# Project 3: Battery Performance Under Different Charge Schedules

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**Abstract**

In this project, an electric vehicle's battery energy use and efficiency is modeled using Simulink. Three different sets of charging and discharging conditions are tested, and the simulation shows that slowly charging and slowly discharging the 6p100s battery wastes much less energy than doing so more quickly.

## 1 Introduction

Modern electric vehicles rely on lithium-ion (often abbreviated Li-ion or LiPo) battery cells for energy storage, as they are ubiquitous and, compared to conventional battery chemistries, have a relatively high power density for their mass. In previous studies (Wiegman 2023), an oversimplified constant-voltage source was used to model the behavior of a vehicle's rechargeable battery, but that idealized model fails to capture inefficiencies in the charge and discharge behavior of the device. In this paper, we present a more accurate model for a vehicle battery, consisting of six parallel banks ($N_p = 6$) of one hundred ($N_s = 100$) lithium cells connected in series: a 6p100s battery, in industry parlance. These cells have a 31 Ah capacity (Alothman 2023), and can be modeled as a variable-voltage source (depending on the state of charge) connected in series with a resistor, a resistor and capacitor in parallel, and then the load.

## 2 Methods

### 2.1 Model

The round-trip efficiency of the battery is modeled according to the block diagram given in Figure 1. The SOC Estimator is a simple Coulomb-counting integrator, the Table Look-up to get the cell's variable-voltage source $V_{oc}$ is a simple linear interpolation of the values given in Table 1, and the Cell Circuit Model is a simple set of differential RC circuit equations as described in Section 1.

Table 1: Look-up table for the open-circuit voltage of a battery cell as a function of State of Charge (SoC).

| SoC | $V_{oc}$ |
|---|---|
| 0.00 | 3.21 |
| 0.10 | 3.27 |
| 0.25 | 3.63 |
| 0.50 | 3.71 |
| 0.75 | 3.93 |
| 0.90 | 4.08 |
| 1.00 | 4.19 |

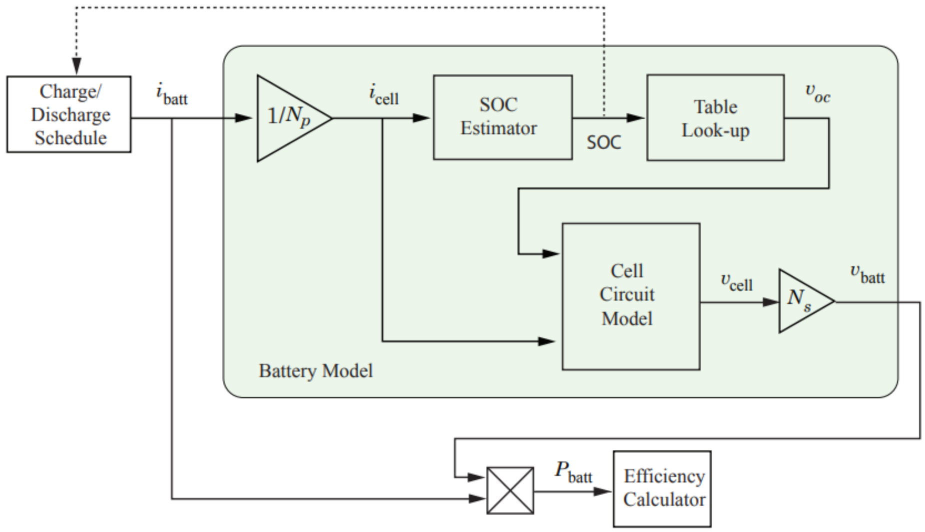


Figure 1: A top-level block diagram of the model, reproduced from Alothman (2023).

The Simulink model for the simulation used in this study is shown in Figure 2. The interiors of the subsystem blocks within (the Charge/Discharge Schedule, Battery, and Efficiency Calculator) are shown in Figures 3, 4, and 6, respectively. Initialization code, providing reference values for several variables in the model, is given in the appendix.

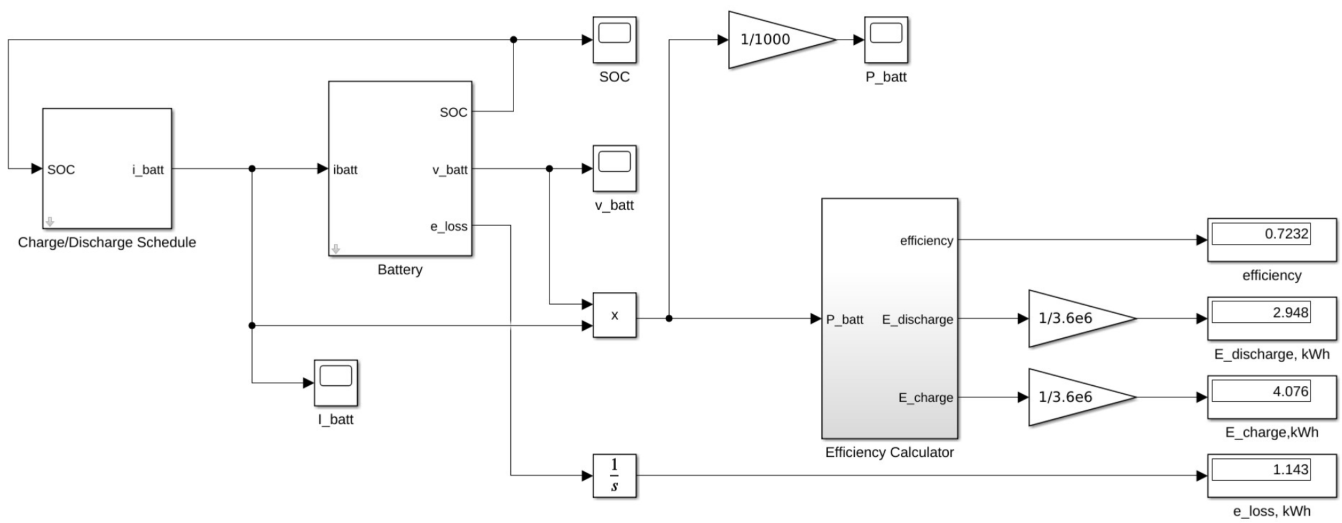


Figure 2: The Simulink model for the whole system.

