All-Solid-State Lithium-Ion Battery
**Introduction**

In all-solid-state lithium batteries the electrolyte is a solid-state ionic conductor. The absence of a liquid electrolyte—and hence the lack of need for a liquid container and separator—implies a larger freedom of design as well as certain advantages in terms of safety.

The conductivity of the solid electrolyte is typically several orders of magnitude lower than that of a traditional liquid electrolyte lithium-ion battery. To mitigate this drawback an all-solid-state lithium-ion battery is often fabricated by thin-film methods, with thicknesses in the range of a few micrometers. These thin-film batteries typically do not make use of porous electrodes; all electrochemical reactions instead take place on the interface between the electrolyte and solid electrode domains.

This example models a thin-film all-solid-state lithium battery in one dimension. Various discharge currents are studied, and the different sources of voltage losses are analyzed.

The example is based on a paper by Danilov and others (Ref. 1).

**Model Definition**

The solid electrolyte differs from a binary concentrated liquid electrolyte, and hence this model does not use the Lithium-Ion Battery interface. Instead, it uses the Tertiary Current Distribution interface to model the electrolyte transport and the electrochemical reactions, solving for the electrolyte potential, $\phi_l$ (SI unit: V), the electrolyte concentration of Li ions, $c_{Li^+}$ (SI unit: mol/m$^3$), and the electric potential of the positive electrolyte-electrode interface boundary, $\phi_{s,bnd}$ (SI unit: V).

In addition, the model uses the Transport of Diluted Species interface to model the transport of lithium in the positive electrode, solving for the concentration of solid lithium, $c_{Li}$.
The model geometry, shown in Figure 1, is in one dimension and consists of two domains: the electrolyte and the positive electrode, 1500 nm and 320 nm thick, respectively. The negative electrode is assumed to have high electric conductivity and is not included in the model.

**ELECTROCHEMICAL REACTIONS**

On the negative electrode, lithium metal reacts with lithium ions in the electrolyte according to

\[
\text{Li} \leftrightarrow \text{Li}^+ + e^-
\]

where the reaction kinetics for this reaction is described using a Butler-Volmer expression

\[
i_{\text{neg}} = Fk_{\text{neg}} \left( \frac{c_{\text{Li}^+}}{c_{\text{Li}^+,0}} \right)^{\alpha_{\text{neg}}} \left( e^{(\alpha_{\text{neg}}F\eta)/(RT)} + e^{-(1-\alpha_{\text{neg}})F\eta}/(RT) \right)
\]
Here $F$ (96485 C/mol) is Faraday’s constant, $k_{\text{neg}}$ (SI unit: mol/(m$^2$·s)) is the rate constant of the reaction, $c_{\text{Li}^0,0}$ is the total concentration of lithium in the electrolyte, $\alpha_{\text{neg}}$ is the charge transfer coefficient for the reaction, $R$ (8.3145 J/(mol·K)) is the molar gas constant, and $T$ (SI unit: K) is the temperature.

On the positive electrode the active electrode material reacts according to

$$\text{LiCoO}_2 \leftrightarrow \text{Li}_{1-x}\text{CoO}_2 + \text{Li}^+ + e^-$$

This reaction is also described using Butler-Volmer kinetics

$$i_{\text{pos}} = i_{0,\text{pos}}(e^{(\alpha_{\text{pos}}F\eta)/(RT)} + e^{-(1 - \alpha_{\text{pos}})F\eta)/(RT)})$$

$$i_{0,\text{pos}} = Fk_{\text{pos}}\left(\frac{(c_{\text{Li},\text{max}} - c_{\text{Li},0})c_{\text{Li}^-}}{(c_{\text{Li},\text{max}} - c_{\text{Li},\text{min}})c_{\text{Li}^-},0}\right)^{\alpha_{\text{pos}}} \left(\frac{c_{\text{Li}} - c_{\text{Li},\text{min}}}{c_{\text{Li},\text{max}} - c_{\text{Li},\text{min}}}\right)^{1 - \alpha_{\text{pos}}}$$

where $c_{\text{Li},\text{max}}$ and $c_{\text{Li},\text{min}}$ are the maximum and minimum levels of lithium in the solid electrode, respectively.

