000, Apr. 2024. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352152X2400584X>
- [20] L. Li, Y. Ren, K. O’Regan, U. R. Koleti, E. Kendrick, W. D. Widanage, and J. Marco, “Lithium-ion battery cathode and anode potential observer based on reduced-order electrochemical single particle model,” *Journal of Energy Storage*, vol. 44, p. 103324, Dec. 2021. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352152X21010161>
- [21] A. K. Koech, G. Mwandila, F. Mulolani, and P. Mwaanga, “Lithium-ion battery fundamentals and exploration of cathode materials: A review,” *South African*

- Journal of Chemical Engineering*, vol. 50, pp. 321–339, Oct. 2024. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1026918524001100>
- [22] S. E. J. O’Kane, W. Ai, G. Madabattula, D. Alonso-Alvarez, R. Timms, V. Sulzer, J. Sophie Edge, B. Wu, G. J. Offer, and M. Marinescu, “Lithium-ion battery degradation: how to model it,” *Physical Chemistry Chemical Physics*, vol. 24, no. 13, pp. 7909–7922, 2022, publisher: Royal Society of Chemistry. [Online]. Available: <https://pubs.rsc.org/en/content/articlelanding/2022/cp/d2cp00417h>
- [23] S. Yang, X. Gao, Y. Li, W. Xie, B. Guo, L. Zhang, and X. Liu, “Minimum lithium plating overpotential control based charging strategy for parallel battery module prevents side reactions,” *Journal of Power Sources*, vol. 494, p. 229772, May 2021. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S037877532100313X>
- [24] M. J. Lain and E. Kendrick, “Understanding the limitations of lithium ion batteries at high rates,” *Journal of Power Sources*, vol. 493, p. 229690, May 2021. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0378775321002330>
- [25] Y. Liu, X. Xu, M. Sadd, O. O. Kapitanova, V. A. Krivchenko, J. Ban, J. Wang, X. Jiao, Z. Song, J. Song, S. Xiong, and A. Matic, “Insight into the Critical Role of Exchange Current Density on Electrodeposition Behavior of Lithium Metal,” *Advanced Science*, vol. 8, no. 5, p. 2003301, 2021, eprint: <https://advanced.onlinelibrary.wiley.com/doi/pdf/10.1002/advs.202003301>. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/advs.202003301>
- [26] P. M. Attia, A. Grover, N. Jin, K. A. Severson, T. M. Markov, Y.-H. Liao, M. H. Chen, B. Cheong, N. Perkins, Z. Yang, P. K. Herring, M. Aykol, S. J. Harris, R. D. Braatz, S. Ermon, and W. C. Chueh, “Closed-loop optimization of fast-charging protocols for batteries with machine learning,” *Nature*, vol. 578, no. 7795, pp. 397–402, Feb. 2020, publisher: Nature Publishing Group. [Online]. Available: <https://www.nature.com/articles/s41586-020-1994-5>

- [27] M. D. Bouguern, A. K. M r, and K. Zaghib, “The critical role of interfaces in advanced Li-ion battery technology: A comprehensive review,” *Journal of Power Sources*, vol. 623, p. 235457, Dec. 2024. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0378775324014095>
- [28] V. A. Agubra, J. W. Fergus, R. Fu, and S.-Y. Choe, “Analysis of effects of the state of charge on the formation and growth of the deposit layer on graphite electrode of pouch type lithium ion polymer batteries,” *Journal of Power Sources*, vol. 270, pp. 213–220, Dec. 2014. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S037877531401180X>
- [29] C. R. Birkl, M. R. Roberts, E. McTurk, P. G. Bruce, and D. A. Howey, “Degradation diagnostics for lithium ion cells,” *Journal of Power Sources*, vol. 341, pp. 373–386, Feb. 2017. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0378775316316998>
- [30] “Choosing an appropriate model · JuliaSimBatteries.” [Online]. Available: https://help.juliahub.com/batteries/stable/model_options/
- [31] M. Doyle, T. F. Fuller, and J. Newman, “Modeling of Galvanostatic Charge and Discharge of the Lithium/Polymer/Insertion Cell,” *Journal of The Electrochemical Society*, vol. 140, no. 6, p. 1526, Jun. 1993, publisher: IOP Publishing. [Online]. Available: <https://iopscience.iop.org/article/10.1149/1.2221597/meta>
- [32] T. Kalogiannis, M. S. Hosen, M. A. Sokkeh, S. Goutam, J. Jaguemont, L. Jin, G. Qiao, M. Berecibar, and J. Van Mierlo, “Comparative Study on Parameter Identification Methods for Dual-Polarization Lithium-Ion Equivalent Circuit Model,” *Energies*, vol. 12, no. 21, p. 4031, Jan. 2019, publisher: Multidisciplinary Digital Publishing Institute. [Online]. Available: <https://www.mdpi.com/1996-1073/12/21/4031>
- [33] A. Farmann and D. U. Sauer, “A study on the dependency of the open-circuit voltage on temperature and actual aging state of lithium-ion batteries,” *Journal of Power Sources*, vol. 347, pp. 1–13, Apr. 2017. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0378775317301088>