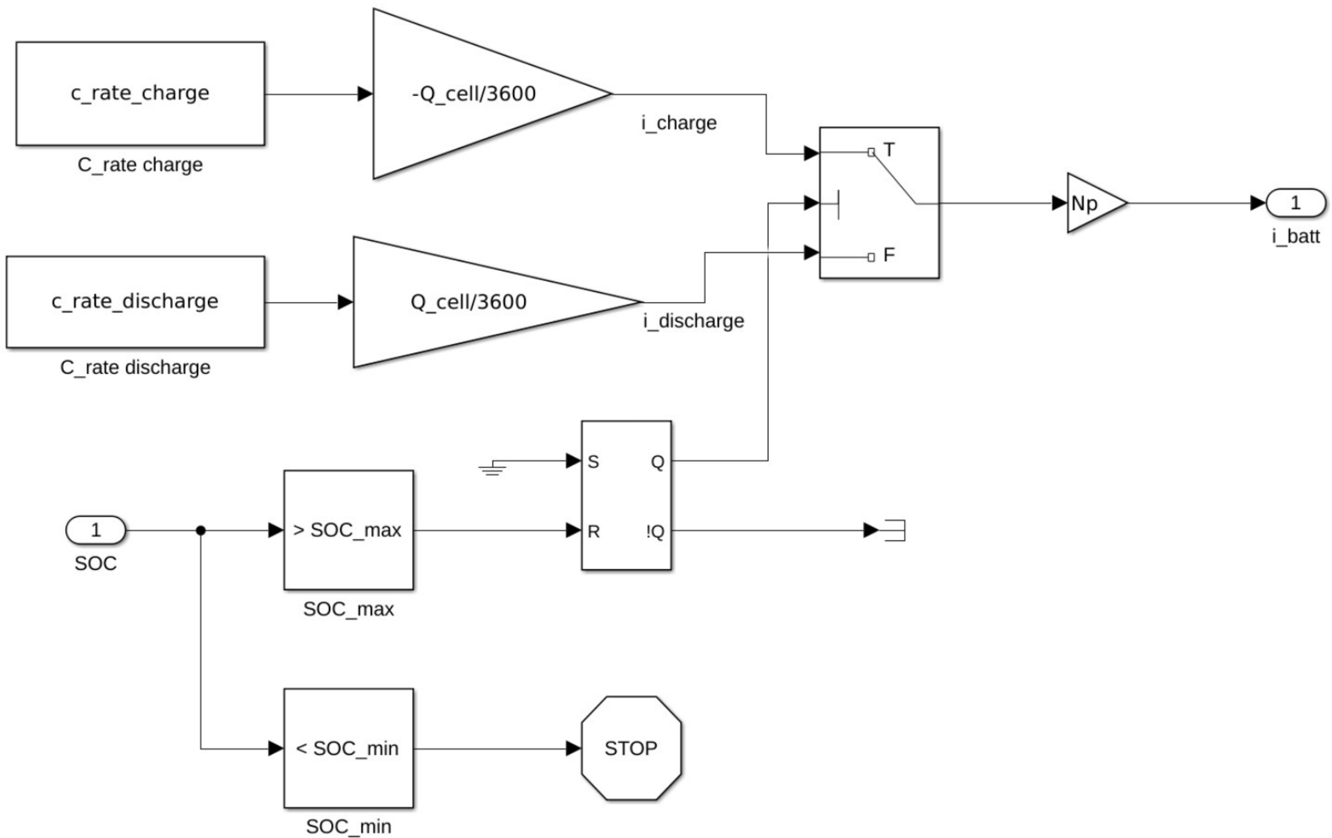


Figure 3: Charge/Discharge Schedule

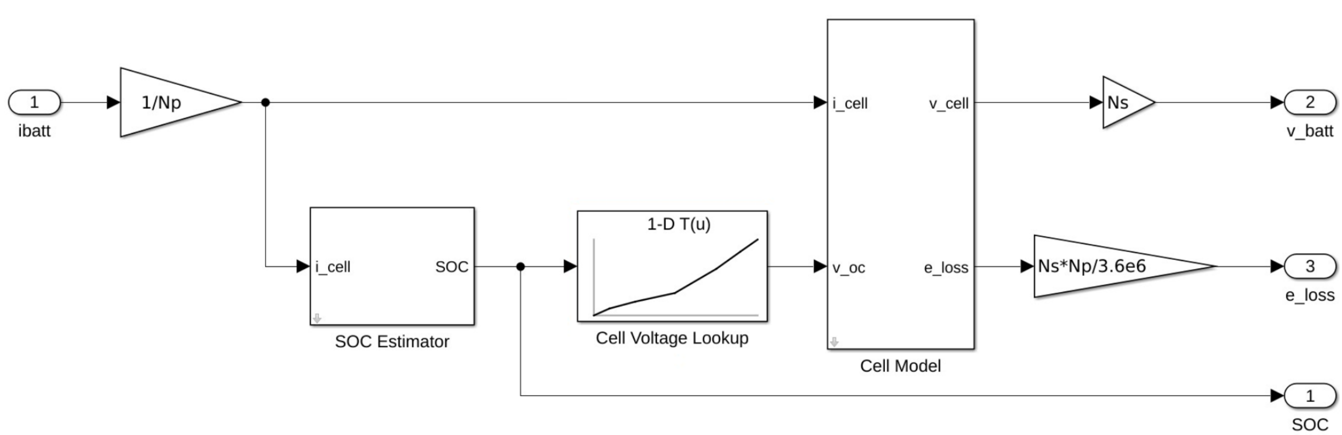


Figure 4: Battery

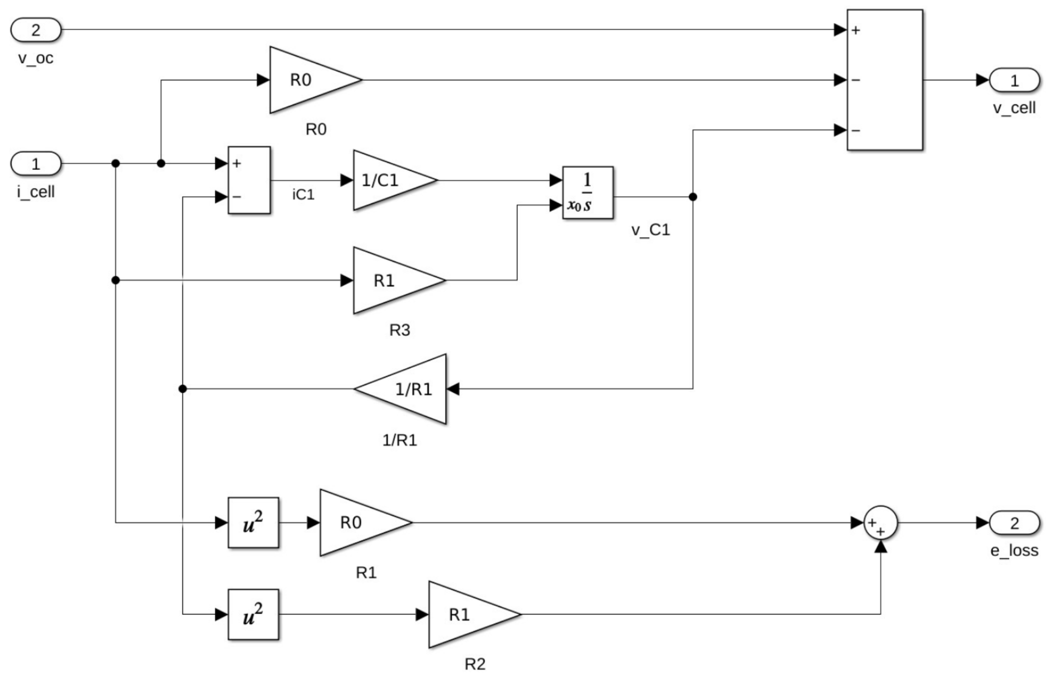


Figure 5: Interior of the “Cell Model” block shown in Figure 4.

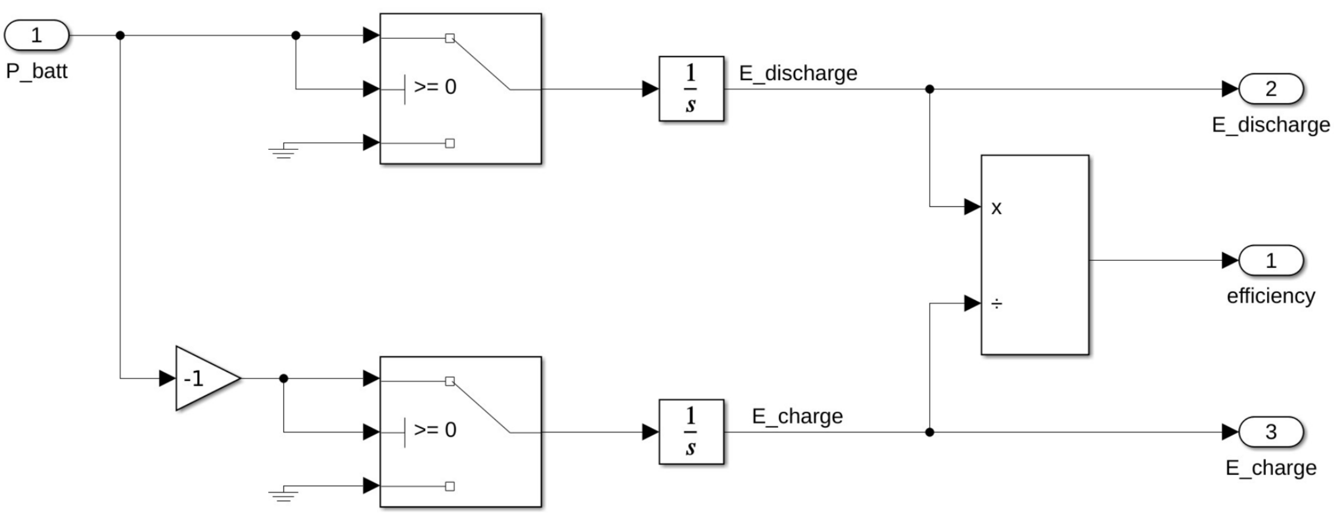


Figure 6: Efficiency Calculator

## 2.2 Charge/Discharge Schedules

Three different charge/discharge schedules were tested with this model. For each case, the battery's overall voltage $V_{batt}$, output current $I_{batt}$, power output $P_{batt}$, and state of charge were plotted over time. In addition, the overall system efficiency, total energy charged, total energy discharged, and total energy lost to resistive heating were recorded for each schedule.

