



Model created in COMSOL Multiphysics 6.4

Power Losses in a Lithium-Ion Battery

Introduction

This tutorial analyzes the power losses in a lithium-ion battery during a Hybrid Pulse Power Characterization (HPPC) test. The model is a continuation of the [Lithium-Ion Battery Rate Capability](#) tutorial, where the total discharge energy was compared between an energy-optimized and a power-optimized battery.

Many physical battery properties affect the polarization and rate capability of a battery cell, for instance:

- the thicknesses of the electrodes and separator layers,
- the porosity of the electrodes and separator layers,
- the active material particle size in the electrodes,
- the choice of active electrode material,
- other material choices, for example, the electrolyte and electronic conductor, and
- the degree of lithiation of the electrode material due to several material properties being dependent on the intercalation state.

The power losses can typically be decreased by using thinner separator and electrode layers, higher porosities, and smaller active material particles. However, minimizing the power losses often results in a decreased capacity of the battery, since when using thinner or more porous electrodes, the relative amount of active electrode material in the cell decreases.

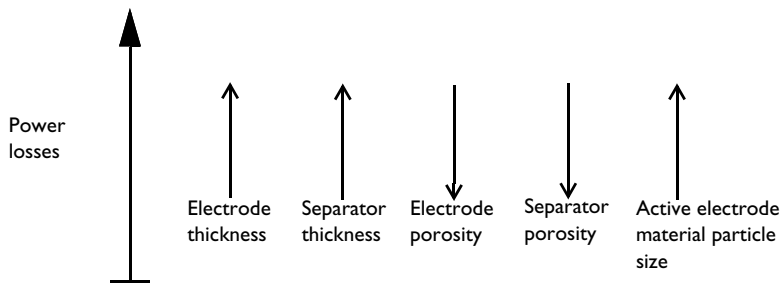


Figure 1: Selection of design parameters in a cell and their relation to power losses. Upward pointing arrows indicate increase, downward pointing decrease. For example, the power capability of a cell decreases with decreased porosity and increased particle size.

The choice of active materials is important as well. Some materials are able to transport intercalated lithium efficiently even at high current loads. Additionally, the electrolyte is also important; for example, polymer batteries are seldom used in high-power applications since these contain a nonliquid electrolyte with poor lithium-ion transport properties.

Model Definition

The model is set up in 1D for a graphite/NMC battery cell. A more detailed description of the model can be found in [Lithium-Ion Battery Base Model in 1D](#).

This tutorial investigates the power losses in a battery subjected to a 10 A discharge pulse for 10 s, followed by a 20 s rest, followed by a 10 A charge for 10 s. The losses are analyzed both for an energy-optimized and a power-optimized cell, featuring positive-electrode thicknesses of 60 μm and 25 μm , respectively. The battery model is parameterized in such a way that when changing the positive-electrode thickness parameter, the negative-electrode layer thicknesses change correspondingly, as discussed in [Lithium-Ion Battery Base Model in 1D](#). Both cells are assumed to fit into a 21700 canister of fixed volume, which means the active cell area, A_{cell} , varies with the thickness parameter; again, see [Lithium-Ion Battery Base Model in 1D](#).

A Load Cycle node is used to define a load cycle comprising a 10 A charge for 10 s, followed by a 20 s rest, followed by a 10 A discharge for 10 s. The initial state of charge is 50 s.

COMPUTING POWER LOSSES

The Lithium-Ion Battery interface automatically defines various power loss variables. These are derived locally in the model geometry from physical gradients and interfacial changes in the Gibbs free energy of the transported and reacting species (ions, intercalated lithium, and electrons) in the cell.

As an example, the local power loss due to electron conduction in a domain, $p_{\text{loss},s}$ (W/m^3) is defined as

$$p_{\text{loss},s} = -\nabla\phi_s \cdot \mathbf{i}_s \quad (1)$$

where \mathbf{i}_s is the electronic current vector (A/m^2) and ϕ_s the electrode phase potential (V).

In addition to the current-conduction power loss defined above, power loss variables are also computed for:

- Electrolyte transport — the power losses associated with ion transport
- Kinetic activation — the power losses associated with the charge transfer processes occurring at the electrode surfaces
- Particle intercalation — the power losses associated with diffusion of intercalated (atomic) lithium in the solid electrode particles

How these are computed is documented in the theory chapter for the Lithium-Ion Battery interface. It should be noted that the power loss variables may sometimes be identical to the heat source variables (also computed automatically by the interface), but are generally not the same, since the heat source variables consider changes in enthalpy rather than the Gibbs free energy.

