

# Analysis of Suitability of Simulation Models in the PyBaMM Simulator and Experimental Data of Lithium-Ion Batteries

Nur Kholifah<sup>1</sup>, Lutfi Rohman<sup>1</sup>✉, Imam Rofi'i<sup>1</sup>

<sup>1</sup> Department of Physics, Faculty of Mathematics and Natural Sciences, University of Jember, Indonesia  
rahman.fmipa@unej.ac.id

## Article Information

### Article history:

Received October 20, 2025

Revised December 05, 2025

Accepted December 25, 2025

### Keywords:

Lithium-ion batteries

PyBaMM

Battery mathematical models

C-Rate

## ABSTRACT

Lithium-ion batteries are rechargeable energy storage devices that store and release energy by shuttling lithium ions between two electrodes with opposite polarities through an electrolyte. High-energy density lithium-ion batteries have been the subject of research, leading to the development of various lithium-ion battery systems, including battery modeling systems. PyBaMM (Python Battery Mathematical Modeling) is a software tool used for quickly and flexibly simulating battery models. The development of electrochemical battery modeling faces several challenges, with one of them being the complexity of the electrochemical battery system involving various chemical reactions and physical processes. Therefore, accurate and valid battery modeling is necessary to predict battery behavior under various operational conditions. This thesis aims to analyze the compatibility of battery simulation models within the PyBaMM simulator with experimental data from lithium-ion batteries. The objective is to gain a better understanding of how well the mathematical models in PyBaMM can represent the actual behavior of lithium-ion batteries. The compatibility analysis between the models and experimental data is performed using the Goodness of Fit Test with the Chi-Square ( $\chi^2$ ) test method. The simulation result obtained in this research consists of voltage versus lithium-ion battery discharge time graphs that compare the PyBaMM simulator models with experimental data. There is no significant difference between the lithium-ion battery models generated from PyBaMM simulations and experimental data. The compatibility of the lithium-ion battery models produces from PyBaMM simulations with experimental data has an accuracy level of 97% - 99%.

This is an open access article under the [CC BY-SA](https://creativecommons.org/licenses/by-sa/4.0/) license.



## Corresponding Author:

Lutfi Rohman

Department of Physics, Faculty of Mathematics and Natural Sciences, University of Jember, Indonesia

Email: << el\_rahman.fmipa@unej.ac.id >>

## 1. Introduction

In this modern era, electrochemical batteries have become one of the crucial components in daily life. Batteries are employed in various electronic devices, electric vehicles, and energy storage systems [1]. Lithium-ion batteries have been widely used due to their high energy density compared to zinc-manganese lead batteries. These batteries have played a crucial role in everyday consumer electronics, electric vehicles, and energy storage industries. However, with the profound advancements in sustainable energy and the rapid revolution of electric vehicles, high-energy-density lithium-ion battery systems have become a focal point of research, leading to the emergence of various lithium-ion battery systems, including battery modeling systems [2].

Mathematical modeling and computer simulation have become crucial components in the development process of lithium-ion batteries. In this regard, PyBaMM (Python Battery Mathematical Modelling) has

emerged as one of the popular simulation frameworks. PyBaMM provides sophisticated and flexible mathematical models to study the behavior of lithium-ion batteries. PyBaMM is a battery modeling library developed in the Python programming language, enabling users to easily implement and execute electrochemical battery models [3]. PyBaMM has been utilized in various battery technology research and development, such as the enhancement of more efficient and safer lithium-ion batteries, the advancement of faster and safer battery charging technologies, and the development of battery temperature control technology to mitigate the risk of fires [4]. The development of electrochemical battery modeling poses several challenges that must be addressed. One of these challenges is the complexity of the electrochemical battery system, involving various chemical reactions and physical processes. Therefore, accurate and valid modeling is required to predict the behavior of the battery under various operational conditions [5][6].

Lithium-ion batteries are a type of rechargeable battery that stores and releases energy through the movement of lithium ions between two electrodes with opposite polarities, known as the cathode and anode, via an electrolyte [7]. Numerous studies have been conducted to enhance the performance of lithium-ion batteries using both organic and inorganic materials. Generally, the materials employed as cathodes include  $\text{LiCoO}_2$ ,  $\text{LiMn}_2\text{O}_4$ ,  $\text{LiCo}_{1/3}\text{Mn}_{1/3}\text{Ni}_{1/3}\text{O}_2$ , and  $\text{LiFePO}_4$ . Meanwhile, the anode is typically made of graphite. Between the cathode and anode, there is a polypropylene/polyethylene membrane containing lithium salt and organic chemicals [8].

