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A Data-Driven Mathematical Model for Deep Cycle Battery Performance Evaluation

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Research Article

Abstract

Deep Cycle Battery (DCB) has become very useful in recent time as it plays a vital role in the delivery of electricity to consumers. DCB serves as a battery bank whether as a single battery or group of batteries wired together in order to store the generated solar energy for a solar power system. The continuous use of DCB in solar power system is undeniable. Whether the DCB is in use or not, its performance deteriorates over time and make users complain about the performance in terms of the discharge rate, charging rate and the operating temperature as compared with the specifications by the manufacturers of the DCBs. Also, when the DCBs are used wrongly it tends to shorten the life spans of the optimum performance. In this research, a nonlinear model was developed for the discharge time of a DCB as a function of load resistance, R, cell internal resistance, r_0 and State of Charge, SoC using discharge data collected from seven battery brands over a period of twelve (12) months. The proposed model parameters gave satisfactory results in the form of low residuals when applied to the experimental data. The proposed model performance conformed to those expected from the experimental data and was further validated using Saslow's model.

Keywords

Deep Cycle Battery, Operating Temperature, State of Charge, and Depth of Charge

Article History

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1. Introduction

Battery is an energy storage device and its one among the promising storage systems for stationary applications due to its simplicity with which they could be designed and installed compared to other storage technologies (Akinyele et. al., 2017; Leadbetter et. al. 2012). Batteries produce direct current and are measured by a capacity, specified as the ability to supply a specific current for a specified length of time (Amp-hours or Ah) and a direct current voltage (Volts DC, or VDC) (Wang et. al., 2013). A specific battery is made up of individual cells that can be combined in series arrays to achieve a desired voltage (increase the battery bank voltage) or connected in parallel to increase the capacity of the array. Battery performance deteriorates over time whether in storage or during use (Ritchie et. al., 2001). In storage, it is due to a variety of chemical mechanism such as corrosion of metal electrodes and limited thermal stability of materials, while during use is due to parasitic reactions (Ritchie et. al., 2001). It is however common to find users complaining about the performance of their batteries in terms of the discharge rate, charging rate and the operating temperature of these batteries as compared with the specifications given by the manufacturers of these batteries. Abusive applications of the batteries shorten their life spans and the user's end up not deriving optimum performance from their use. Although these batteries are used in the tropical region like Nigeria for electrical power backup, there has been no experimental test done to obtain a working mathematical model that will help estimate and optimize their performance under field conditions.

So much work has been done in battery energy storage such as in (Akinyele et. al., 2017; Hill et. al., 2012;

Fathima et. al., 2014; Li 2009; Halicka et.al., 2015; Luo et. al., 2015) and in degradation such as in (Ritchie et. al., 2001; Barcellona et. al. 2015) with promising results. In Svoboda et. al. (2007), the researchers listed charge factor, Amp-hour throughput, discharge rate, time between full charge, time at low SoC, partial cycling and temperature as stress factors which make it easier to characterize battery operating conditions and link them to aging.

A common issue with analyzing machining operations is the lack of or absence of empirical models or equations to aid such analysis. Even when such equations exist, they are too complex and analyzing them becomes cumbersome and sometimes near-impossible. This research therefore aims to develop a mathematical model based on the discharge data of the batteries that will aid predicting the discharge time of deep cycle batteries and the analysis and optimization of the performance of similar battery types under varying load conditions.

2. Equipment and Methods

Equipment

The following equipment were used in the research namely; Seven (7) different brands of 100AH, 12V deep cycle batteries, Seven (7) 1000VA with 12V inverter, SOMA Battery Load Tester (BLT), Light bulbs of rating (700W, 500W and 200W) - seven in each category, Seven (7) Temperature sensors and battery data acquisition system designed specifically to read and record the ambient temperature with the aid of the temperature sensors; read and log the battery State of Charge (SoC) from 100% (full charge) to 20% (80% Depth of Discharge, DoD). The setup is as shown in Figure 1.

Figure 1: Experimental setup of data collection

Developed Model

The following are the steps for the developed model namely;

Step 1: The terminal voltage, state of charge (SoC), depth of discharge (DoD), internal resistance (r_0) and load resistance (R) were recorded under the different load conditions (200W, 500W and 700W).

Step 2: A semi-log plot of the terminal voltage against the discharge time was done for all seven batteries considered as (A, B, C, D, E, F, G).