The overpotential, $\eta$ (SI unit: V), is generally defined as

$$\eta = \phi_s - \phi_l - E_{\text{eq}}$$

where $\phi_s$ (SI unit: V) is the potential of the electrode (solid) and $E_{\text{eq}}$ (SI unit: V) is the equilibrium potential of the reaction. $E_{\text{eq}}$ is set to 0 for negative electrode. For the positive electrode the equilibrium potential depends on the concentration of lithium in the electrode. Use an interpolation polynomial, based on empirical data, to describe this behavior.

Set the negative electrode to an electric potential of zero volts, and apply a current condition on the positive electrode.

**ELECTROLYTE EQUATIONS**

The electrolyte is a solid-state Li$_3$PO$_4$ electrolyte. The chemical reaction

$$\text{Li}^0 \leftrightarrow \text{Li}^+ + n^-$$

describes the ionization reaction in the electrolyte, where immobile oxygen-bonded lithium (Li$^0$) is transferred to mobile Li$^+$ ions and uncompensated negative charges (n$^-$).

The dissociation rate for this reaction is denoted by $k_d$, and the inverse reaction rate by $k_r$, so that the overall rate for the electrolyte transfer reaction is written as
At equilibrium the fraction of the total amount of lithium that is dissociated, $\delta$, is

$$c_{Li^+}^{eq} = c_n^{eq} = \delta c_0$$

with the result that $k_d$ is related to $k_r$ according to

$$k_d = \frac{k_r c_0 \delta^2}{(1 - \delta)}$$

The transport of $Li^+$ and $n^-$ is described by the Nernst-Planck equation

$$N_i = -D_i \nabla c_i + \frac{z_i F}{RT} D_i \nabla \phi_i$$

where $D_i$ is the species diffusion coefficient and $z_i$ the species charge.

Assume local electroneutrality so that $c_{Li^+} = c_n$ at all times.

Couple the flux on the electrolyte boundaries to the electrochemical reactions using Faraday’s law.

**SOLID LITHIUM TRANSPORT IN THE ELECTRODE**

In the positive electrode, solid lithium is transported by Fick’s law

$$N_{Li} = -D_{Li} \nabla c_{Li}$$

Couple the flux of solid lithium on the electrode-electrolyte boundary to the electrochemical reactions using Faraday’s law.

Set the flux of solid lithium to zero on the right most boundary.

**STUDY**

Solve the model using a time-dependent study, solving for a range of discharge currents.

Use a stop condition to stop the solver process when the concentration of the left most boundary of the electrode exceeds a maximum value.

**Results and Discussion**

Figure 2 shows the electrolyte concentration of $Li^+$ at the last time-step of the solver for various discharge currents. The concentration deviation from the equilibrium concentration at the electrodes is higher for higher discharge currents.
Figure 2: Electrolyte concentration at end of discharge for various discharge rates.

Figure 3 shows the concentration profile of solid lithium in the positive electrode. The concentration gradients get steeper with higher discharge rates.
Figure 3: Concentration profile of solid lithium in the positive electrode at end of discharge for various discharge rates.

A comparison of the discharge curves for the different discharge rates is shown in Figure 4. The position (voltage) of the plateau before depletion is shifted downwards for higher discharge rates. The reason for this are the higher internal losses for higher currents.
Figure 4: Discharge curves (cell voltage vs. time) for various discharge rates.

Figure 5 compares the different voltage losses; the activation overpotentials of the positive and negative electrode reactions, the electrolyte potential drop and the concentration over potential. The concentration overpotential is calculated as:

\[ \eta_{\text{conc}} = E_{eq}(c_{Li}) - \bar{E}_{eq}(\bar{c}_{Li}) \]

where \( \bar{c}_{Li} \) is the average concentration of solid lithium in the positive electrode.

The largest changes are seen in the concentration overpotential. The reason for this is the voltage plateau of the equilibrium potential towards end of discharge, compared to the large initial equilibrium voltage drop for a fully charged battery. The electrolyte voltage drop and overpotential of the positive electrode reaction also undergo changes during the discharge. This is also due to concentration changes in the electrolyte and the positive electrode. The anode overpotential is small throughout the whole simulation.
Figure 5: Comparing different sources of voltage loss during a 51.2 C discharge.

Reference


Application Library path: Batteries_and_Fuel_Cells_Module/Batteries, _General/solid_state_li_battery

Modeling Instructions

From the File menu, choose New.

NEW

In the New window, click Model Wizard.
**MODEL WIZARD**

1. In the **Model Wizard** window, click **1D**.

2. In the **Select Physics** tree, select **Electrochemistry>Tertiary Current Distribution, Nernst-Planck>Tertiary, Electroneutrality**.