The interface also defines integrated power loss variables, which for this 1D example is computed as

$$P_{\text{loss}, s} = \int -\nabla\phi_s \cdot \mathbf{i}_s A_{\text{cell}} \partial\Omega \quad (2)$$

for the total electron conduction loss.

Integrated total loss variables per model tree feature node (**Porous Electrode**, **Separator**, and so on) are also available.

Results and Discussion

[Figure 2](#) shows the cell voltage and corresponding C-rates for the two cell configurations. The C-rates are slightly higher for the power-optimized (positive electrode thickness of 25 μm) battery compared to the energy-optimized (positive electrode thickness of 60 μm) battery. The reason for this is that the total current and volume are fixed, in combination with the energy-optimized battery having a higher capacity. The polarization (voltage

deviation from the rest voltage) is however still higher for the energy-optimized cell, despite the slightly lower C-rate.

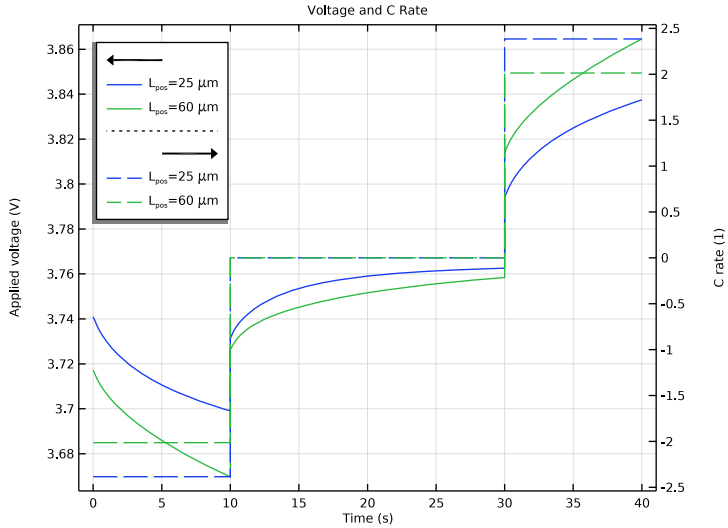


Figure 2: Cell voltage and current C-rates versus time.

Figure 3 shows the local power losses in the energy-optimized cell (left) and the power-optimized cell (right) at 1 s (top) and 9 s (bottom) into the discharge pulse, whereas Figure 4 shows the corresponding power losses integrated over the whole cell during the course of the whole simulation. The power losses stemming from electron conduction are fairly small and both the distribution and magnitude of the losses stays more or less constant during each pulse. The kinetic activation losses also stay fairly constant during each pulse. When it comes the electrolyte transport and particle intercalation losses, however, these increase significantly during each pulse. This is related to the buildup of concentration gradients during each pulse. During the rest period (between $t = 10$ s and 30 s in Figure 4), the electrode and activation losses are close to zero, whereas the electrolyte and particle intercalation losses show a slow relaxation behavior as the concentration gradients get reduced. The power losses are generally higher for the energy-optimized cell, with the electrolyte transport-related losses being the main contributor, when integrated over all domains.

