



Going Beyond the Electrical in Modeling Energy Storage Systems

Tom Grimble

Senior Application Engineer
Modeling and Simulation
MathWorks
tgrimble@mathworks.com



Key Takeaways

- Energy Storage can extend far beyond just electrical modeling
- Critical to simulate real world power storage challenges
- Use MATLAB & Simulink to accelerate problem solving throughout the design cycle



Growth in Grid Connected Energy Storage

The way we generate energy is changing



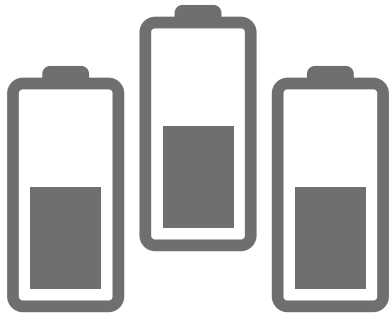
The way we use energy is changing



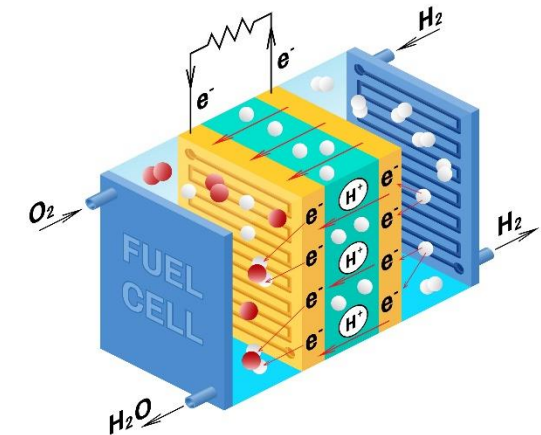
Almost 100GW of energy storage projects proposed and under development across the UK

Energy Storage is not just Batteries

How long do we need to store energy for?

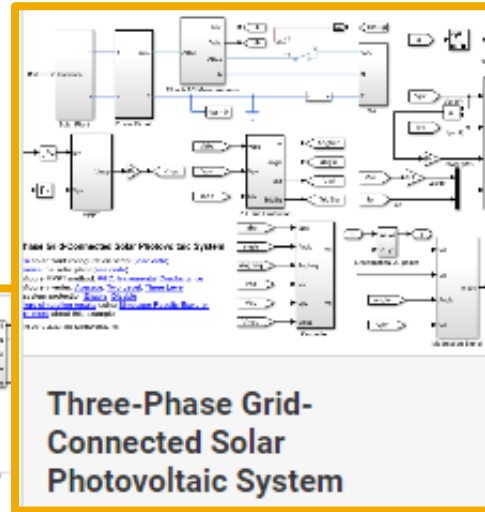


Cost and scalability?



Location and infrastructure?

Exploring Technology Options

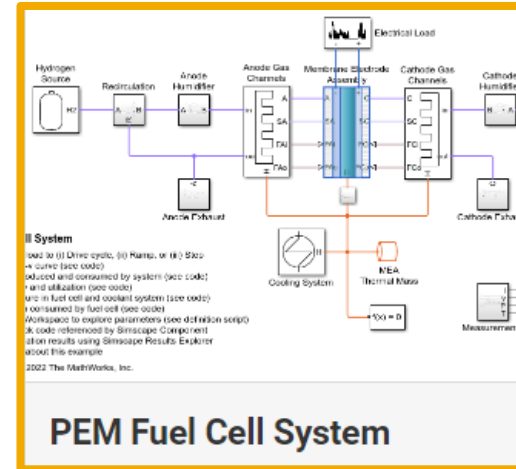
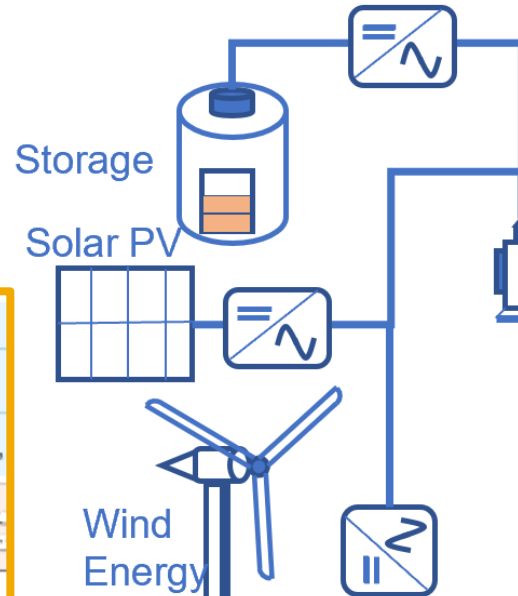