3. Click **Add**.

4. In the **Concentrations** table, enter the following settings:

   - \( c_{\text{Li}_\text{ion}} \)
   - \( c_n \)

5. In the **Select Physics** tree, select **Chemical Species Transport>Transport of Diluted Species (tds)**.

6. Click **Add**.

7. In the **Added physics interfaces** tree, select **Transport of Diluted Species (tds)**.

8. In the **Concentrations** table, enter the following settings:

   - \( c_{\text{Li}} \)

9. Click **Study**.

10. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Time Dependent**.

11. Click **Done**.

**GLOBAL DEFINITIONS**

Load the parameters for this model from a text file.

**Parameters**

1. On the **Home** toolbar, click **Parameters**.

2. In the **Settings** window for **Parameters**, locate the **Parameters** section.

3. Click **Load from File**.

4. Browse to the model’s Application Libraries folder and double-click the file **solid_state_li_battery_parameters.txt**.

**GEOMETRY**

Now build the geometry, consisting of two domains, using an interval.

**Interval 1 (i1)**

1. On the **Geometry** toolbar, click **Interval**.
2 In the Settings window for Interval, locate the Interval section.

3 From the Number of intervals list, choose Many.

4 In the Points text field, type $0, L, L+M$.

5 Click Build All Objects.

6 Click the Zoom Extents button on the Graphics toolbar.

**Definitions**

Load the variables for this model from a text file.

*Variables*

1 On the Home toolbar, click Variables and choose Local Variables.

2 In the Settings window for Variables, locate the Variables section.

3 Click Load from File.

4 Browse to the model’s Application Libraries folder and double-click the file *solid_state_li_battery_variables.txt*.

**Materials**

Load the equilibrium potential for the positive electrode from the material library.

**Add Material**

1 On the Home toolbar, click Add Material to open the Add Material window.

2 Go to the Add Material window.

3 In the tree, select Batteries and Fuel Cells>Electrodes>LCO Electrode, LiCoO2 (Positive, Li-ion Battery).

4 Click Add to Component in the window toolbar.

**Materials**

*LCO Electrode, LiCoO2 (Positive, Li-ion Battery) (mat1)*

1 In the Model Builder window, under Component 1 (comp1)>Materials click LCO Electrode, LiCoO2 (Positive, Li-ion Battery) (mat1).

2 In the Settings window for Material, locate the Geometric Entity Selection section.

3 From the Geometric entity level list, choose Boundary.

4 Select Boundary 2 only.

5 On the Home toolbar, click Add Material to close the Add Material window.
TERTIARY CURRENT DISTRIBUTION, NERNST-P HANCK (TCDEE)

Now start setting up the physics for the tertiary current distribution. The current distribution interface is only active in the electrolyte domain.

1. In the Model Builder window, under Component 1 (comp1) click Tertiary Current Distribution, Nernst-Planck (tcdee).
2. In the Settings window for Tertiary Current Distribution, Nernst-Planck, locate the Species section.
3. From the From electroneutrality list, choose \( c_n \).
4. Select Domain 1 only.

Electrolyte 1

1. In the Model Builder window, under Component 1 (comp1)>Tertiary Current Distribution, Nernst-Planck (tcdee) click Electrolyte 1.
2. In the Settings window for Electrolyte, locate the Model Input section.
3. In the \( T \) text field, type \( T \).
4. Locate the Diffusion section. In the \( D_{\text{Li}^+} \) text field, type \( D_{\text{Li}^+} \).
5. In the \( D_{\text{en}} \) text field, type \( D_{\text{en}} \).
6. Locate the Migration in Electric Field section. In the \( z_{\text{Li}^+} \) text field, type 1.
7. In the \( z_{\text{en}} \) text field, type -1.

Reactions 1

1. In the Model Builder window, right-click Tertiary Current Distribution, Nernst-Planck (tcdee) and choose Additional Sources>Reactions.
2. Select Domain 1 only.
3. In the Settings window for Reactions, locate the Reaction Rates section.
4. In the \( R_{\text{Li}^+} \) text field, type \( r_{\text{Li}^+} \).
5. In the \( R_{\text{en}} \) text field, type \( r_{\text{en}} \).

Electrode Surface 1

1. Right-click Tertiary Current Distribution, Nernst-Planck (tcdee) and choose Electrode Surface.
2. Select Boundary 1 only.

Electrode Reaction 1

1. In the Model Builder window, expand the Electrode Surface 1 node, then click Electrode Reaction 1.
In the Settings window for Electrode Reaction, locate the Model Input section.