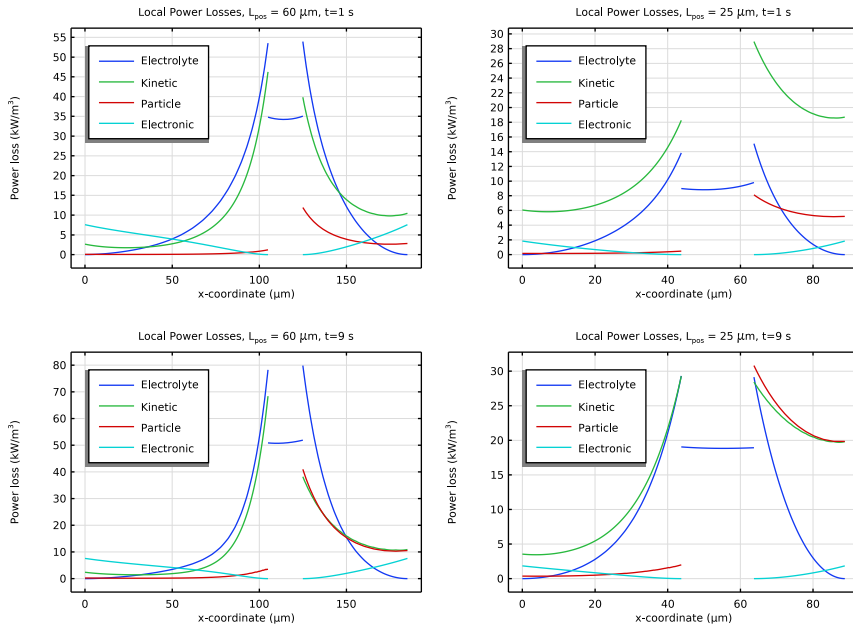


Figure 3: Local power losses stemming from electrolyte transport (blue lines), kinetic activation (green lines), particle intercalation transport (red lines) and electron conduction in the electrodes (cyan lines) in the energy-optimized cell (left) and the power-optimized cell (right) at 1 s (top) and 9 s (bottom) into the discharge pulse.

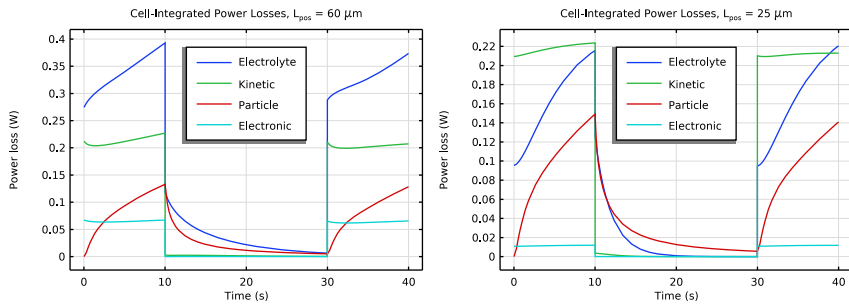


Figure 4: Cell-integrated power losses in the energy-optimized (left) and the power-optimized cell (right).

Figure 5 shows the power losses integrated separately over the negative electrode, the separator and the positive electrode. For this model, the power loss contributions from the two electrodes are dominating over the separator.

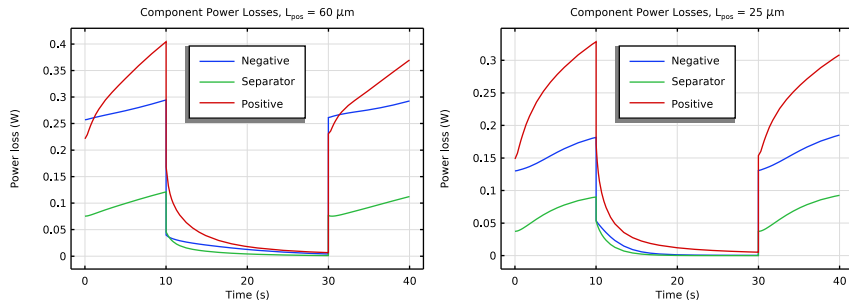


Figure 5: Power losses integrated per component; the negative electrode (blue lines), the separator (green lines) and the porous electrode (red lines) domains in the energy-optimized (left) and the power-optimized cell (right).

Finally, Figure 6 compares the total sum of all power losses for the energy and power-optimized cases.

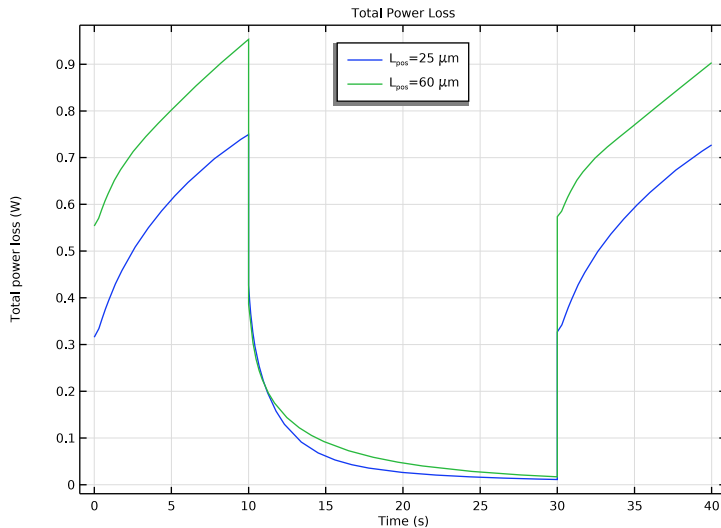


Figure 6: Total power losses for the energy optimized (green line) and the power optimized (blue line) cell.