Three-Phase Grid-Connected Solar Photovoltaic System

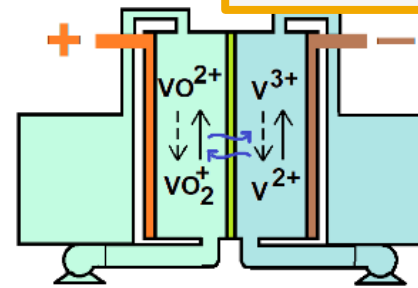
Brayton Cycle (Gas Turbine)

Wind Turbine

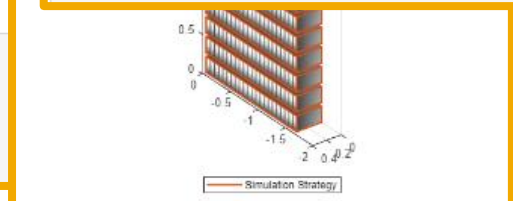
Photovoltaic Thermal (PV/T) Hybrid Solar Panel



Peak Shaving with Battery Energy Storage System



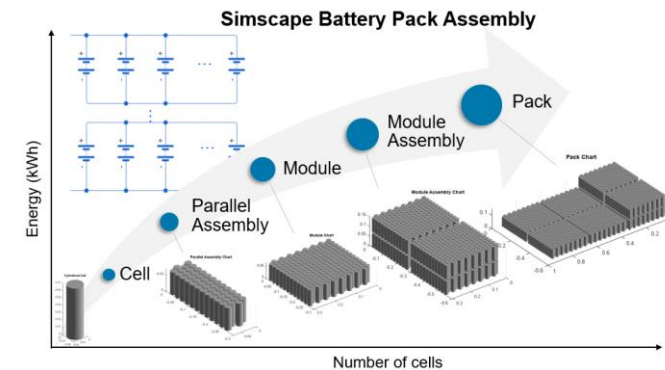
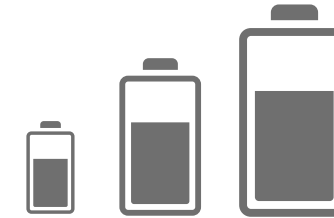
Liquid Air Energy Storage System



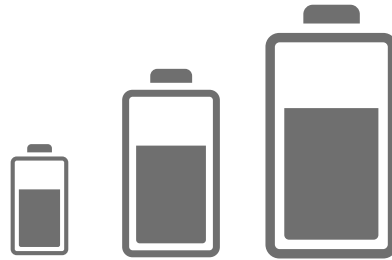
Evaluate Performance of Grid-Forming Battery Energy Storage Systems in Solar PV Plants

Different Phases of Design

- System concepts, sizing and costs
- Detailed component & control design
- Modelling faults to design protection systems



Concept Stage



System Exploration

Technoeconomic analysis

Early design with many assumptions

Water

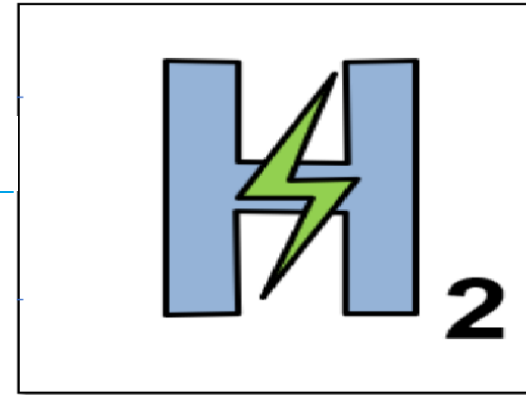


Sun
(irradiance)



Solar Array

Electricity



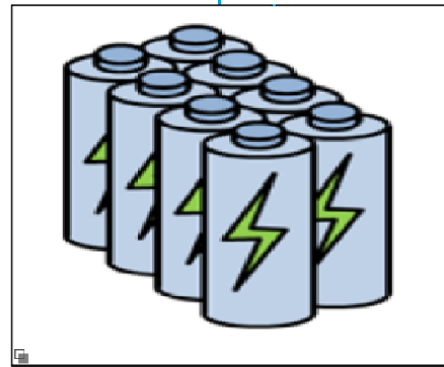
Electrolyzer



Hydrogen
(gas)