#### Slow-Charge, Slow-Discharge

The first scenario tested in this study was that of slowly charging and then slowly discharging. In this case, the battery was initialized with a SoC of 0.2 (that is, charged to 20% of maximum capacity), charged at a C-rate of 0.2 until full, and then discharged at a C-rate of 0.2 until it returned to a SoC of 0.2.

#### Fast-Charge, Slow-Discharge

The second scenario tested in this study was that of quickly charging and then slowly discharging. In this case, the battery was initialized with a SoC of 0.2 (as before), charged at a C-rate of 2.0 until full (ten times faster than before!), and then discharged at a C-rate of 0.2 until it reached a SoC of 0.2 (as before).

#### Fast-Charge, Fast-Discharge

The third and final scenario tested in this study was that of quickly charging and then quickly discharging a smaller amount of energy. In this case, the battery was initialized with a SoC of 0.5, charged at a C-rate of 2.0 until it reached a SoC of 0.55, and then discharged at a C-rate of 2.0 until it returned to a SoC of 0.5.

# 3 Results & Analysis

## 3.1 Slow-Charge, Slow-Discharge

The results from simulating the first scenario are summarized in Table 2. As $E_{charge} = E_{discharge} + E_{loss}$, energy is properly conserved, so we can be assured that the simulation did not erroneously misplace any energy. As expected, the slower input and output of energy in this schedule means that there is relatively little energy lost to resistance in the circuit, so the efficiency is quite high.

Table 2: Results from the first schedule (slow/slow).

| Quantity | Symbol | Value | Units |
|---|---|---|---|
| Efficiency | — | 96.66 | % |
| Energy Charged | $E_{charge}$ | 58.03 | kWh |
| Energy Discharged | $E_{discharge}$ | 56.09 | kWh |
| Energy Lost | $E_{loss}$ | 1.94 | kWh |

Plots of the battery's overall voltage $V_{batt}$, output current $I_{batt}$, power output $P_{batt}$, and state of charge are shown in Figures 7, 8, 9, and 10, respectively, with further analysis included in their associated captions.

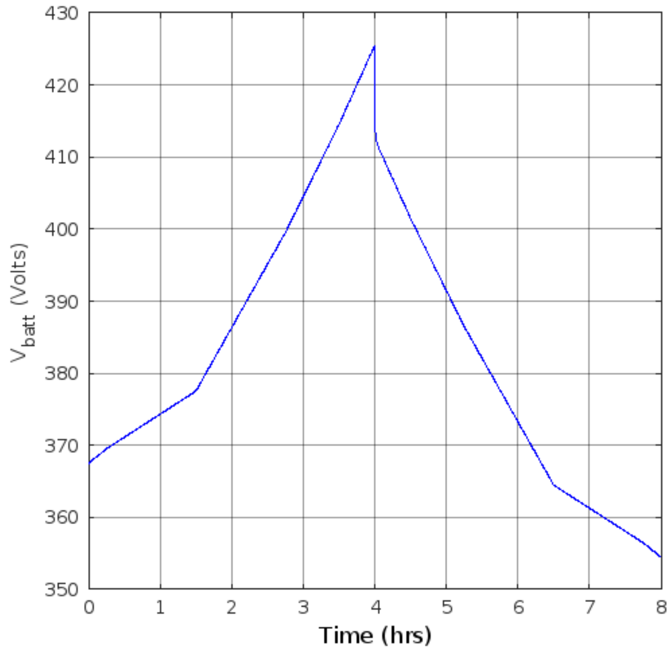


Figure 7: Battery voltage during the slow-charge, slow-discharge schedule. For a short period before reaching maximum capacity at t = 4 hours, note how the battery voltage exceeded the maximum cell voltage of 420 volts. This occurred because this model does not include any cell-protection features, only a simple constant-current charger. In a real battery, circuitry must be included to ensure that the charger switches to a constant-voltage mode when a constant-current supply would overvolt the battery, as otherwise the battery could be damaged and may explode or catch fire.

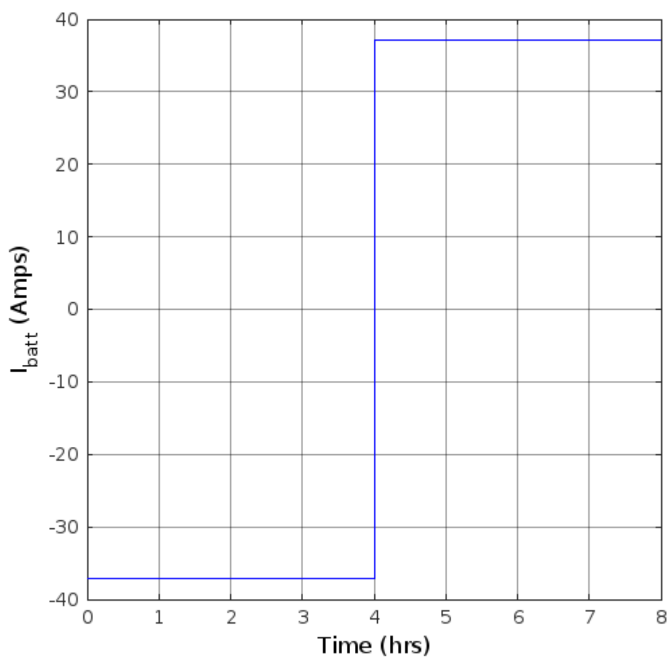


Figure 8: Battery output current during the slow-charge, slow-discharge schedule. The total battery capacity is 186 Ah (because the 31 Ah cells are in six parallel stacks), so a C-rate of 0.2 would give a charge rate of 37.2 A: exactly what we see in this plot.