Step 3: A close study of the plots were undertaken to ascertain the nature and/or degree of the function to be fit to the dataset.

Step 4: Based on the outcome in step 3, different non-linear model was fitted to the data and the one with the best fit chosen.

Step 5: The chosen model was compared with a model developed by Saslow using the same data set to see how our developed model performs.

The discharge data for the various batteries were combined along with the associated internal resistances of the corresponding batteries and the load resistances under the various discharge currents. After rigorous effort, an equation of the form;

$$t = \beta_1 \left[R + r_0 \ln\left(\frac{SoC_0}{SoC}\right)\right] + \beta_2 R SoC \qquad (1)$$

was considered appropriate for the data set, where SoC is the state of charge (in %), SoC0 is the state of charge at full capacity, β1 and β2 are parameters to be estimated using nonlinear regression analysis with SoC, R and r0 as variables and t as response.

Taking SoC0 as 100, equation (1) becomes

$$t = \beta_1 \left[R + r_0 \ln\left(\frac{100}{SoC}\right)\right] + \beta_2 RSoC \qquad (2)$$

Statistical 8.0 software was used to fit the data in Table A1 to the model to give $\beta_1$as 8.25006 and β_2 as -0.08265.

Consequently, equation (2) becomes:

$$t = 8.250006 \left[R + r_0 \ln\left(\frac{100}{SoC}\right)\right] - 0.08265 * R * SoC$$

(3)

A plot of the predicted values using the nonlinear regression model against the observed discharge time values from the experimental data was obtained.

For validation purpose, the data from battery B under 200W load, the experimental discharge time was compared to the prediction results from proposed model and Saslow's model (Saslow, 2008).

$$t = \frac{RQ_0}{E}\left[1 - \frac{Q}{Q_0} - \frac{r_0}{R} ln\left(\frac{Q}{Q_0}\right)\right] \qquad (4)$$

Replacing Q with SoC and Q_0 with 100, Saslow's model becomes;

$$t = \frac{100R}{E}\left[1 - \frac{SoC}{100} - \frac{r_0}{R} ln\left(\frac{SoC}{100}\right)\right] \qquad (5)$$

3. Results and Discussion

The discharge data for battery A is shown in Table 1 and the corresponding discharge curve is shown in Figure 2 using a semi-log plot.

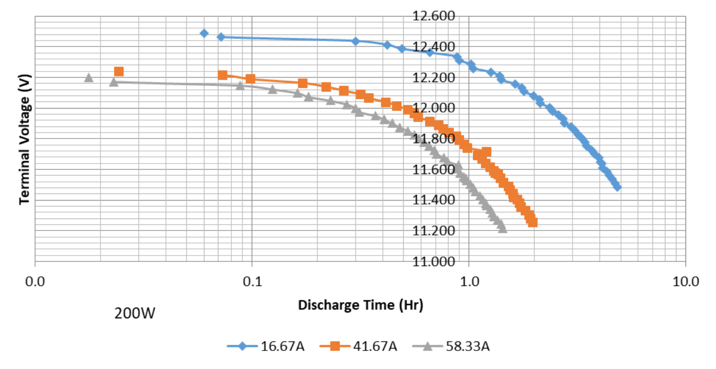


Figure 2 Discharge curve for Battery A

Similarly, the discharge curves for batteries B to G are shown in Figure 3

The curve has two components; a linear component and a logarithmic component. A careful examination of the discharge curves for the batteries shown in Figure 2 and Figure 3 reveals that the relationship between the discharge time and the variables state of charge (SoC), internal resistance (r_0) and the load resistance (R) are nonlinear.

Figure 4 shows the predicted values against the experimental values and Figure 5 shows the plot of the residual against the discharge time. There is a close fit between the value predicted using the model and the observed values from the experiment. This is further highlighted from the residual plot of Figure 5.