Reference

I. A. Nyman, T.G. Zavalis, R. Elger, M. Behm, and G. Lindbergh, “Analysis of the Polarization in Li-Ion Battery Cell by Numerical Simulations,” *J. Electrochem. Soc.*, vol. 157, no. 11, pp. A1236–A1246, 2010.

Application Library path: Battery_Design_Module/Lithium-Ion_Batteries, _Performance/lib_power_losses

Modeling Instructions

APPLICATION LIBRARIES

- 1 From the **File** menu, choose **Application Libraries**.
- 2 In the **Application Libraries** window, select **Battery Design Module > Lithium-Ion Batteries, Performance > lib_base_model_Id** in the tree.
- 3 Click  **Open**.

In this tutorial we will perform an HPPC (hybrid pulse power characterization) test on the battery model you just loaded. The combined discharge–rest–charge load profile will be applied at 50% state of charge.

GLOBAL DEFINITIONS



Parameters I

- 1 In the **Model Builder** window, under **Global Definitions** click **Parameters I**.
- 2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
- 3 In the table, enter the following settings:

Name	Expression	Value	Description
soc_init	50[%]	0.5	Initial SOC

Parameters - Pulse

Add a second group of parameters from a text file.

- 1 In the **Home** toolbar, click  **Parameters** and choose **Add > Parameters**.
- 2 In the **Settings** window for **Parameters**, type Parameters - Pulse in the **Label** text field.
- 3 Locate the **Parameters** section. Click  **Load from File**.

- 4 Browse to the model's Application Libraries folder and double-click the file `lib_power_losses_parameters.txt`.

LITHIUM-ION BATTERY (LIION)


Load Cycle 1

- 1 In the **Model Builder** window, expand the **Component 1 (comp1) > Lithium-Ion Battery (liion)** node, then click **Load Cycle 1**.
- 2 In the **Settings** window for **Load Cycle**, locate the **Continuation Conditions** section.
- 3 Select the **Use elapsed time only** checkbox.

C Rate 1

- 1 In the **Model Builder** window, expand the **Load Cycle 1** node.
- 2 Right-click **C Rate 1** and choose **Delete**.

Current 1


- 1 In the **Physics** toolbar, click  **Attributes** and choose **Current**.
- 2 In the **Settings** window for **Current**, locate the **Current** section.
- 3 In the I_{set} text field, type `-I_pulse`.
- 4 Locate the **Continuation Conditions** section. Select the **Elapsed time** checkbox.
- 5 In the t_{max} text field, type `t_pulse`.

LITHIUM-ION BATTERY (LIION)

Load Cycle 1

In the **Model Builder** window, expand the **Component 1 (comp1) > Definitions** node, then click **Component 1 (comp1) > Lithium-Ion Battery (liion) > Load Cycle 1**.

Rest 1

- 1 In the **Physics** toolbar, click  **Attributes** and choose **Rest**.
- 2 In the **Settings** window for **Rest**, locate the **Continuation Conditions** section.
- 3 In the t_{max} text field, type `t_rest`.

Load Cycle 1

In the **Model Builder** window, click **Load Cycle 1**.

Current 2

- 1 In the **Physics** toolbar, click  **Attributes** and choose **Current**.
- 2 In the **Settings** window for **Current**, locate the **Current** section.

3 In the I_{set} text field, type `I_pulse`.

Porous Electrode - Negative

Proceed as follows to enable computation of the intercalation power losses in the electrode particles:

Particle Intercalation 1

- 1 In the **Model Builder** window, expand the **Component 1 (comp1) > Lithium-Ion Battery (liion) > Porous Electrode - Negative** node, then click **Particle Intercalation 1**.
- 2 In the **Settings** window for **Particle Intercalation**, locate the **Material** section.
- 3 From the **Particle material** list, choose **Graphite, LixC6 MCMB (Negative, Li-ion Battery) (mat2)**.
- 4 Click to expand the **Heat of Mixing and Power Losses** section. Select the **Define particle-resolved heat of mixing and power losses** checkbox.

Particle Intercalation 1

- 1 In the **Model Builder** window, expand the **Porous Electrode - Positive** node, then click **Particle Intercalation 1**.
- 2 In the **Settings** window for **Particle Intercalation**, locate the **Material** section.
- 3 From the **Particle material** list, choose **NMC 111, LiNi0.33Mn0.33Co0.33O2 (Positive, Li-ion Battery) (mat3)**.
- 4 Locate the **Heat of Mixing and Power Losses** section. Select the **Define particle-resolved heat of mixing and power losses** checkbox.