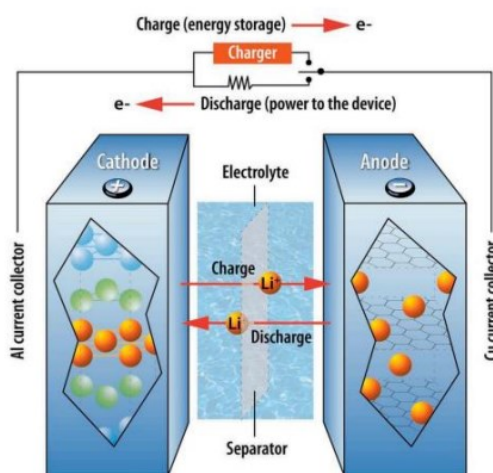


Figure 1. Principles of Lithium-Ion Battery Operation [7]

In previous studies, computationally efficient battery modeling can be employed to rapidly and accurately estimate battery performance. The complexity of the battery system poses a challenge in lithium-ion battery modeling. Hence, a simplified battery modeling is required to reduce computational complexity and simulation time. The simplification of the model can reduce computational complexity without compromising accuracy, achieving a simulation time 5000 times faster than real-time [6].

In this study, we analyzed the compatibility of battery simulation models found in the PyBaMM simulator with existing lithium-ion battery experimental data. These battery models are complex mathematical models used to simulate the characteristics and behavior of batteries. In the compatibility analysis, a comparison will be made, specifically evaluating key parameters, namely cell voltage over the battery discharge time at various C-rate values. By comparing simulation results with experimental data, a better understanding will be gained of the extent to which the mathematical models in PyBaMM can accurately represent the actual behavior of lithium-ion batteries.

## 2. Method

This research method is a simulation using PyBaMM, which is developed using git version control, with the source code accessible through the PyBaMM GitHub repository. It can be executed on Linux, MacOS, and Windows systems that have Python versions 3.6 to 3.8 installed.

### 2.1. Lithium-Ion Batteries

This battery has a special structure and components that enable the flow of lithium ions between the positive electrode (cathode) and the negative electrode (anode) during the charging and discharging processes [9]. The lithium-ion battery is one type of voltaic cell, which is an electrochemical cell capable of generating

electrical energy through chemical reactions within the battery cell. In a voltaic cell, the positive electrode is referred to as the cathode, and the negative electrode is referred to as the anode [10]. The cathode is responsible for releasing lithium ions during the charging process and receiving them during the discharging process [11]. The negative electrode (anode) is made of carbon material such as graphite, serving as a storage site for lithium ions when the battery is in a charged state. During the discharge process, lithium ions will move from the anode to the cathode through the electrolyte [12].

The electrolyte is a solution or solid material that conducts lithium ions between positive and negative electrodes. In lithium-ion batteries, the electrolyte typically consists of an organic electrolyte solution or a solid polymer electrolyte [13]. The separator is a thin layer situated between the positive and negative electrodes to prevent direct contact between them. The separator must possess permeable properties to lithium ions, allowing ions to move through the separator while preventing direct contact that could lead to short circuits or battery damage [11].

## 2.2. Battery Mathematical Models

The mathematical battery model is a mathematical representation of the operational system of a battery by considering key factors that influence battery performance. The mathematical battery model is utilized for the design and optimization of new models as well as real-time battery performance control [14]. Furthermore, battery modeling is required for the functionality of battery management systems, such as state-of-charge estimation, state-of-health estimation, and fast charging [6].