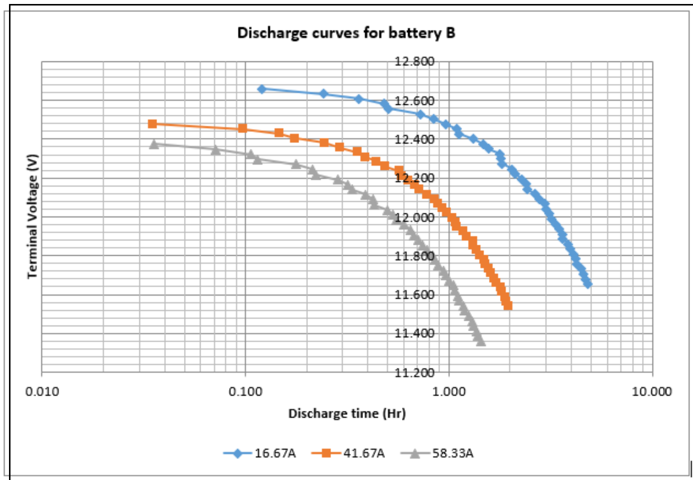
The plot in Figure 5 shows a random distribution of the residuals. The absence of observable patterns such as series of increasing or decreasing points; a predominance of positive or negative residuals; increasing residuals with increasing fits indicates that the residuals are normally distributed.

The outcome of both models is presented inf Figure 6.

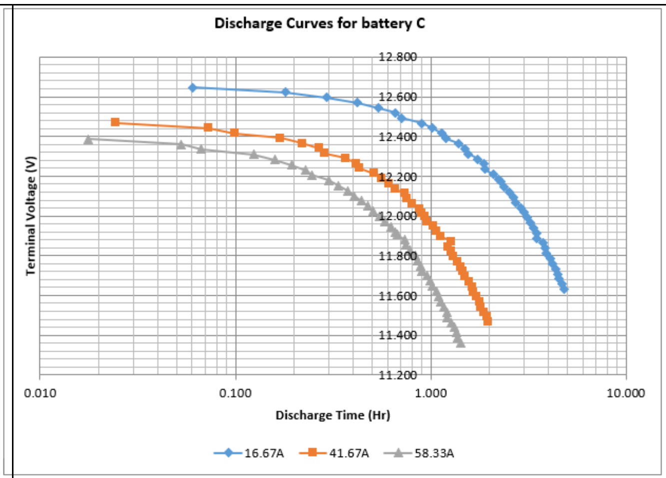
Table

200W				**500W**				**700W**			
V (V)	**SoC (%)**	**DoD (%)**	**t (Hr.)**	**V (V)**	**SoC (%)**	**DoD (%)**	**t (Hr.)**	**V (V)**	**SoC (%)**	**DoD (%)**	**t (Hr.)**
12.501	100.000	0.000	0.000	12.250	100.000	0.000	0.000	12.211	100.000	0.000	0.000
12.488	99.000	1.000	0.060	12.238	99.000	1.000	0.024	12.198	99.000	1.000	0.018
12.463	97.000	3.000	0.072	12.213	97.000	3.000	0.073	12.174	97.000	3.000	0.023
12.437	95.000	5.000	0.301	12.188	95.000	5.000	0.098	12.149	95.000	5.000	0.088
12.412	93.000	7.000	0.421	12.163	93.000	7.000	0.171	12.124	93.000	7.000	0.124
12.386	91.000	9.000	0.489	12.138	91.000	9.000	0.220	12.099	91.000	9.000	0.162
12.361	89.000	11.000	0.662	12.113	89.000	11.000	0.264	12.074	89.000	11.000	0.182
12.336	87.000	13.000	0.883	12.088	87.000	13.000	0.317	12.049	87.000	13.000	0.230
12.310	85.000	15.000	0.903	12.064	85.000	15.000	0.346	12.025	85.000	15.000	0.274
12.285	83.000	17.000	1.023	12.039	83.000	17.000	0.415	12.000	83.000	17.000	0.301
12.259	81.000	19.000	1.047	12.014	81.000	19.000	0.464	11.975	81.000	19.000	0.312
12.234	79.000	21.000	1.264	11.989	79.000	21.000	0.523	11.950	79.000	21.000	0.372
12.209	77.000	23.000	1.385	11.964	77.000	23.000	0.561	11.925	77.000	23.000	0.407
12.183	75.000	25.000	1.405	11.939	75.000	25.000	0.584	11.901	75.000	25.000	0.443
12.158	73.000	27.000	1.626	11.914	73.000	27.000	0.659	11.876	73.000	27.000	0.478
12.132	71.000	29.000	1.746	11.889	71.000	29.000	0.725	11.851	71.000	29.000	0.524
12.107	69.000	31.000	1.785	11.864	69.000	31.000	0.757	11.826	69.000	31.000	0.560
12.082	67.000	33.000	1.987	11.840	67.000	33.000	0.806	11.801	67.000	33.000	0.585
12.056	65.000	35.000	2.108	11.815	65.000	35.000	0.872	11.777	65.000	35.000	0.620
12.031	63.000	37.000	2.119	11.790	63.000	37.000	0.904	11.752	63.000	37.000	0.656
12.005	61.000	39.000	2.349	11.765	61.000	39.000	0.953	11.727	61.000	39.000	0.691
11.980	59.000	41.000	2.424	11.740	59.000	41.000	0.986	11.702	59.000	41.000	0.710
11.955	57.000	43.000	2.590	11.715	57.000	43.000	1.202	11.677	57.000	43.000	0.763
11.929	55.000	45.000	2.711	11.690	55.000	45.000	1.100	11.653	55.000	45.000	0.798
11.904	53.000	47.000	2.747	11.665	53.000	47.000	1.149	11.628	53.000	47.000	0.892
11.878	51.000	49.000	2.952	11.640	51.000	49.000	1.198	11.603	51.000	49.000	0.870
11.853	49.000	51.000	3.073	11.616	49.000	51.000	1.247	11.578	49.000	51.000	0.905
11.828	47.000	53.000	3.194	11.591	47.000	53.000	1.296	11.553	47.000	53.000	0.941
11.815	46.000	54.000	3.234	11.578	46.000	54.000	1.321	11.541	46.000	54.000	0.969
11.802	45.000	55.000	3.314	11.566	45.000	55.000	1.367	11.528	45.000	55.000	0.977
11.777	43.000	57.000	3.435	11.541	43.000	57.000	1.395	11.504	43.000	57.000	1.013
11.751	41.000	59.000	3.486	11.516	41.000	59.000	1.444	11.479	41.000	59.000	1.049
11.726	39.000	61.000	3.677	11.491	39.000	61.000	1.520	11.454	39.000	61.000	1.070
11.701	37.000	63.000	3.798	11.466	37.000	63.000	1.543	11.429	37.000	63.000	1.121
11.675	35.000	65.000	3.979	11.441	35.000	65.000	1.592	11.404	35.000	65.000	1.157
11.650	33.000	67.000	4.040	11.416	33.000	67.000	1.610	11.380	33.000	67.000	1.193
11.637	32.000	68.000	4.091	11.404	32.000	68.000	1.666	11.367	32.000	68.000	1.201