STUDY 1

Step 2: Time Dependent



Specify the initial and final time of the simulation in the times list.

- 1 In the **Model Builder** window, expand the **Study 1** node, then click **Step 2: Time Dependent**.
- 2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.
- 3 From the **Time unit** list, choose **s**.
- 4 In the **Output times** text field, type `0 2*t_pulse+t_rest`.

Parametric Sweep

Add a parametric sweep varying the positive electrode thickness parameter. This will perform the HPPC simulation both for a power optimized and an energy-optimized



battery. When varying the L_pos parameter, the negative electrode thickness is automatically updated based on the correlation defined in the **Parameters 1** node.

- 1 In 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:

Parameter name	Parameter value list	Parameter unit
L_pos (Positive electrode thickness)	25 60	um


Solution 1 (sol1)

Enable to store all steps taken by the time-dependent solver. This will produce smooth plots when visualizing the results.

- 1 In 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**, locate the **General** section.
- 4 From the **Times to store** list, choose **Steps taken by solver**.
- 5 In the **Study** toolbar, click  **Compute**.

RESULTS

Voltage and C Rate

- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type Voltage and C Rate in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol3)**.
- 4 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

Global 1

- 1 Right-click **Voltage and C Rate** and choose **Global**.
- 2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1) > Lithium-Ion Battery > Load Cycle 1 > liion.lci.E_app - Applied voltage - V**.

- 3 Click to expand the **Legends** section. Find the **Include** subsection. Clear the **Description** checkbox.
- 4 Find the **Prefix and suffix** subsection. In the **Prefix** text field, type V_{oltage} , .
- 5 Click to expand the **Legends** section. From the **Legends** list, choose **Manual**.
- 6 In the table, enter the following settings:

Legends
L _{pos} =25 μm
L _{pos} =60 μm

Global 2

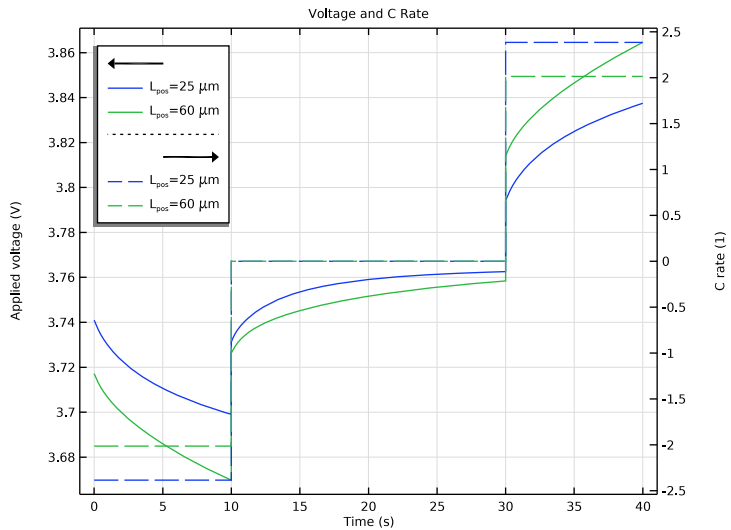
- 1 In the **Model Builder** window, right-click **Voltage and C Rate** and choose **Global**.
- 2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1) > Lithium-Ion Battery > Load Cycle 1 > liion.lci.C_app - C rate - 1**.
- 3 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Cycle (reset)**.
- 4 Find the **Line style** subsection. From the **Line** list, choose **Dashed**.
- 5 Locate the **Legends** section. Find the **Include** subsection. Clear the **Description** checkbox.
- 6 Find the **Prefix and suffix** subsection. In the **Prefix** text field, type C_{rate} , .
- 7 From the **Legends** list, choose **Manual**.
- 8 In the table, enter the following settings:

Legends
L _{pos} =25 μm
L _{pos} =60 μm

Voltage and C Rate

- 1 In the **Model Builder** window, click **Voltage and C Rate**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Plot Settings** section.
- 3 Select the **Two y-axes** checkbox.
- 4 In the table, select the **Plot on secondary y-axis** checkbox for **Global 2**.
- 5 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