The implementation of mathematical models is crucial for understanding and optimizing the performance of lithium-ion batteries [15]. Here are some common applications of mathematical models for lithium-ion batteries: Prediction of Battery Performance in Various Scenarios, Battery Design and Optimization, Development of Battery Management Systems (BMS)

## 2.3. PyBaMM

PyBaMM (Python Battery Mathematical Modelling) is a software used to rapidly and flexibly simulate battery models. The goal of PyBaMM is to expedite research in battery modeling by providing an open-source framework that enables collaboration among institutions and across disciplines. PyBaMM is developed using git version control, with the source code accessible through the PyBaMM GitHub repository. It can be executed on Linux, MacOS, and Windows systems that have Python versions 3.6 to 3.8 installed [3]. PyBaMM provides a modular working environment where existing or new tools can be integrated to construct a continuum model for batteries, thereby enabling better collaboration and a greater impact in battery modeling research [5].

PyBaMM has several models that support the development process and simulation analysis of lithium-ion battery systems. Here are some battery models available in the PyBaMM simulator: (1) Single Particle Model (SPM) is a simple mathematical model that depicts a battery cell as a single particle or electrode. It is a very basic model that neglects complex internal phenomena within the battery. SPM only considers variations in electrolyte concentration and electrode potential as functions of time [16]. (2) Single Particle Model with Electrolyte (SPMe) is an extension of the SPM that takes into account ion transport in the electrolyte surrounding the battery particle. This includes ion diffusion within the electrolyte surrounding the battery particle [16]. (3) Many Particle Model (MPM) is a mathematically more complex model compared to SPM and SPMe. MPM is used to model electrode heterogeneity in lithium-ion batteries. This model depicts many electrode particles interacting within the battery [17]. (4) Doyle-Fuller-Newman (DFN) is a highly comprehensive and complex model to describe battery behavior. The DFN model takes into account ion dynamics in the electrolyte as well as electrochemical responses within the battery cell, allowing for more accurate modeling of battery performance under various conditions. DFN is one of the most sophisticated and accurate models for battery modeling but also requires intensive computation and more detailed data [16].

## 2.4. Current Rate (C-Rate)

The battery possesses charging and discharging speeds controlled by the battery's C-Rate. Current Rate (C-Rate) is the measurement of the current when the battery is being charged or discharged. The battery capacity is commonly assessed and labeled with a 1C value. This means that a fully charged battery with a capacity of 10Ah can deliver 10 Amperes for one hour. A battery with the same capacity (10Ah) discharged at a 0.5C rate can provide 5 Amperes for two hours, and if discharged at a 2C rate, it can deliver 20 Amperes for 30 minutes. The relationship between charging and discharging currents with C-Rate and battery capacity is illustrated by Equation 1, while the relationship between charging and discharging currents with charging and discharging time is represented by Equation 2 [18].

$$I = C_r \times C \quad (1)$$

$$t = \frac{C}{I} \quad (2)$$

Understanding the C-Rate of the battery is crucial because the stored and available energy in the battery depends on the charging and discharging rates.

### 2.5. Simulation Methods, Conditions, and Parameters

The simulation is conducted based on experiments conducted by Ecker in 2015 on lithium-ion batteries with Kokam SLPB 75106100 battery cell type. The specifications of the Kokam SLPB 75106100 battery cell structure are presented in Table 1.

Table 1. Specification of Kokam SLPB 75106100 Battery Cell [19]

Battery Cell Parameters	Anode	Cathode	Separator
<i>Material</i>	<i>Graphite</i>	$\text{Li}(\text{Ni}_{0.4}\text{Co}_{0.6})\text{O}_2$	<i>Polyethylene</i>
<i>Total thickness of one sheet [<math>\mu\text{m}</math>]</i>	$162 \pm 2$	$124 \pm 1$	19
<i>Thickness current collector [<math>\mu\text{m}</math>]</i>	$14.7 \pm 0.06$	$15.11 \pm 0.01$	-
<i>Length [mm]</i>	103	101	-
<i>Width [mm]</i>	87	85	-
<i>Surface area [<math>\text{mm}^2</math>]</i>	8961	8585	-
<i>Porosity [%]</i>	$32.9 \pm 0.5$	$29.6 \pm 0.7$	$50.8 \pm 2$
<i>Median particle radius [<math>\mu\text{m}</math>]</i>	$8,7 \pm 0,9$	$6,5 \pm 0,1$	-
<i>Tortuosity factor</i>	$2.03 \pm 0.006$	$1.94 \pm 0.006$	$1.67 \pm 0.02$

The lithium-ion battery simulation is carried out through six systematically arranged steps in the flowchart shown in Figure 2.