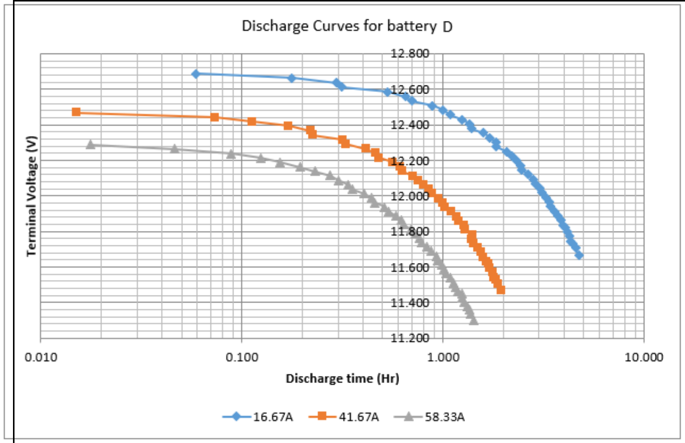
200W				500W				700W			
V (V)	**SoC (%)**	**DoD (%)**	**t (Hr.)**	**V (V)**	**SoC (%)**	**DoD (%)**	**t (Hr.)**	**V (V)**	**SoC (%)**	**DoD (%)**	**t (Hr.)**
11.612	30.000	70.000	4.126	11.379	30.000	70.000	1.716	11.342	30.000	70.000	1.247
11.586	28.000	72.000	4.343	11.354	28.000	72.000	1.739	11.318	28.000	72.000	1.283
11.561	26.000	74.000	4.428	11.329	26.000	74.000	1.815	11.293	26.000	74.000	1.302
11.536	24.000	76.000	4.586	11.304	24.000	76.000	1.892	11.268	24.000	76.000	1.356
11.510	22.000	78.000	4.707	11.280	22.000	78.000	1.915	11.243	22.000	78.000	1.411
11.485	20.000	80.000	4.829	11.255	20.000	80.000	1.965	11.218	20.000	80.000	1.429