- [34] “ICLOCS2: A MATLAB Toolbox for Optimization Based Control.” [Online]. Available: <http://www.ee.ic.ac.uk/ICLOCS/default.htm>
- [35] M. A. A. Mohamed, T. F. Yu, G. Ramsden, J. Marco, and T. Grandjean, “Advancements in parameter estimation techniques for 1RC and 2RC equivalent circuit models of lithium-ion batteries: A comprehensive review,” *Journal of Energy Storage*, vol. 113, p. 115581, Mar. 2025. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352152X25002944>
- [36] Z. Chen, D. L. Danilov, L. H. J. Raijmakers, K. Chayambuka, M. Jiang, L. Zhou, J. Zhou, R.-A. Eichel, and P. H. L. Notten, “Overpotential analysis of graphite-based Li-ion batteries seen from a porous electrode modeling perspective,” *Journal of Power Sources*, vol. 509, p. 230345, Oct. 2021. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0378775321008570>
- [37] G. Tucker, R. Drummond, and S. R. Duncan, “Optimal fast charging of lithium ion batteries: between model-based and data-driven methods,” *Journal of The Electrochemical Society*, vol. 170, no. 12, Dec. 2023, publisher: The Electrochemical Society. [Online]. Available: <https://eprints.whiterose.ac.uk/id/eprint/209066/>
- [38] S. Wang, R. Zhou, Y. Ren, M. Jiao, H. Liu, and C. Lian, “Advanced data-driven techniques in AI for predicting lithium-ion battery remaining useful life: a comprehensive review,” *Green Chemical Engineering*, vol. 6, no. 2, pp. 139–153, Jun. 2025. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2666952824000645>
- [39] N. Kamyab, J. Weidner, and R. White, “Mixed Mode Growth Model for the Solid Electrolyte Interface (SEI),” *Journal of The Electrochemical Society*, vol. 166, pp. A334–A341, Jan. 2019.
- [40] J. A. Kuzhiyil, T. Damoulas, F. B. Planella, and W. D. Widanage, “Lithium-ion battery degradation modelling using universal differential equations: Development of a cost-effective parameterisation methodology,” *Applied Energy*, vol. 382, p. 125221,

- Mar. 2025. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0306261924026059>
- [41] K. A. Severson, P. M. Attia, N. Jin, N. Perkins, B. Jiang, Z. Yang, M. H. Chen, M. Aykol, P. K. Herring, D. Fraggadakis, M. Z. Bazant, S. J. Harris, W. C. Chueh, and R. D. Braatz, “Data-driven prediction of battery cycle life before capacity degradation,” *Nature Energy*, vol. 4, no. 5, pp. 383–391, May 2019, publisher: Nature Publishing Group. [Online]. Available: <https://www.nature.com/articles/s41560-019-0356-8>
- [42] “Bayesian Optimization Algorithm - MATLAB & Simulink.” [Online]. Available: <https://uk.mathworks.com/help/stats/bayesian-optimization-algorithm.html>
- [43] M.-K. Tran, M. Mathew, S. Janhunen, S. Panchal, K. Raahemifar, R. Fraser, and M. Fowler, “A comprehensive equivalent circuit model for lithium-ion batteries, incorporating the effects of state of health, state of charge, and temperature on model parameters,” *Journal of Energy Storage*, vol. 43, p. 103252, Nov. 2021. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352152X2100949X>
- [44] J. Tebbe, A. Hartwig, A. Jamali, H. Senobar, A. Wahab, M. Kabak, H. Kemper, and H. Khayyam, “Innovations and prognostics in battery degradation and longevity for energy storage systems,” *Journal of Energy Storage*, vol. 114, p. 115724, Apr. 2025. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352152X25004372>
- [45] L. Chen, C. Chang, X. Liu, J. Jiang, Y. Jiang, and A. Tian, “Physics-informed neural networks for small sample state of health estimation of lithium-ion batteries,” *Journal of Energy Storage*, vol. 122, p. 116559, Jun. 2025. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352152X25012721>
- [46] X. Lin, H. E. Perez, S. Mohan, J. B. Siegel, A. G. Stefanopoulou, Y. Ding, and M. P. Castanier, “A lumped-parameter electro-thermal model for cylindrical batteries,” *Journal of Power Sources*, vol. 257, pp. 1–11, Jul. 2014. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0378775314001244>