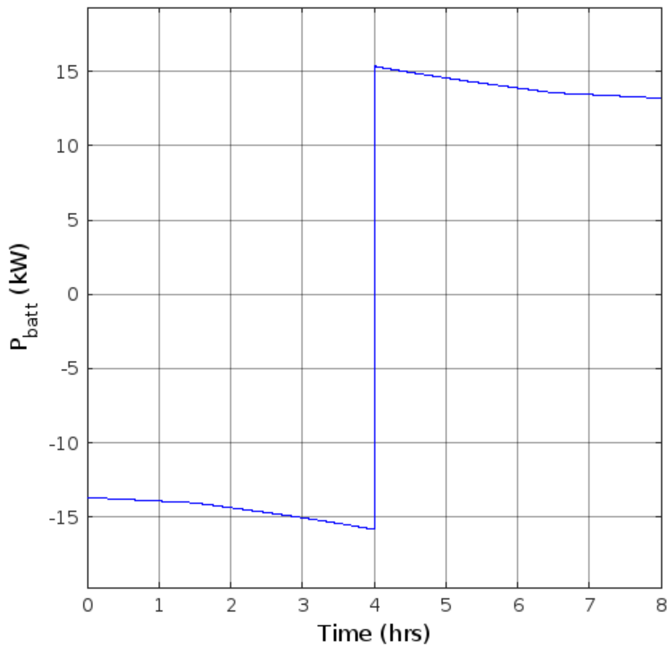


Figure 9: Battery output power during the slow-charge, slow-discharge schedule. The bends in the power input/output correspond to when the SoC reaches the reference points in Table 1.

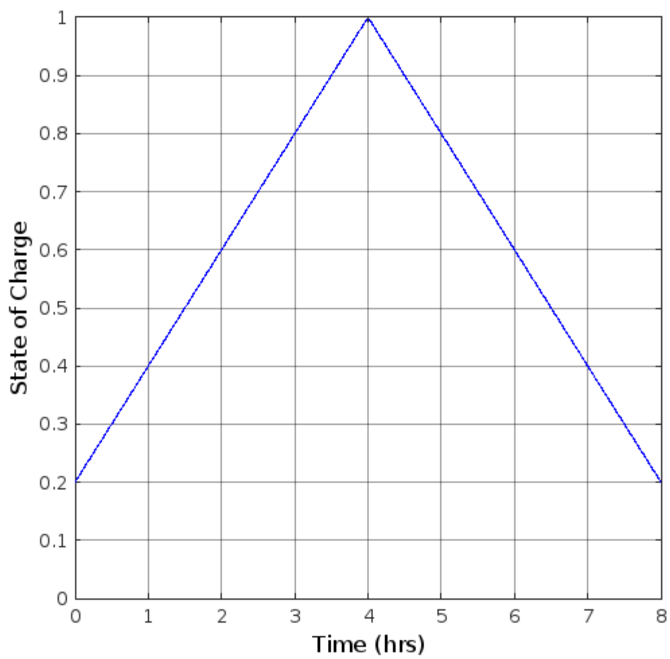


Figure 10: Battery state of charge throughout the slow-charge, slow-discharge schedule. A single charge rate for input energy (0.2) and output energy (-0.2) means that the plot of the SoC has a straight line for each leg of the schedule.

### 3.2 Fast-Charge, Slow-Discharge

The results from simulating the second scenario are summarized in Table 3. Just as before, $E_{loss}$ is about equal to $E_{charge} - E_{discharge}$, so energy is indeed conserved properly. In comparison to the previous schedule, there is a significant drop in efficiency (over ten percent!): this is due to the additional energy lost to resistance in the circuit, as current is required to flow at higher rates to move charge at the faster scheduled rate.

Table 3: Results from the second schedule (fast/slow).

| Quantity | Symbol | Value | Units |
|---|---|---|---|
| Efficiency | — | 84.04 | % |
| Energy Charged | $E_{charge}$ | 66.75 | kWh |
| Energy Discharged | $E_{discharge}$ | 56.10 | kWh |
| Energy Lost | $E_{loss}$ | 10.67 | kWh |

Plots of the battery's overall voltage $V_{batt}$, output current $I_{batt}$, power output $P_{batt}$, and state of charge are shown in Figures 11, 12, 13, and 14, respectively, with further analysis included in their associated captions.

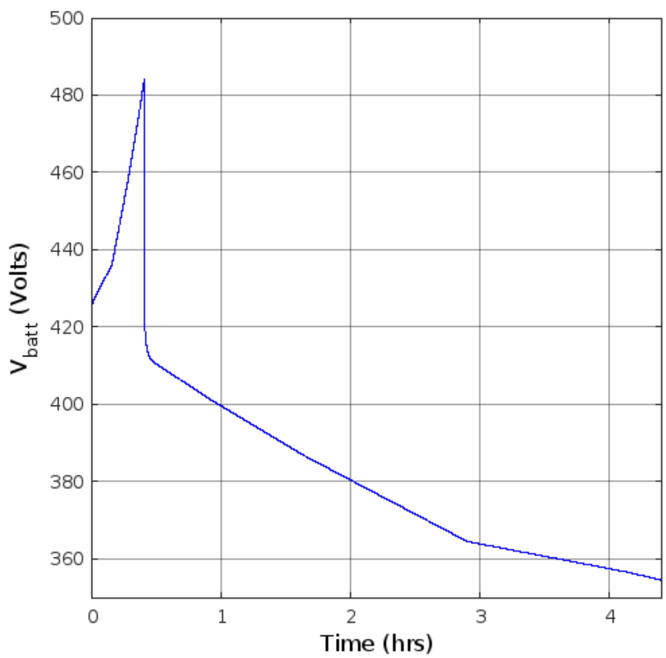


Figure 11: Battery voltage during the fast-charge, slow-discharge schedule. Note how the applied voltage is higher than the maximum cell voltage throughout the entire charging period. This occurs because the extremely high charge rate mandates a high voltage so that a very high current can be pushed into the battery. Just as noted in the caption for Figure 7, this would not happen in a real battery, as this simulation uses an overly simple charger and does not model any cell protection circuitry.