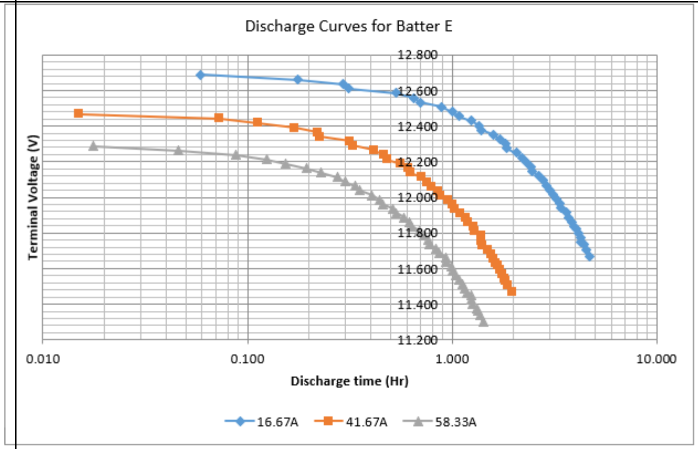
(a) Discharge curve for Battery B



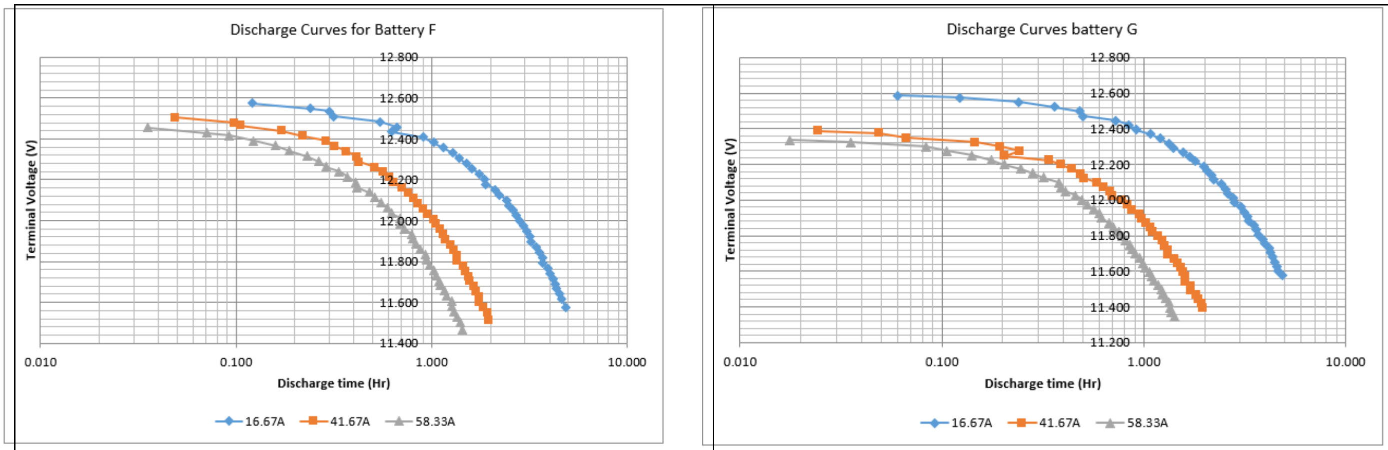
(b) Discharge curve for Battery C



(c) Discharge curve for Battery D



(d) Discharge curve for Battery E



(e) Discharge curve for Battery F

(f) Discharge curve for Battery G

Figure 3: Discharge Curve for Batteries B – G

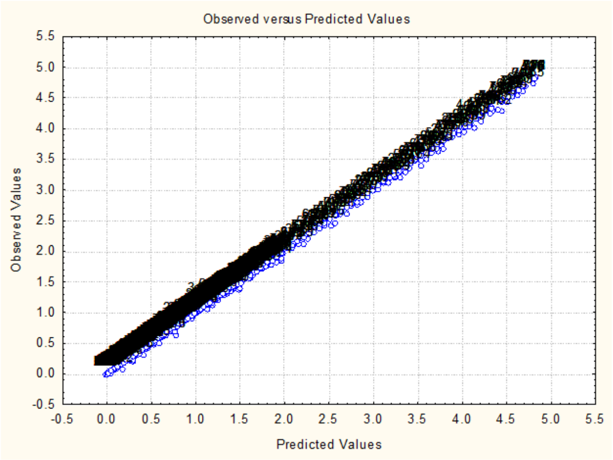


Figure 4: Predicted values vs experimental values

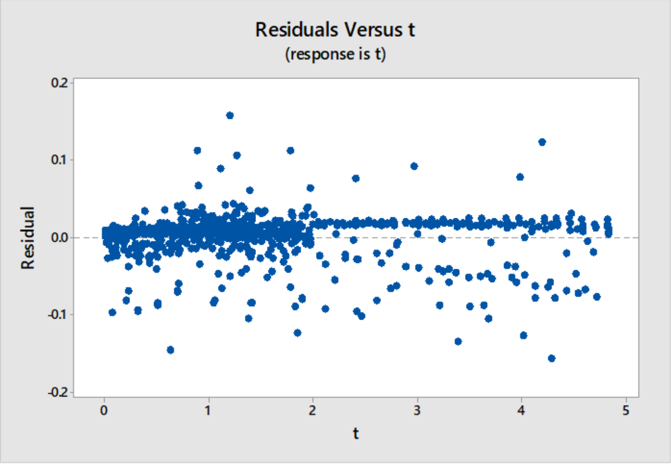


Figure 5: Plot of residual vs discharge time

4. Conclusion

Modern appliances and equipment use batteries as their source of energy, so their correct operation is based on the actual performances of the battery. Hence, there is a need to obtain a working mathematical model that will help estimate and optimize the battery performance under field conditions.

The carefully chosen model parameters gave satisfactory results in the form of low residuals when applied to the experimental data. The result is in agreement with that obtained using Saslow's model when the models were applied to the experimental data sets. The model performed satisfactorily under expected experimental condition in predicting the discharge time of battery B and other batteries considered in this research.

This is one case where data agrees with theory and could serve as a basic for analysing and optimizing of deep cycle batteries which before now lacked robust mathematical representation.

References

Akinyele, D., Belikov, J., and Levron, Y. (2017). "Battery Storage Technologies for Electrical Applications: Impact in Stand-Alone Photovoltaic Systems". Energies, 10(11), pp. 1-39.

Barcellona, S., Brenna, M., Foiadelli, F., Longo, M., Piegari, L. (2015). "Analysis of Ageing Effect on Li-Polymer Batteries", The Scientific World Journal, 2015, pp. 1-8.

Fathima, A. H. and Palanisamy K., (2014). "Battery energy storage applications in wind integrated systems — A review," 2014 International Conference on Smart Electric Grid (ISEG), pp. 1-8.