6 In the **Voltage and C Rate** toolbar, click  **Plot**.



Local Power Losses


1 In the **Home** toolbar, click  **Add Plot Group** and choose **ID Plot Group**.

Create a plot of the local power losses as follows:


- 2 In the **Settings** window for **ID Plot Group**, type Local Power Losses in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol3)**.
- 4 From the **Parameter selection (L_pos)** list, choose **From list**.
- 5 In the **Parameter values (L_pos (um))** list box, select **25**.
- 6 From the **Time selection** list, choose **Interpolated**.
- 7 In the **Times (s)** text field, type 1.
- 8 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.
- 9 In the **Title** text area, type Local Power Losses, $L_{\text{pos}} = \text{eval}(L_{\text{pos}} \cdot 1e6) \text{ } \mu\text{m}$, $t = \text{eval}(t) \text{ s}$.

Line Graph 1


- 1 Right-click **Local Power Losses** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **Selection** section.
- 3 From the **Selection** list, choose **All domains**.

- 4 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component I (compI) > Lithium-Ion Battery > Power losses > liion.p_loss_l - Electrolyte transport power loss - W/m³**.
- 5 Locate the **y-Axis Data** section. From the **Unit** list, choose **kW/m³**.
- 6 Select the **Description** checkbox. In the associated text field, type **Electrolyte**.
- 7 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 8 In the **Expression** text field, type **x**.
- 9 From the **Unit** list, choose **μm**.
- 10 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 11 Find the **Include** subsection. Clear the **Solution** checkbox.
- 12 Select the **Description** checkbox.
- 13 In the **Local Power Losses** toolbar, click  **Plot**.

Line Graph 2

- 1 Right-click **Line Graph 1** and choose **Duplicate**.
- 2 In the **Settings** window for **Line Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component I (compI) > Lithium-Ion Battery > Power losses > liion.p_loss_act - Kinetic activation power loss - W/m³**.
- 3 Locate the **y-Axis Data** section. In the **Description** text field, type **Kinetic**.
- 4 In the **Local Power Losses** toolbar, click  **Plot**.

Line Graph 3

- 1 Right-click **Line Graph 2** and choose **Duplicate**.
- 2 In the **Settings** window for **Line Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component I (compI) > Lithium-Ion Battery > Power losses > liion.p_loss_inter - Particle intercalation transport power loss - W/m³**.
- 3 Locate the **y-Axis Data** section. In the **Description** text field, type **Particle**.
- 4 In the **Local Power Losses** toolbar, click  **Plot**.

Line Graph 4

- 1 Right-click **Line Graph 3** and choose **Duplicate**.
- 2 In the **Settings** window for **Line Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component I (compI) > Lithium-Ion Battery > Power losses > liion.p_loss_s - Electron conduction power loss - W/m³**.
- 3 Locate the **y-Axis Data** section. In the **Description** text field, type **Electronic**.

4 In the **Local Power Losses** toolbar, click  **Plot**.

Local Power Losses

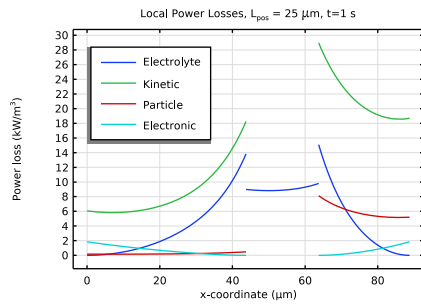
1 In the **Model Builder** window, click **Local Power Losses**.

2 In the **Settings** window for **ID Plot Group**, locate the **Plot Settings** section.

3 Select the **y-axis label** checkbox. In the associated text field, type Power loss (kW/m³).

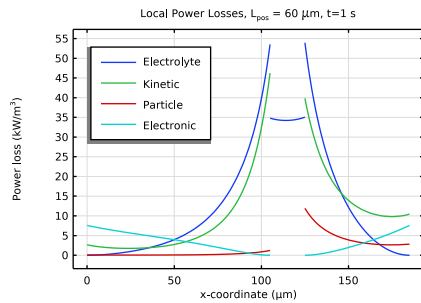
4 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

5 In the **Local Power Losses** toolbar, click  **Plot**.



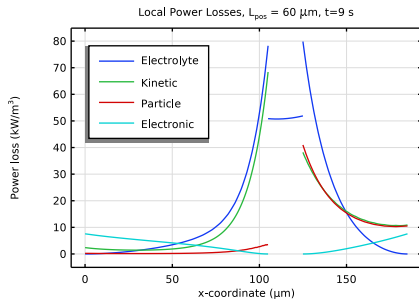
6 Locate the **Data** section. In the **Parameter values (L_pos (um))** list box, select **60**.