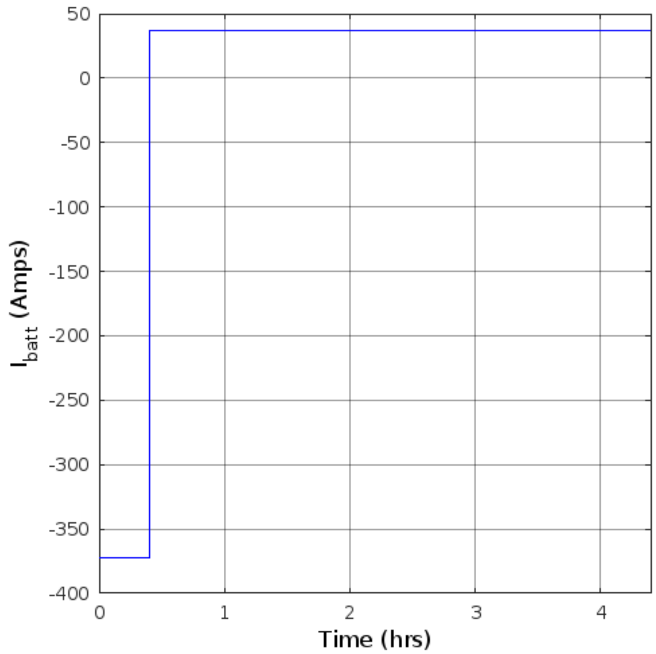


Figure 12: Battery output current during the fast-charge, slow-discharge schedule. Note how the input current is ten times greater in magnitude than the output current, as expected for charging at a C-rate of 2.0 and discharging at a C-rate of 0.2.

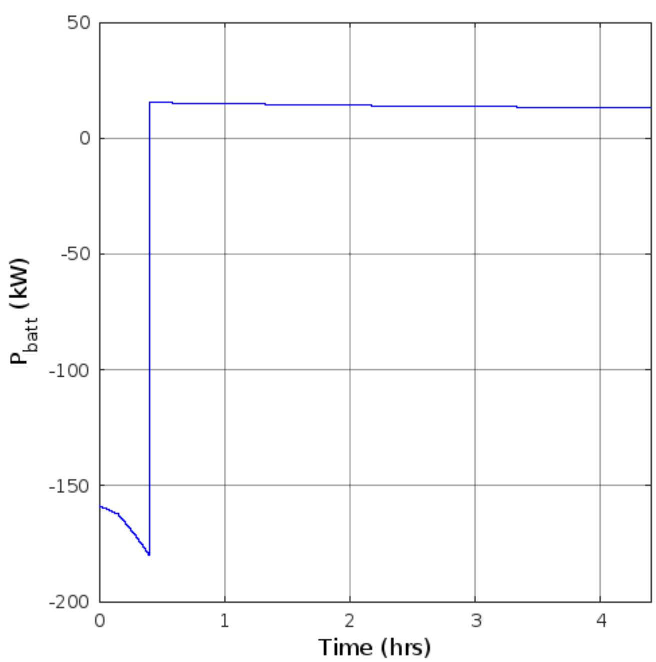


Figure 13: Battery output power during the fast-charge, slow-discharge schedule. The bends in the power input/output correspond to when the SoC reaches the reference points in Table 1.

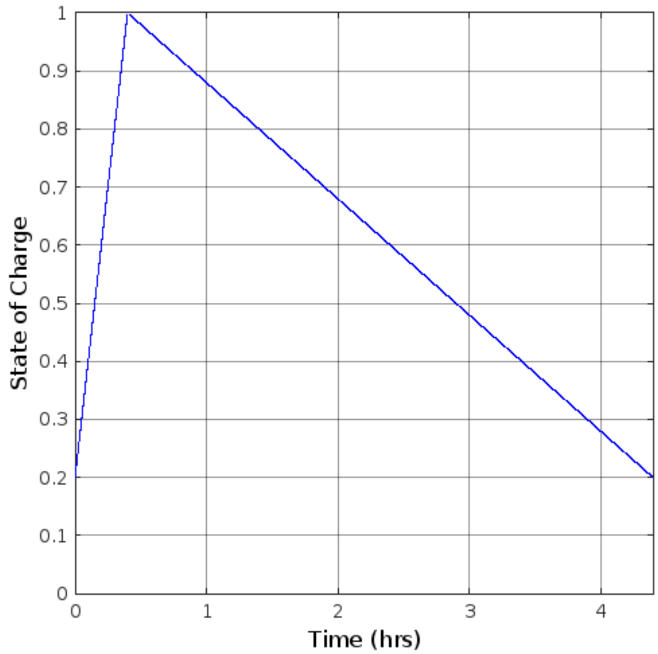


Figure 14: Battery state of charge throughout the fast-charge, slow-discharge schedule. As noted in the caption for Figure 10, each leg is straight due to the constant rate of charge and discharge in the schedule, but in this case the first slope is much steeper because the charge rate is much faster than the discharge rate.