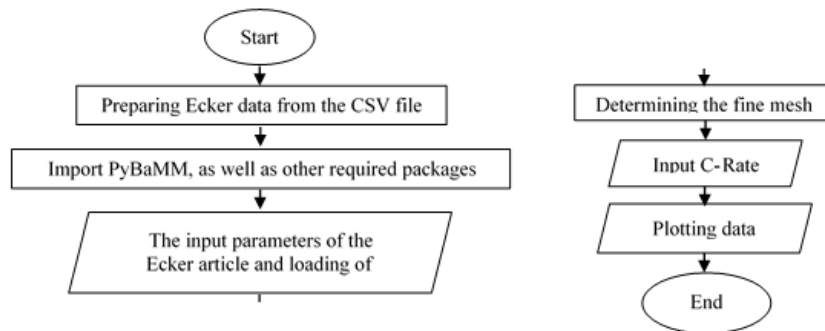


Figure 2. Flowchart PyBaMM Simulation Stages

Experimental data, in the form of graphical data, is processed and converted into a CSV file using WebPlotDigitizer.com. This CSV data will be used as a reference in the PyBaMM simulation. The simulation is run with several input parameters presented in Table 2.

Figure 3. Table 2 Input Parameter

Parameter	Value
<i>Model</i>	<i>SPM, SPM<sub>e</sub>, MPM, DFN</i>
<i>Parameter Set</i>	Ecker2015
<i>C-Rate</i>	0.25; 1; 3; 5

The simulation results obtained from this research consist of a comparison graph between the model in the PyBaMM simulator and experimental data.

The analysis of model fit with experimental data was conducted using the Goodness of Fit Test system with the Chi-Square ( $\chi^2$ ) test method. The Chi-Square test is a statistical technique used to assess the extent to which the generated model aligns with experimental data. It is one of the most commonly used non-parametric statistical methods for testing the adequacy of a model on categorical or grouped data. The Chi-Square test can be formulated by Equation 3:

$$\chi^2 = \sum_{i=1}^n \frac{(O_i - E_i)^2}{E_i} \quad (3)$$

The model under examination is considered good when the result of the Chi-Square test is small. The smaller the resulting Chi-Square value, the better the model used in the study.

### 3. Result and Discussions

In The results of this research present a comparison graph of experimental data with a lithium-ion battery model in the PyBaMM simulator that encapsulates the relationship between cell voltage and lithium-ion battery discharge time. The comparison of three models (SPM, SPMe, DFN) with various C-Rate values is presented in Figures 3 (C-Rate 0.25C), Figure 4 (C-Rate 1C), Figure 5 (C-Rate 3C), and Figure 6 (C-Rate 5C), depicting the relationship between cell voltage and lithium-ion battery discharge time.

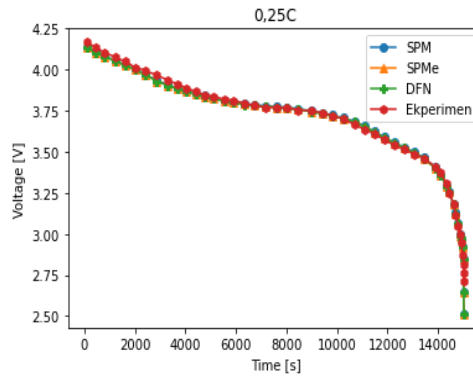


Figure 3. Comparison of Simulation Models at C-Rate 0.25C

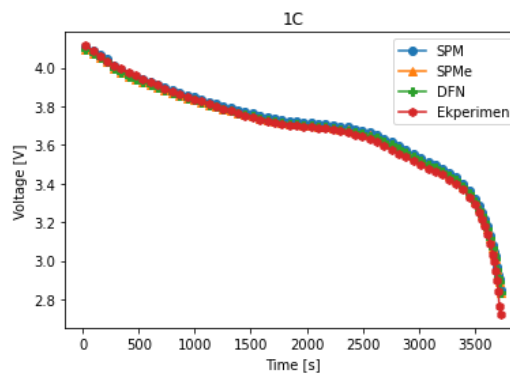


Figure 4. Comparison of Simulation Models at C-Rate 1C

Figures 3 and 4 sequentially present a comparison of SPM, SPMe, and DFN models with experimental data at C-Rate 0.25C and C-Rate 1C, demonstrating consistent results among the three graphs. This indicates that all models can effectively represent the actual battery behavior based on the utilized experimental data at both C-Rate 0.25C and C-Rate 1C.