Halicka, K., Lombardi, P., Styczynski, Z.A. (2015). "Future-oriented analysis of battery technologies". In Proceedings of the IEEE International Conference on Industrial Technology. pp. 1019-1024.

Hill, C., Such, M., Chen, D., Gonzalez, J., Grady, W.M. (2012). "Battery Energy Storage for Enabling Integration of Distributed Solar Power Generation. Smart Grid", IEEE Transactions on Smart Grid, 3(2), pp. 850-857.

Leadbetter, J., and Swan, L.G., (2012). "Selection of battery technology to support grid-integrated renewable electricity". Journal of Power Sources, 216, pp. 376-386.

Li, P. (2009). "Energy storage is the core of renewable technologies". IEEE Nanotechnology Magazine, 2(4), pp. 13-18.

Luo, X., Wang, J., Dooner, M., Clarke, J. (2015). "Overview of current development in electrical energy storage technologies and the application potential in power system operation". Applied Energy, 137, pp. 511-536.

Ritchie A.G., Lakeman B., Burr P., Carter P., Barnes P.N., Bowles P. (2001). "Battery Degradation and Ageing. In: Mallinson L.G. (eds) Ageing Studies and Lifetime Extension of Materials". Springer, Boston, MA. pp. 523-527.

Saslow, W. M. (2008) ‘How batteries discharge: A simple model’, American Journal of Physics, 76(3), pp. 218–223.

Svoboda, V., Wenzl, H., Kaiser, R., Jossen, A., Baring-Gould, I., Manwell, J., Lundsager, P., Bindner, H., Cronin, T., Nørgård, P., Ruddell, A., Perujo, A., Douglas, K. Rodrigues, C., Joyce, A., Tselepis, S., Borg, N.V.D, Nieuwenhout, F., Wilmot, N., Mattera, F., and Sauer, D.U. (2007). “Operating conditions of batteries in off-grid renewable energy systems”. Solar Energy, 81(11), pp. 1409-1425.

Wang, C., Wu, H., Chen, Z., McDowell, M.T., Cui, Y., and Bao, Z., (2013).” Self-healing chemistry enables the stable operation of silicon microparticle anodes for high-energy lithium-ion batteries”. Nature Chemistry 5, pp. 1042–1048.