3 In the $T$ text field, type $T$.

4 Locate the Electrode Kinetics section. From the Kinetics expression type list, choose Butler-Volmer.

5 In the $i_0$ text field, type $i_0\_neg$.

6 In the $\alpha_a$ text field, type $alpha\_neg$.

7 In the $\alpha_c$ text field, type $1\,-\,alpha\_neg$.

8 Locate the Stoichiometric Coefficients section. In the $\nu_{eLiion}$ text field, type $-1$.

Electrode Surface 2

1 In the Model Builder window, right-click Tertiary Current Distribution, Nernst-Planck (tdee) and choose Electrode Surface.

2 Select Boundary 2 only.

3 In the Settings window for Electrode Surface, locate the Boundary Condition section.

4 From the Boundary condition list, choose Average current density.

5 In the $i_{l,\,average}$ text field, type $-i_{\,1C\,*\,C\,rate}$.

6 In the $\phi_{s,\,ext,\,init}$ text field, type $4$.

Electrode Reaction 1

The model uses the equilibrium potential available in the material library. The available total Li concentration ($c_{Eeqref}$) is same as $c_{Li\_max}$.

1 In the Model Builder window, expand the Electrode Surface 2 node, then click Electrode Reaction 1.

2 In the Settings window for Electrode Reaction, locate the Model input section.

3 Click Make All Model Inputs Editable in the upper-right corner of the section. Locate the Model Input section. In the $T$ text field, type $T$.

4 Locate the Equilibrium Potential section. From the $E_{eq}$ list, choose User defined. In the associated text field, type $mat1\,elpot\,Eeq\,int1(c_{Li}/c_{Li\_max})$.

5 Locate the Electrode Kinetics section. From the Kinetics expression type list, choose Butler-Volmer.

6 In the $i_0$ text field, type $i_0\,pos$.

7 In the $\alpha_a$ text field, type $alpha\_pos$.

8 In the $\alpha_c$ text field, type $1\,-\,alpha\_pos$.

9 Locate the Stoichiometric Coefficients section. In the $\nu_{eLiion}$ text field, type $-1$. 
Initial Values 1
1 In the Model Builder window, under Component 1 (comp1)>Tertiary Current Distribution, Nernst-Planck (tcdee) click Initial Values 1.
2 In the Settings window for Initial Values, locate the Initial Values section.
3 In the c_Liion text field, type c_Li_ion_init.

TRANSPORT OF DILUTED SPECIES (TDS)
Now set up the physics for the transport of solid lithium in the electrode.

On the Physics toolbar, click Tertiary Current Distribution, Nernst-Planck (tcdee) and choose Transport of Diluted Species (tds).
1 In the Model Builder window, under Component 1 (comp1) click Transport of Diluted Species (tds).
2 Select Domain 2 only.
3 In the Settings window for Transport of Diluted Species, locate the Transport Mechanisms section.
4 Clear the Convection check box.

Transport Properties 1
1 In the Model Builder window, under Component 1 (comp1) click Transport of Diluted Species (tds).
2 In the Settings window for Transport Properties, locate the Diffusion section.
3 In the DcLi text field, type D_Li.

Electrode Surface Coupling 1
1 In the Model Builder window, right-click Transport of Diluted Species (tds) and choose Electrode Surface Coupling.
2 Select Boundary 2 only.

Reaction Coefficients 1
1 In the Model Builder window, expand the Electrode Surface Coupling 1 node, then click Reaction Coefficients 1.
2 In the Settings window for Reaction Coefficients, locate the Model Inputs section.
3 From the i.loc list, choose Local current density, Electrode Reaction 1 (tcdee/eebii2/er1).
4 Locate the Stoichiometric Coefficients section. In the νcLi text field, type 1.
Initial Values 1
1 In the Model Builder window, under Component 1 (comp1) > Transport of Diluted Species (tds) click Initial Values 1.
2 In the Settings window for Initial Values, locate the Initial Values section.
3 In the \(c_{Li}\) text field, type \(c_{Li\_init}\).

MESH 1
Use a mesh with a finer resolution close to the electrode-electrolyte interface boundaries.

Size 1
1 In the Model Builder window, under Component 1 (comp1) right-click Mesh 1 and choose Size.
2 In the Settings window for Size, locate the Element Size section.
3 From the Predefined list, choose Finer.