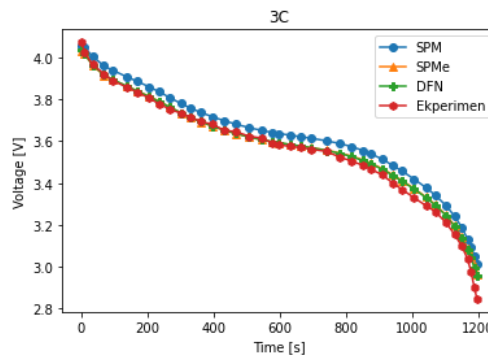


Figure 5. Comparison of Simulation Models at C-Rate 3C

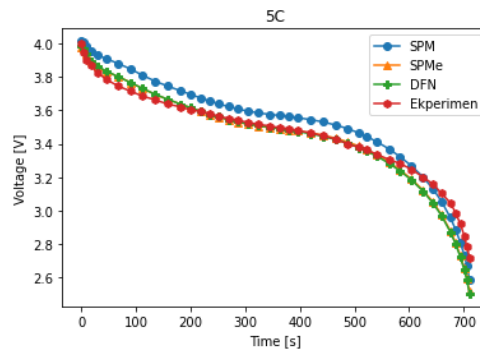


Figure 5. Comparison of Simulation Models at C-Rate 5C

Figures 5 and 6 consecutively present a comparison of SPM, SPMe, and DFN models with experimental data at C-Rate 3C and C-Rate 5C, demonstrating differences in the graphs formed by the SPM model. This indicates that the SPMe and DFN models can better represent the actual behavior of the battery based on the experimental data used, especially at C-Rate 3C and C-Rate 5C, compared to the SPM model. The congruence between experimental data and the model was analyzed using the Goodness of Fit Test system with the Chi-Square ( $\chi^2$ ) test method, resulting in analysis outcomes as indicated in Table 3.

Table 3 Analysis of Model Suitability

Model	C-Rate	Chi-Square ( $\chi^2$ )		Model Accuracy Level	Analysis of Model Suitability
		$\chi^2$ calculated	$\chi^2$ table		
SPM	0.25C	0.025	71.201	99.37%	Suitable
	1C	0.031	95.625	99.14%	Suitable
	3C	0.062	63.69	98.09%	Suitable
	5C	0.096	66.206	97.60%	Suitable
SPMe	0.25C	0.025	71.201	99.36%	Suitable
	1C	0.019	95.625	99.40%	Suitable
	3C	0.017	63.69	99.26%	Suitable
	5C	0.097	66.206	98.44%	Suitable
DFN	0.25C	0.025	71.201	99.36%	Suitable
	1C	0.019	95.625	99.41%	Suitable
	3C	0.014	63.69	99.32%	Suitable
	5C	0.107	66.206	98.37%	Suitable

The main purpose of the Chi-Square test is to examine the hypothesis that there is no correlation between two or more groups and to assess the extent to which the observed data distribution (in this study, experimental data) matches the expected distribution (in this study, the data of lithium-ion battery models in the PyBaMM simulator) [20]. The hypotheses of this study are as follows: Hypothesis 1: There is no difference between the battery simulation models in the PyBaMM simulator and the experimental data.

Hypothesis 2: There is a difference between the battery simulation models in the PyBaMM simulator and the experimental data.

The results of the Chi-Square test are then compared between the calculated Chi-Square ( $\chi^2$  observed) and the Chi-Square from the table ( $\chi^2$  expected). The Chi-Square value in the table depends on the degrees of freedom (df) and its significance level ( $\alpha$ ). The degrees of freedom (df) are the number of categories (k) minus 1, while the significance level ( $\alpha$ ) reflects the acceptable error level. The commonly used significance levels are 0.05 (5%) or 0.01 (1%) [20]. Hypothesis 1 cannot be rejected if the calculated  $\chi^2$  value is smaller than the table  $\chi^2$  value. Conversely, Hypothesis 1 is rejected if the calculated  $\chi^2$  value is greater than the table  $\chi^2$  value [21].