- [47] A. B. Khan, V.-L. Pham, T.-T. Nguyen, and W. Choi, “Multistage constant-current charging method for Li-Ion batteries,” in *2016 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific)*, Jun. 2016, pp. 381–385. [Online]. Available: <https://ieeexplore.ieee.org/document/7512982>
- [48] M. Usman Tahir, A. Sangwongwanich, D.-I. Stroe, and F. Blaabjerg, “Overview of multi-stage charging strategies for Li-ion batteries,” *Journal of Energy Chemistry*, vol. 84, pp. 228–241, Sep. 2023. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2095495623003091>
- [49] P. Keil and A. Jossen, “Charging protocols for lithium-ion batteries and their impact on cycle life—An experimental study with different 18650 high-power cells,” *Journal of Energy Storage*, vol. 6, pp. 125–141, May 2016. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352152X16300147>
- [50] “How Do I Make an LSTM Model with Multiple Inputs?” [Online]. Available: <https://datasciencedojo.com/blog/how-do-i-make-an-lstm-model-with-multiple-inputs/>
- [51] P. Kollmeyer, C. Vidal, M. Naguib, and M. Skells, “LG 18650HG2 Li-ion Battery Data and Example Deep Neural Network xEV SOC Estimator Script,” vol. 3, Mar. 2020, publisher: Mendeley Data. [Online]. Available: <https://data.mendeley.com/datasets/cp3473x7xv/3>
- [52] H. Ritchie, P. Rosado, and M. Roser, “Access to Energy,” *Our World in Data*, Sep. 2019. [Online]. Available: <https://ourworldindata.org/energy-access>
- [53] “Global Electricity Review 2024.” [Online]. Available: <https://ember-energy.org/latest-insights/global-electricity-review-2024>
- [54] H. Ritchie and P. Rosado, “Energy Mix,” *Our World in Data*, Jul. 2020. [Online]. Available: <https://ourworldindata.org/energy-mix>
- [55] A. S. Brouwer, M. van den Broek, A. Seebregts, and A. Faaij, “Impacts of large-scale Intermittent Renewable Energy Sources on electricity systems, and how these can

- be modeled,” *Renewable and Sustainable Energy Reviews*, vol. 33, pp. 443–466, May 2014. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1364032114000987>
- [56] “Trends in the electric car industry – Global EV Outlook 2025 – Analysis.” [Online]. Available: <https://www.iea.org/reports/global-ev-outlook-2025/trends-in-the-electric-car-industry-3>
- [57] J. Schmitt, M. Rehm, A. Karger, and A. Jossen, “Capacity and degradation mode estimation for lithium-ion batteries based on partial charging curves at different current rates,” *Journal of Energy Storage*, vol. 59, p. 106517, Mar. 2023. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352152X22025063>
- [58] N. Omar, M. A. Monem, Y. Firouz, J. Salminen, J. Smekens, O. Hegazy, H. Gaulous, G. Mulder, P. Van den Bossche, T. Coosemans, and J. Van Mierlo, “Lithium iron phosphate based battery – Assessment of the aging parameters and development of cycle life model,” *Applied Energy*, vol. 113, pp. 1575–1585, Jan. 2014. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0306261913007393>
- [59] Q. Wang, B. Jiang, B. Li, and Y. Yan, “A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles,” *Renewable and Sustainable Energy Reviews*, vol. 64, pp. 106–128, Oct. 2016. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1364032116301435>
- [60] S. Guo, R. Xiong, K. Wang, and F. Sun, “A novel echelon internal heating strategy of cold batteries for all-climate electric vehicles application,” *Applied Energy*, vol. 219, pp. 256–263, Jun. 2018. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0306261918303817>
- [61] Q. Lin, J. Wang, R. Xiong, W. Shen, and H. He, “Towards a smarter battery management system: A critical review on optimal charging methods of lithium ion batteries,” *Energy*, vol. 183, pp. 220–234, Sep. 2019. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0360544219312605>