Size 2
1 In the Model Builder window, right-click Mesh 1 and choose Size.
2 In the Settings window for Size, locate the Geometric Entity Selection section.
3 From the Geometric entity level list, choose Boundary.
4 Select Boundaries 1 and 2 only.
5 Locate the Element Size section. From the Predefined list, choose Extremely fine.
6 Right-click Mesh 1 and choose Edge.
7 In the Settings window for Mesh, click Build All.

DEFINITIONS
Before solving the model, define integration and average operators to use during postprocessing, and for setting up the stop condition in the study.

Integration 1 (intop1)
1 On the Definitions toolbar, click Component Couplings and choose Integration.
2 In the Settings window for Integration, locate the Source Selection section.
3 From the Geometric entity level list, choose Boundary.
4 Select Boundary 2 only.

Integration 2 (intop2)
1 On the Definitions toolbar, click Component Couplings and choose Integration.
2 In the Settings window for Integration, locate the Source Selection section.
3 From the Geometric entity level list, choose Boundary.

4 Select Boundary 1 only.

Average 1 (aveop1)
1 On the Definitions toolbar, click Component Couplings and choose Average.
2 Select Domain 2 only.

STUDY 1
Use a parametric sweep for solving for a range of discharge currents. Modify the tolerance for the solver and set a stop condition.

Parametric Sweep
1 On the Study toolbar, click Parametric Sweep.
2 In the Settings window for Parametric Sweep, locate the Study Settings section.
3 Click Add.
4 In the table, enter the following settings:

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Parameter value list</th>
<th>Parameter unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_rate</td>
<td>1.6 3.2 6.4 12.8 25.6 51.2</td>
<td></td>
</tr>
</tbody>
</table>

Step 1: Time Dependent
1 In the Model Builder window, under Study 1 click Step 1: Time Dependent.
2 In the Settings window for Time Dependent, locate the Study Settings section.
3 In the Times text field, type 0 3600.
4 From the Tolerance list, choose User controlled.
5 In the Relative tolerance text field, type 1e-4.

Solution 1 (sol1)
1 On the Study toolbar, click Show Default Solver.
2 In the Model Builder window, expand the Solution 1 (sol1) node, then click Time-Dependent Solver 1.
3 In the Settings window for Time-Dependent Solver, click to expand the Output section.
Store all steps taken by the solver to capture the steep voltage drop just before the stop condition triggers the solver to stop.
4 From the Times to store list, choose Steps taken by solver.
5 Right-click Study 1>Solver Configurations>Solution 1 (sol1)>Time-Dependent Solver 1 and choose Stop Condition.
6 In the Settings window for Stop Condition, locate the Stop Expressions section.

7 Click Add.

8 In the table, enter the following settings:

<table>
<thead>
<tr>
<th>Stop expression</th>
<th>Stop if</th>
<th>Active</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>comp1.intop1(comp1.c_Li)/c_Li_max&gt;0.999</td>
<td>true</td>
<td>✓</td>
<td>Stop expression 1</td>
</tr>
</tbody>
</table>

Specify that the solution is to be stored both before and after the stop condition is reached.

9 Locate the Output at Stop section. From the Add solution list, choose Steps before and after stop.

10 Clear the Add warning check box.

11 On the Study toolbar, click Compute.

RESULTS
The following steps reproduce the figures in the Results and Discussion section of the model documentation.

Boundary Electrode Potential vs Ground (tcdee)
1 In the Model Builder window, under Results click Boundary Electrode Potential vs Ground (tcdee).

2 In the Settings window for 1D Plot Group, type Discharge Curves in the Label text field.

3 Click to expand the Title section. From the Title type list, choose Manual.

4 In the Title text area, type Cell voltage.

5 Locate the Axis section. Select the Manual axis limits check box.

6 In the x minimum text field, type 0.

7 In the x maximum text field, type 2500.

8 In the y minimum text field, type 3.7.

9 In the y maximum text field, type 4.2.

10 On the Discharge Curves toolbar, click Plot.

Concentration (tcdee)
1 In the Model Builder window, under Results click Concentration (tcdee).