### 3.3 Fast-Charge, Fast-Discharge

The results from simulating the third scenario are summarized in Table 4. As before, we can successfully confirm the conservation of energy by checking that $E_{charge}$ is about equal to $E_{discharge} + E_{loss}$. In this case, we can see that efficiency has taken an even larger hit compared to the first scenario (around 25% worse!) than even the second schedule did. This was expected, as this aggressive charge/discharge schedule requires the battery to take in and output charge at high rates in both directions, leading to large resistive losses.

Table 4: Results from the third schedule (fast/fast).

| Quantity | Symbol | Value | Units |
|---|---|---|---|
| Efficiency | — | 72.32 | % |
| Energy Charged | $E_{charge}$ | 4.076 | kWh |
| Energy Discharged | $E_{discharge}$ | 2.948 | kWh |
| Energy Lost | $E_{loss}$ | 1.143 | kWh |

Plots of the battery's overall voltage $V_{batt}$, output current $I_{batt}$, power output $P_{batt}$, and state of charge are shown in Figures 15, 16, 17, and 18, respectively, with further analysis included in their associated captions.

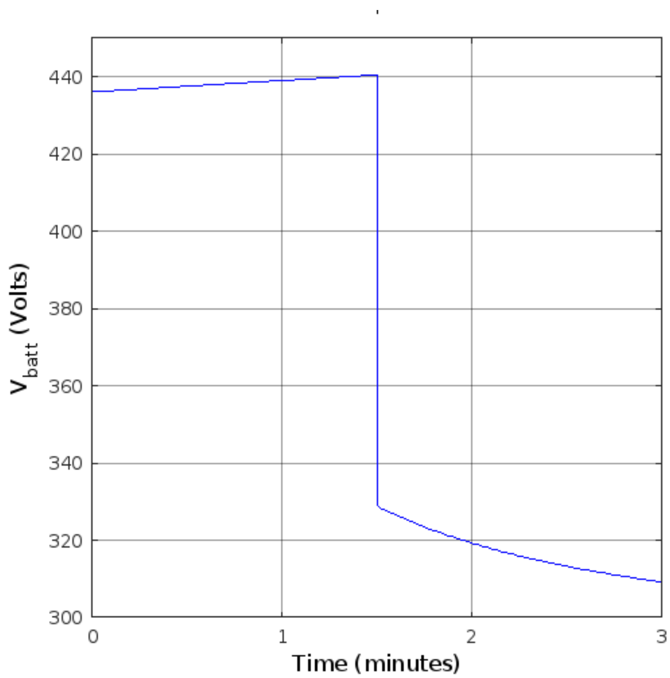


Figure 15: Battery voltage during the fast-charge, fast-discharge schedule. Note how the applied voltage is higher than the maximum cell voltage throughout the entire charging period, just as it was in Figure 11. However, this plot also shows an output voltage lower than the minimum cell voltage during the discharging period: this is because the demanded discharge rate is so much higher than in the other schedules. This is not actually as unrealistic as it may first appear; this droop in voltage is due to trying to draw more power from the battery than it is capable of doing efficiently, so the "apparent" voltage (as seen by the load) is lower than what the battery can output at this SoC when less current is required. A properly designed system would need to ensure that it does not run into brown-out errors during any surges in power draw like this.

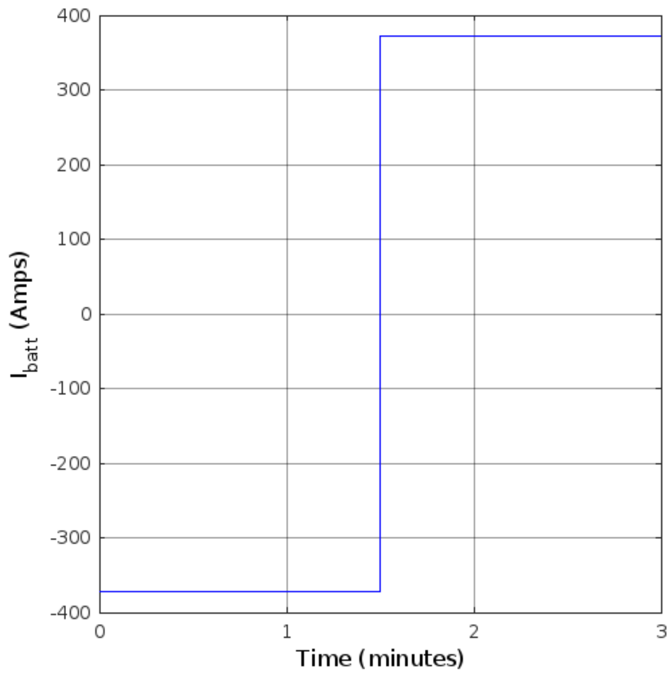


Figure 16: Battery output current during the fast-charge, fast-discharge schedule. Just as in the first scenario, the input and output currents are symmetrical because the charging C-rate is equal to the discharging C-rate in this schedule.