7 In the **Local Power Losses** toolbar, click  **Plot**.



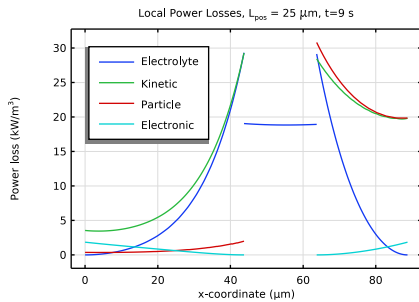
8 In the **Times (s)** text field, type 9.

9 In the **Local Power Losses** toolbar, click  **Plot**.




10 In the **Parameter values (L_pos (um))** list box, select **25**.

11 In the **Local Power Losses** toolbar, click  **Plot**.



Cell-Integrated Power Losses

There are also corresponding predefined variables available that are integrated for all domains. To plot these cell-integrated variables, proceed as follows:

- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type Cell-Integrated Power Losses in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol3)**.
- 4 From the **Parameter selection (L_pos)** list, choose **From list**.
- 5 In the **Parameter values (L_pos (um))** list box, select **25**.
- 6 Locate the **Title** section. From the **Title type** list, choose **Manual**.
- 7 In the **Title** text area, type Cell-Integrated Power Losses, L_{pos} = `eval(L_pos*1e6) \mu m`.

Global 1

- 1 Right-click **Cell-Integrated Power Losses** and choose **Global**.
- 2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1) > Lithium-Ion Battery > Power losses > Cell integrated > liion.P_loss_1 - Electrolyte transport power loss - W**.
- 3 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
liion.P_loss_1	W	Electrolyte

- 4 Click to expand the **Legends** section. Find the **Include** subsection. Clear the **Solution** checkbox.

Global 2

- 1 Right-click **Global 1** and choose **Duplicate**.
- 2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1) > Lithium-Ion Battery > Power losses > Cell integrated > liion.P_loss_act - Kinetic activation power loss - W**.
- 3 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
liion.P_loss_act	W	Kinetic

- 4 In the **Cell-Integrated Power Losses** toolbar, click  **Plot**.


Global 3

- 1 Right-click **Global 2** and choose **Duplicate**.
- 2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1) > Lithium-Ion Battery > Power losses > Cell integrated > liion.P_loss_inter - Particle intercalation transport power loss - W**.
- 3 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
liion.P_loss_inter	W	Particle


- 4 In the **Cell-Integrated Power Losses** toolbar, click  **Plot**.

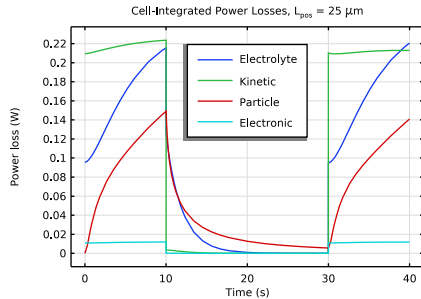
Global 4

- 1 Right-click **Global 3** and choose **Duplicate**.
- 2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1) > Lithium-Ion Battery > Power losses > Cell integrated > liion.P_loss_s - Electron conduction power loss - W**.
- 3 In the **Cell-Integrated Power Losses** toolbar, click  **Plot**.
- 4 Locate the **y-Axis Data** section. In the table, enter the following settings:

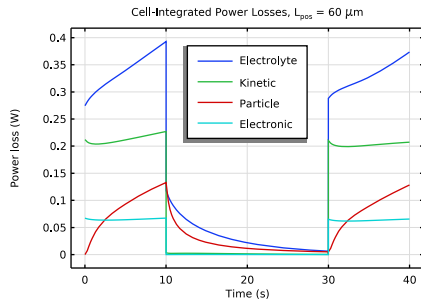
Expression	Unit	Description
liion.P_loss_s	W	Electronic

Cell-Integrated Power Losses


- 1 In the **Model Builder** window, click **Cell-Integrated Power Losses**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Plot Settings** section.
- 3 Select the **y-axis label** checkbox. In the associated text field, type **Power loss (W)**.
- 4 Locate the **Legend** section. From the **Position** list, choose **Upper middle**.
- 5 In the **Cell-Integrated Power Losses** toolbar, click  **Plot**.