The results of the analysis using the Chi-Square ( $\chi^2$ ) test method, presented in Table 3, indicate that the outputs generated by the SPM, SPMe, and DFN models in the PyBaMM simulator are in accordance with the experimental data of lithium-ion batteries. The lithium-ion battery model in the PyBaMM simulator as a whole

can effectively represent the relationship between cell voltage and discharge time, aligning well with experimental data. The comparison of the model with experimental data shows an accuracy level of 97% - 99%, with a model-data difference tolerance of 1%, as indicated by the alpha value of 0.01. This implies that the model is considered to be different from the experimental data if the calculated  $\chi^2$  value > the tabulated  $\chi^2$  value. However, the overall Chi-Square test results indicate that the calculated  $\chi^2$  value is less than the tabulated  $\chi^2$  value at  $\alpha = 0.01$ . Since the calculated  $\chi^2$  value is less than the tabulated  $\chi^2$  value, the first hypothesis is not rejected. In other words, there is no significant difference between the experimental data of the lithium-ion battery and the lithium-ion battery model in the PyBaMM simulator. This suggests that the lithium-ion battery model in the PyBaMM simulator is consistent with the experimental data of the lithium-ion battery.

The comparison chart and analysis results from the Chi-Square test indicate that both the SPMe and DFN models can better represent the actual behavior of batteries based on the experimental data used, compared to the SPM model. Based on the Chi-Square analysis results ( $\chi^2$ ), the DFN model shows superior performance with a smaller Chi-Square value compared to the SPMe model. Therefore, the best model capable of representing the actual behavior of batteries based on the experimental data used is the DFN model. These findings align with the literature stating that DFN is one of the most sophisticated and accurate models for battery modeling [16]. The second-best model in the ranking is the SPMe model, followed by the SPM model. These results also correspond to literature indicating that SPM is a simple mathematical model depicting the battery cell as a single particle or electrode, whereas SPMe is an extension of the SPM model, taking into account ion movement in the electrolyte surrounding the battery particle [16]. Therefore, the SPMe model can better represent experimental data for lithium-ion batteries compared to the SPM model.

#### 4. Conclusion

There is no significant difference between the lithium-ion battery models produced by PyBaMM simulation and experimental data. The accuracy level of the lithium-ion battery model generated by PyBaMM with experimental data ranges from 97% to 99%, indicating that the model closely aligns with the actual behavior of lithium-ion batteries. These results suggest that PyBaMM is a reliable simulator for representing the characteristics of lithium-ion batteries. Furthermore, based on the chi-square test analysis, it was found that the most optimal mathematical model in representing the actual behavior of batteries is the DFN model, followed by the SPMe model, and then the SPM model. Therefore, this research contributes significantly to understanding and enhancing the modeling of lithium-ion batteries through the use of PyBaMM simulation, with the DFN model being the preferred choice in this context.

#### ACKNOWLEDGEMENTS

Author thanks to LP2M University of Jember for the Financial Support to Hibah Keris IMSAR.

#### REFERENCES

- [1]. I. Maulana and A. Chobir, "Studi elektrokimia baterai aluminium-udara dengan silika xerogel sebagai bahan elektroda," *Journal of Energy and Electrical Engineering (JEEE)*, vol. 01, no. 01, pp. 25 – 28, 2019.
- [2]. W. Chen, "A review of materials and their future development trends for lithium-ion battery anodes," in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics Publishing, Aug. 2020. doi: 10.1088/1755-1315/546/2/022026.
- [3]. V. Sulzer, S. G. Marquis, R. Timms, M. Robinson, and S. J. Chapman, "Python battery mathematical modelling (PyBaMM)," *J Open Res Softw*, vol. 9, pp. 1–8, 2021, doi: 10.5334/JORS.309.
- [4]. J. S. Horner, G. Whang, I. V. Kolesnichenko, T. N. Lambert, B. S. Dunn, and S. A. Roberts, "A pseudo-two-dimensional (P2D) model for FeS<sub>2</sub> conversion cathode batteries," Jun. 2022, doi: 10.1016/j.jpowsour.2022.231893.
- [5]. J. N. Njoku, C. I. Nwakanma, J.-M. Lee, and D.-S. Kim, "Model comparison and selection for battery digital twin development using PyBaMM," *Kumoh National Institute of Technology, Korea*, 2023, doi: 10.1115/1.4002475.
- [6]. Z. Khalik, M. C. F. Donkers, and H. J. Bergveld, "Model simplifications and their impact on computational complexity for an electrochemistry-based battery modeling toolbox," *J Power Sources*, vol. 488, Mar. 2021, doi: 10.1016/j.jpowsour.2020.229427.