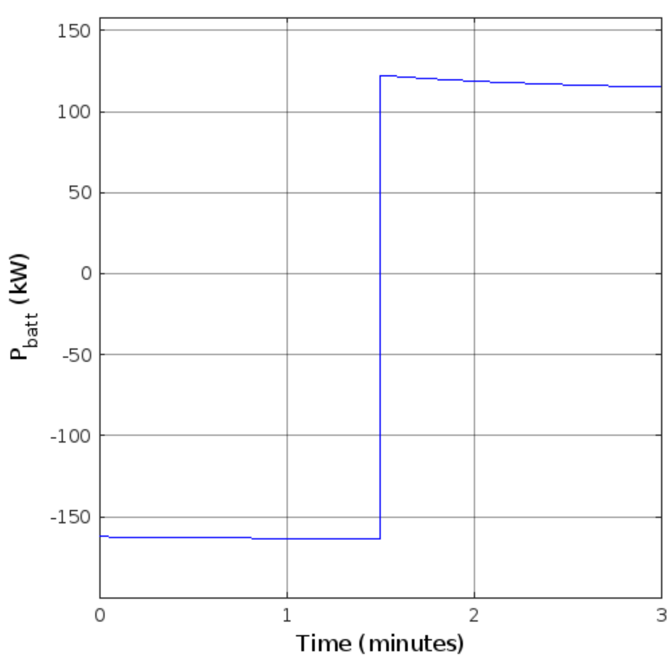


Figure 17: Battery output power during the fast-charge, fast-discharge schedule. Because this schedule only operates within a small range of SoC, the input and output sections of this plot are fairly straight.

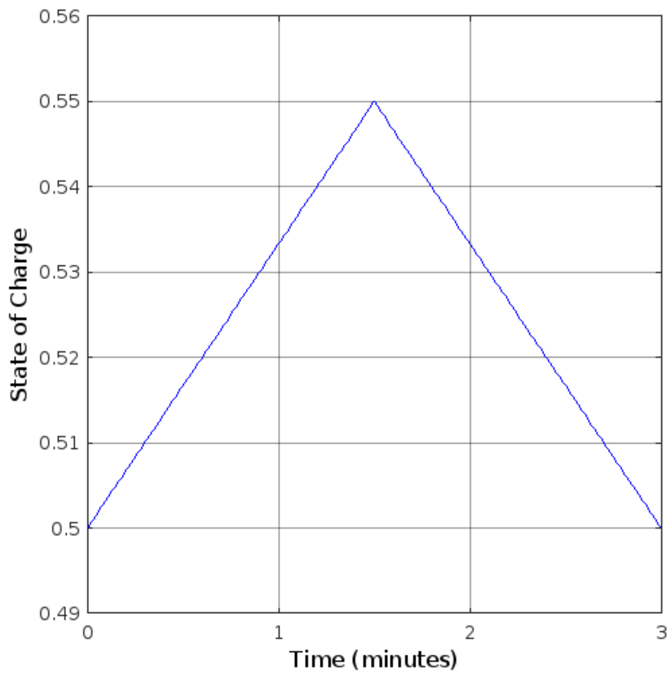


Figure 18: Battery state of charge throughout the fast-charge, fast-discharge schedule. A single charge rate for input energy (2.0) and output energy (-2.0) means that the two legs of the plot are straight and symmetrical.

# 4 Discussion

The results discussed in the previous section all fit within reasonable bounds and lead to conclusions that one would expect of lithium batteries; the tables and figures for each charge/discharge schedule explain the conclusions that one can derive from each measurement and why they are reasonable for this kind of system.

However, for a final set of error checks, one can see if the plotted battery power output matches what should be expected based on the plotted voltage and current. The table below summarizes this verification; the fact that these numbers are nearly equal provides reassurance that the simulation is working properly.

Table 5: A comparison between the value of $P_{batt}$, as estimated by reading Figures 9, 13, 17 (rightmost column), and the value of $P_{batt}$ if calculated by multiplying the values of $V_{batt}$ (as estimated by reading Figures 7, 11, 15) and $I_{batt}$ (as estimated by reading Figures 8, 12, 16) and converting to kilowatts (second to rightmost column). As the two numbers are quite similar for each time point, this verifies that the simulation is calculating power correctly.

| Schedule | Time | $V_{batt}$ (plot) | $I_{batt}$ (plot) | $P_{batt}$ (calculated) | $P_{batt}$ (plot) |
|---|---|---|---|---|---|
| 1 | Charge Start | 368 | -37 | -13.6 | -14 |
| | Charge End | 425 | -37 | -15.7 | -16 |
| | Discharge Start | 412 | 37 | 15.2 | 15 |
| | Discharge End | 355 | 37 | 13.1 | 13 |
| 2 | Charge Start | 430 | -370 | -159 | -160 |
| | Charge End | 485 | -370 | -179 | -175 |
| | Discharge Start | 415 | 37 | 15.3 | 15 |
| | Discharge End | 355 | 37 | 13.1 | 15 |
| 3 | Charge Start | 435 | -370 | -161 | -160 |
| | Charge End | 440 | -370 | -163 | -160 |
| | Discharge Start | 330 | 370 | 122 | 120 |
| | Discharge End | 310 | 370 | 115 | 115 |

# A Appendix

**init.m**

```
% Cell parameters
Capacity = 31; % Ampere-hours
Q_cell = Capacity*3600; % cell capacity in Coulombs

% R0 resistance
R0 = 0.009;

% R1 Resistance
R1 = 0.0015; %Ohms

% C1 Capacitance
C1 = 3.5e4; %Farads

Ns = 100;  % Number of series cells
Np = 6;    % Number of parallel cells

% set simulation conditions
SOC_init = 0.5;
SOC_max = 0.55;
SOC_min = 0.5; % a.k.a. SOC_final; must be <= SOC_init
c_rate_charge = 2.0;
c_rate_discharge = 2.0;
```

## References


Alothman, Maryam. 2023. “ECE 51018 Project 3 Instructions.”

Wiegman, TJ. 2023. “Project 1: Analysis of a Parallel Hybrid Electric Vehicle.”