- [62] “Trends in electric vehicle batteries – Global EV Outlook 2024 – Analysis.” [Online]. Available: <https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-vehicle-batteries>
- [63] L. Gaines, K. Richa, and J. Spangenberg, “Key issues for Li-ion battery recycling,” *MRS Energy & Sustainability*, vol. 5, p. E14, Jan. 2018. [Online]. Available: <https://www.cambridge.org/core/journals/mrs-energy-and-sustainability/article/key-issues-for-liion-battery-recycling/F37D3914A1F5A8FD0ED3EF901664D126>
- [64] L. Sheng, L. Su, and H. Zhang, “Experimental determination on thermal parameters of prismatic lithium ion battery cells,” *International Journal of Heat and Mass Transfer*, vol. 139, pp. 231–239, Aug. 2019. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0017931019314358>
- [65] H. Ritchie, “Tracking global data on electric vehicles,” *Our World in Data*, Feb. 2024. [Online]. Available: <https://ourworldindata.org/electric-car-sales>
- [66] “Energy Consumption in the UK 2024.”
- [67] “New report: European battery storage grows 15% in 2024, EU energy storage action plan needed - SolarPower Europe.” [Online]. Available: <https://www.solarpowereurope.org/press-releases/new-report-european-battery-storage-grows-15-in-2024-eu-energy-storage-action-plan-needed>
- [68] A. Mauger, C. Julien, and H. Xie, “Composite anodes for lithium-ion batteries: Status and trends,” *AIMS Materials Science*, vol. 3, pp. 1054–1106, Jul. 2016.
- [69] Z. Li, J. Huang, B. Yann Liaw, V. Metzler, and J. Zhang, “A review of lithium deposition in lithium-ion and lithium metal secondary batteries,” *Journal of Power Sources*, vol. 254, pp. 168–182, May 2014. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0378775313020880>
- [70] Y. Li, M. Vilathgamuwa, T. Farrell, S. S. Choi, N. T. Tran, and J. Teague, “A physics-based distributed-parameter equivalent circuit model for lithium-ion

- batteries,” *Electrochimica Acta*, vol. 299, pp. 451–469, Mar. 2019. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0013468618328883>
- [71] S. J. Moura, F. B. Argomedeo, R. Klein, A. Mirtabatabaei, and M. Krstic, “Battery State Estimation for a Single Particle Model With Electrolyte Dynamics,” *IEEE Transactions on Control Systems Technology*, vol. 25, no. 2, pp. 453–468, Mar. 2017. [Online]. Available: <http://ieeexplore.ieee.org/document/7489035/>
- [72] J. M. Reniers, G. Mulder, and D. A. Howey, “Review and Performance Comparison of Mechanical-Chemical Degradation Models for Lithium-Ion Batteries,” *Journal of The Electrochemical Society*, vol. 166, no. 14, p. A3189, Sep. 2019, publisher: IOP Publishing. [Online]. Available: <https://iopscience.iop.org/article/10.1149/2.0281914jes/meta>
- [73] J. Xu, K. Xiong, T. Tang, Y. Chen, D. Hu, D. Hou, M. Yu, and J. Ding, “Precise Determination of the Continuous Entropic Coefficient Profile of Lithium-Ion Batteries Using Frequency-Domain Method,” Rochester, NY, Apr. 2024. [Online]. Available: <https://papers.ssrn.com/abstract=4803435>
- [74] F. Wang, Z. Zhai, Z. Zhao, Y. Di, and X. Chen, “Physics-informed neural network for lithium-ion battery degradation stable modeling and prognosis,” *Nature Communications*, vol. 15, no. 1, p. 4332, May 2024, publisher: Nature Publishing Group. [Online]. Available: <https://www.nature.com/articles/s41467-024-48779-z>
- [75] M. Aykol, C. B. Gopal, A. Anapolsky, P. K. Herring, B. van Vlijmen, M. D. Berliner, M. Z. Bazant, R. D. Braatz, W. C. Chueh, and B. D. Storey, “Perspective—Combining Physics and Machine Learning to Predict Battery Lifetime,” *Journal of The Electrochemical Society*, vol. 168, no. 3, p. 030525, Mar. 2021, publisher: IOP Publishing. [Online]. Available: <https://doi.org/10.1149/1945-7111/abec55>
- [76] “Doyle-Fuller-Newman Model (DFN) — PyBaMM v25.10.1 Manual.” [Online]. Available: <https://docs.pybamm.org/en/stable/source/examples/notebooks/models/DFN.html>