- 6 Locate the **Data** section. In the **Parameter values (L_pos (um))** list box, select **60**.



Component Power Losses

- 1 In the **Results** toolbar, click  **ID Plot Group**.

Furthermore, there are integrated variables for the total losses of each domain node that you plot as follows:

- 2 In the **Settings** window for **ID Plot Group**, type **Component Power Losses** in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol3)**.
- 4 From the **Parameter selection (L_pos)** list, choose **From list**.
- 5 In the **Parameter values (L_pos (um))** list box, select **25**.
- 6 Locate the **Title** section. From the **Title type** list, choose **Manual**.
- 7 In the **Title** text area, type **Component Power Losses, L_{pos} = eval(L_pos*1e6) \mu m**.

Global 1

- 1 Right-click **Component Power Losses** and choose **Global**.
- 2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1) > Lithium-Ion Battery > Power losses > Feature-node integrated > liion.pcel.P_loss - Total power loss - W**.
- 3 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 4 From the **Legends** list, choose **Manual**.

5 In the table, enter the following settings:

Legends
Negative

Global 2

- 1 In the **Model Builder** window, right-click **Component Power Losses** and choose **Global**.
- 2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1) > Lithium-Ion Battery > Power losses > Feature-node integrated > liion.sep1.P_loss - Total power loss - W**.
- 3 Locate the **Legends** section. Select the **Show legends** checkbox.
- 4 From the **Legends** list, choose **Manual**.
- 5 In the table, enter the following settings:

Legends
Separator

- 6 In the **Component Power Losses** toolbar, click  **Plot**.

Global 3

- 1 Right-click **Component Power Losses** and choose **Global**.
- 2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1) > Lithium-Ion Battery > Power losses > Feature-node integrated > liion.pce2.P_loss - Total power loss - W**.
- 3 Locate the **Legends** section. From the **Legends** list, choose **Manual**.
- 4 In the table, enter the following settings:

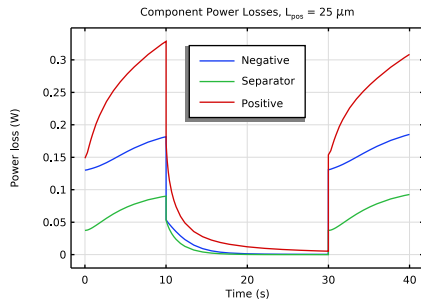
Legends
Positive

- 5 Select the **Show legends** checkbox.

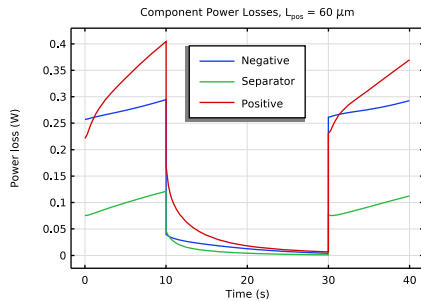
Component Power Losses

- 1 In the **Model Builder** window, click **Component Power Losses**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Plot Settings** section.
- 3 Select the **y-axis label** checkbox. In the associated text field, type **Power loss (W)**.
- 4 Locate the **Legend** section. From the **Position** list, choose **Upper middle**.


- 5 In the **Component Power Losses** toolbar, click  **Plot**.



- 6 Locate the **Data** section. In the **Parameter values (L_pos (um))** list box, select **60**.



Total Power Loss

- 1 In the **Results** toolbar, click  **ID Plot Group**.

Finally, plot the total of all power losses.

- 2 In the **Settings** window for **ID Plot Group**, type Total Power Loss in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol3)**.
- 4 Locate the **Title** section. From the **Title type** list, choose **Label**.

Global 1

- 1 Right-click **Total Power Loss** and choose **Global**.
- 2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1) > Lithium-Ion Battery > Power losses > Cell integrated > liion.P_loss - Total power loss - W**.
- 3 Locate the **Legends** section. Find the **Include** subsection. Clear the **Description** checkbox.


- 4 From the **Legends** list, choose **Manual**.
- 5 In the table, enter the following settings:

Legends

$L_{\text{pos}}=25 \text{ } \mu\text{m}$

$L_{\text{pos}}=60 \text{ } \mu\text{m}$

Total Power Loss

- 1 In the **Model Builder** window, click **Total Power Loss**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Legend** section.
- 3 From the **Position** list, choose **Upper middle**.
- 4 In the **Total Power Loss** toolbar, click  **Plot**.