Predict performance over a year

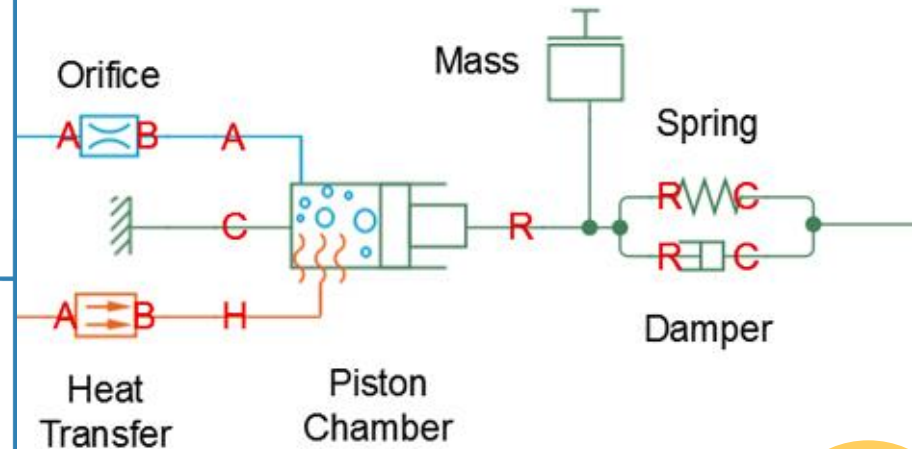
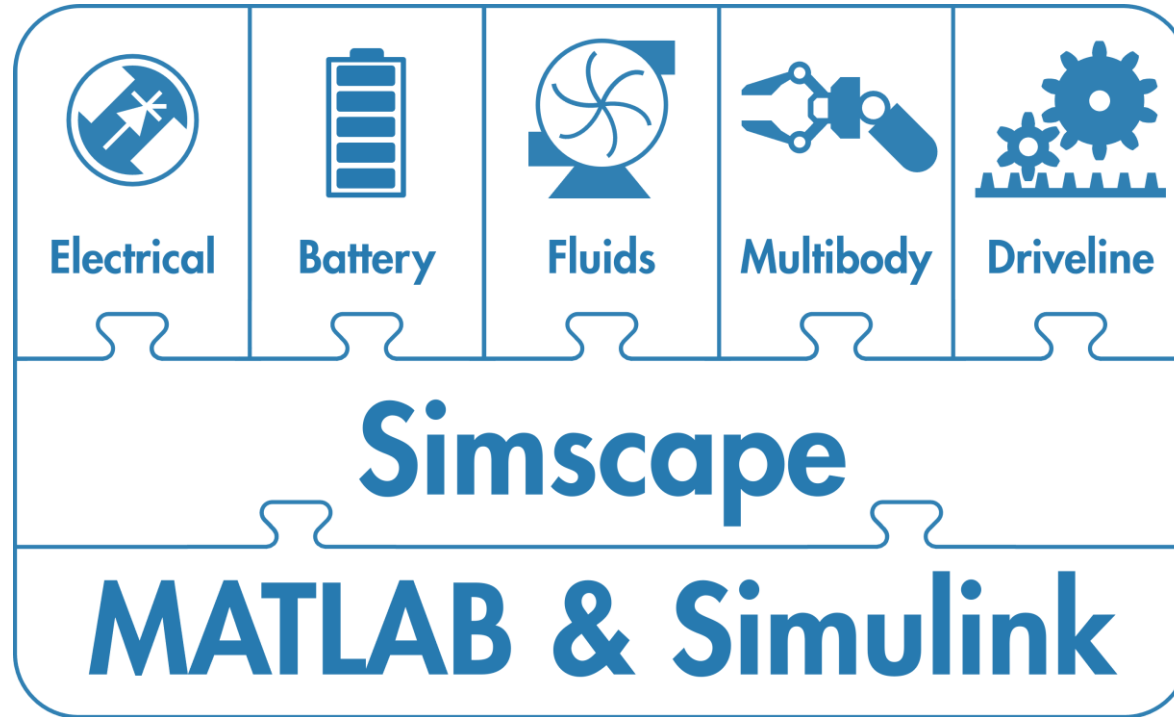