- 
- [7]. P. U. Nzereogu, A. D. Omah, F. I. Ezema, E. I. Iwuoha, and A. C. Nwanya, "Anode materials for lithium-ion batteries: A review," *Applied Surface Science Advances*, vol. 9. 2022. doi: 10.1016/j.apsadv.2022.100233.
- [8]. H. J. Kim *et al.*, "A comprehensive review of li-ion battery materials and their recycling techniques," *Electronics (Switzerland)*, vol. 9, no. 7. MDPI AG, pp. 1–44, Jul. 01, 2020. doi: 10.3390/electronics9071161.
- [9]. B. Scrosati and J. Garche, "Lithium batteries: Status, prospects and future," *Journal of Power Sources*, vol. 195, no. 9. pp. 2419–2430, May 01, 2010. doi: 10.1016/j.jpowsour.2009.11.048.
- [10]. M. R. Harahap, "Sel Elektrokimia: Karakteristik dan Aplikasi," *CIRCUIT: Jurnal Ilmiah Pendidikan Teknik Elektro*, vol. 2, no. 1, Jul. 2016, doi: 10.22373/crc.v2i1.764.
- [11]. S. G. Marquis, "Long-term degradation of lithium-ion batteries," PhD thesis, University of Oxford, 2020.
- [12]. A. M. Nolan, Y. Zhu, X. He, Q. Bai, and Y. Mo, "Computation-accelerated design of materials and interfaces for all-solid-state lithium-ion batteries," *Joule*, vol. 2, no. 10. Cell Press, pp. 2016–2046, Oct. 17, 2018. doi: 10.1016/j.joule.2018.08.017.
- [13]. L. Xia, E. Najafi, H. J. Bergveld, and M. C. F. Donkers, "A computationally efficient implementation of an electrochemistry-based model for lithium-ion batteries," in *IFAC-PapersOnLine*, Elsevier B.V., Jul. 2017, pp. 2169–2174. doi: 10.1016/j.ifacol.2017.08.276.
- [14]. A. M. Ramos, "On the well-posedness of a mathematical model for lithium-ion batteries," *Appl Math Model*, vol. 40, no. 1, 2016, doi: 10.1016/j.apm.2015.05.006.
- [15]. B. Sri Kaloko, "Pemodelan aliran daya pada system energi mobil listrik," *Jurnal Teknologi Technoscintia*, vol. 2, no. 2, 2010.
- [16]. S. G. Marquis, V. Sulzer, R. Timms, C. P. Please, and S. J. Chapman, "An asymptotic derivation of a single particle model with electrolyte," May 2019, [Online]. Available: <http://arxiv.org/abs/1905.12553>
- [17]. T. L. Kirk, J. Evans, C. P. Please, and S. J. Chapman, "Modelling electrode heterogeneity in lithium-ion batteries: unimodal and bimodal particle-size distributions," Jun. 2020, [Online]. Available: <http://arxiv.org/abs/2006.12208>
- [18]. Power-Sonic Corporation, "What is a battery c rating?," 2021. [Online]. Available: [www.power-sonic.com](http://www.power-sonic.com)
- [19]. M. Ecker, S. Käbitz, I. Laresgoiti, and D. U. Sauer, "Parameterization of a physico-chemical model of a lithium-ion battery," *J Electrochem Soc*, vol. 162, no. 9, pp. A1849–A1857, 2015, doi: 10.1149/2.0541509jes.
- [20]. U. Maryam, W. Somayasa, Ruslan, L. Gubu, and Jufra, "Estimasi parameter dan uji goodness of fit untuk data biner berpasangan," *Jurnal Matematika, Komputasi dan Statistika*, vol. 2, no. 1, 2022.
- [21]. A. Heryana, "Uji chi-square", 2020. [Online]. Available: <https://www.researchgate.net/publication/341539841> doi: 10.13140/RG.2.2.23266.15047.