2 In the Settings window for 1D Plot Group, locate the Data section.
From the Time selection list, choose Last.

**Line Graph 1**
1. In the Model Builder window, expand the Concentration (tcdee) node, then click Line Graph 1.
2. In the Settings window for Line Graph, click to expand the Legends section.
3. Select the Show legends check box.
4. From the Legends list, choose Manual.
5. In the table, enter the following settings:

<table>
<thead>
<tr>
<th>Legend</th>
<th>C_rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_rate=1.6</td>
<td></td>
</tr>
<tr>
<td>C_rate=3.2</td>
<td></td>
</tr>
<tr>
<td>C_rate=6.4</td>
<td></td>
</tr>
<tr>
<td>C_rate=12.8</td>
<td></td>
</tr>
<tr>
<td>C_rate=25.6</td>
<td></td>
</tr>
<tr>
<td>C_rate=51.2</td>
<td></td>
</tr>
</tbody>
</table>

6. On the Concentration (tcdee) toolbar, click Plot.

**Concentration (tds)**
1. In the Model Builder window, under Results click Concentration (tds).
2. In the Settings window for ID Plot Group, locate the Data section.
3. From the Time selection list, choose Last.
4. Click to expand the Legend section. From the Position list, choose Lower left.

**Line Graph**
1. In the Model Builder window, expand the Concentration (tds) node, then click Line Graph.
2. In the Settings window for Line Graph, locate the Legends section.
3. Select the Show legends check box.
4. From the Legends list, choose Manual.
5. In the table, enter the following settings:

<table>
<thead>
<tr>
<th>Legend</th>
<th>C_rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_rate=1.6</td>
<td></td>
</tr>
<tr>
<td>C_rate=3.2</td>
<td></td>
</tr>
<tr>
<td>C_rate=6.4</td>
<td></td>
</tr>
</tbody>
</table>
On the **Concentration (tds)** toolbar, click **Plot**.

**1D Plot Group 5**

1. On the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.
2. In the **Settings** window for **1D Plot Group**, click to expand the **Title** section.
3. From the **Title type** list, choose **Manual**.
4. In the **Title** text area, type **Voltage losses comparison**.
5. Locate the **Plot Settings** section. Select the **x-axis label** check box.
6. In the associated text field, type **Time (s)**.
7. Select the **y-axis label** check box.
8. In the associated text field, type **Voltage (V)**.
9. Click to expand the **Axis** section. Select the **Manual axis limits** check box.
10. In the **x minimum** text field, type **0**.
11. In the **x maximum** text field, type **50**.
12. In the **y maximum** text field, type **0.02**.
13. In the **y minimum** text field, type **-0.3**.
14. Locate the **Legend** section. From the **Position** list, choose **Lower left**.

**Global 1**

1. Right-click **1D Plot Group 5** and choose **Global**.
2. In the **Settings** window for **Global**, locate the **y-Axis Data** section.
3. In the table, enter the following settings:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>intop1(tcdee.Eeq_er1)-comp1.mat1.elpot.Eeq_int1(av eop1(c_Li)/c_Li_max)</td>
<td></td>
<td>Concentration overpotential</td>
</tr>
</tbody>
</table>

**Global 2**

1. In the **Model Builder** window, under **Results** right-click **1D Plot Group 5** and choose **Global**.
2. In the **Settings** window for **Global**, locate the **y-Axis Data** section.
3 In the table, enter the following settings:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>intop1(tcdee.eta_er1)</td>
<td>V</td>
<td>Charge transfer overpotential, positive electrode</td>
</tr>
</tbody>
</table>

**Global 3**

1 Right-click **1D Plot Group 5** and choose **Global**.
2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.
3 In the table, enter the following settings:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>intop1(phil)-intop2(phil)</td>
<td>V</td>
<td>Electrolyte potential drop</td>
</tr>
</tbody>
</table>

**Global 4**

1 Right-click **1D Plot Group 5** and choose **Global**.
2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.
3 In the table, enter the following settings:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>intop2(tcdee.eta_er1)</td>
<td>V</td>
<td>Charge transfer overpotential, negative electrode</td>
</tr>
</tbody>
</table>

**1D Plot Group 5**

1 In the **Model Builder** window, under **Results** click **1D Plot Group 5**.
2 In the **Settings** window for **1D Plot Group**, locate the **Axis** section.
3 Select the **Manual axis limits** check box.
4 In the **x minimum** text field, type 0.
5 In the **x maximum** text field, type 50.
6 In the **y minimum** text field, type -0.3.
7 In the **y maximum** text field, type 0.02.
8 On the **1D Plot Group 5** toolbar, click **Plot**.
9 In the **Model Builder** window, right-click **1D Plot Group 5** and choose **Rename**.
10 In the **Rename 1D Plot Group** dialog box, type **Comparison of voltage losses** in the **New label** text field.
11 Click **OK**.