- [77] W. Guo, Z. Sun, S. B. Vilsen, J. Meng, and D. I. Stroe, “Review of “grey box” lifetime modeling for lithium-ion battery: Combining physics and data-driven methods,” *Journal of Energy Storage*, vol. 56, p. 105992, Dec. 2022. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352152X22019806>
- [78] G. Xu, J. Xu, and Y. Zhu, “LSTM-based estimation of lithium-ion battery SOH using data characteristics and spatio-temporal attention,” *PLOS ONE*, vol. 19, no. 12, p. e0312856, Dec. 2024, publisher: Public Library of Science. [Online]. Available: <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0312856>
- [79] H. Liu, I. H. Naqvi, F. Li, C. Liu, N. Shafiei, Y. Li, and M. Pecht, “An analytical model for the CC-CV charge of Li-ion batteries with application to degradation analysis,” *Journal of Energy Storage*, vol. 29, p. 101342, Jun. 2020. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2352152X20300517>
- [80] B. Y. Liaw, R. G. Jungst, A. Urbina, and T. L. Paez, “Modeling of Battery Life I. The Equivalent Circuit Model (ECM) Approach.”
- [81] “Doyle Fuller Newman Battery Model,” Nov. 2025. [Online]. Available: <https://www.batterydesign.net/modelling/doyle-fuller-newman-battery-model/>
- [82] V. Sulzer, S. Marquis, R. Timms, M. Robinson, and S. Chapman, *Python Battery Mathematical Modelling (PyBaMM)*, Feb. 2020.
- [83] M. Auch, T. Kuthada, S. Giese, and A. Wagner, “Influence of Lithium-Ion-Battery Equivalent Circuit Model Parameter Dependencies and Architectures on the Predicted Heat Generation in Real-Life Drive Cycles,” *Batteries*, vol. 9, no. 5, p. 274, May 2023, publisher: Multidisciplinary Digital Publishing Institute. [Online]. Available: <https://www.mdpi.com/2313-0105/9/5/274>
- [84] J. S. Edge, S. O’Kane, R. Prosser, N. D. Kirkaldy, A. N. Patel, A. Hales, A. Ghosh, W. Ai, J. Chen, J. Yang, S. Li, M.-C. Pang, L. B. Diaz, A. Tomaszewska, M. W. Marzook, K. N. Radhakrishnan, H. Wang, Y. Patel, B. Wu, and G. J. Offer, “Lithium ion battery degradation: what you need

- to know,” *Physical Chemistry Chemical Physics*, vol. 23, no. 14, pp. 8200–8221, Apr. 2021, publisher: The Royal Society of Chemistry. [Online]. Available: <https://pubs.rsc.org/en/content/articlelanding/2021/cp/d1cp00359c>
- [85] “ARTECH HOUSE U.K.: Battery Management Systems, Volume III: Physics-Based Methods.” [Online]. Available: <https://uk.artechhouse.com/Battery-Management-Systems-Volume-III-Physics-Based-Methods-P2201.aspx>
- [86] J. Xu, K. Xiong, T. Tang, Y. Chen, D. Hu, D. Hou, M. Yu, and J. Ding, “Precise determination of the continuous entropic coefficient profile of lithium-ion batteries using frequency-domain method,” *Measurement*, vol. 240, p. 115578, Jan. 2025. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0263224124014635>