Energy storage



Identify optimal location

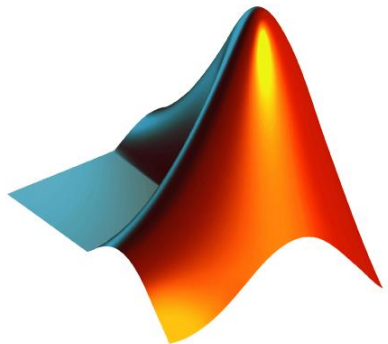
Technoeconomic Analysis with MATLAB, Simulink & Simscape



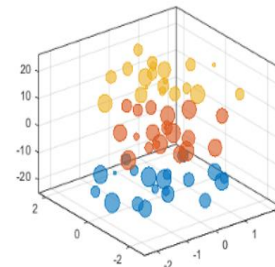
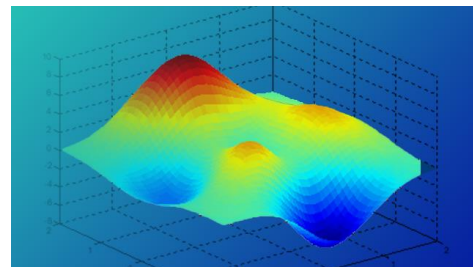
What about



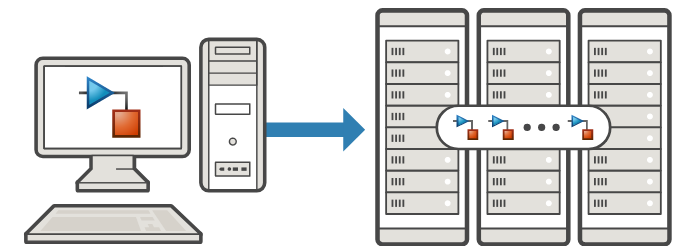
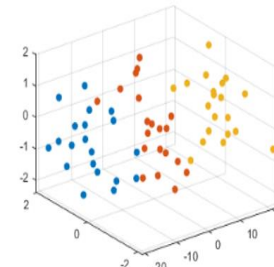
?



Optimization Algorithms



Visualization



Prototype

Scale

Parallelization & Scaling

MATLAB R2023a

Try the New Desktop

Search Documentation

FILE

NAVIGATE

Text

CODE

SECTION

RUN

Run

Step

Stop

C:\Users\tgrimble\Dev\green-hydrogen-production\8760

Live Editor - C:\Users\tgrimble\Dev\green-hydrogen-production\8760\parsimScenariosLive.mlx

parsimScenariosLive.mlx

untitled.mlx *

locatonsSearch.m

parsimScenarios.m

Energy System Design Exploration with MATLAB & Simulink

```

1 loadPriceData;
2
3 load('StationData_UPDATE');
4 vertcat(StationData.Name)

```

Plot a sample

```

5 f = figure;
6 t= tiledlayout(f,2,1);
7
8 a = nexttile;
9 plot(a,1:1:24*365,StationData(1).Irradiance);
10 xlabel("Time (hours)")
11 ylabel("Irradiance (W/m^2)")
12
13 b = nexttile;
14 plot(b,1:1:24,price24)
15 xlabel("Time (hours)")
16 ylabel("Price ($/MWh)")

```

Define scenario input objects

```

17 simIn = Simulink.SimulationInput('green_hydrogen_microgrid_ROM_8760')

```

Zoom: 100%

UTF-8

LF

script

Ln 4 Col 26

green_hydrogen_microgrid_ROM_8760 - Simulink

SIMULATION

DEBUG

MODELING

FORMAT

APPS

PROJECT

FILE

LIBRARY

PREPARE

Stop Time 24*3600*3

Normal

Fast Restart

Step Back

Run

Step Forward

Stop

REVIEW RESULTS

green_hydrogen_microgrid_ROM_8760

Copyright MathWorks 2021

1 year in a few seconds

This is a model of a DC microgrid that provides power to an electrolyzer using a solar array and a stylized energy storage system and grid connection. This model can be used to evaluate the operational characteristics of producing green hydrogen over a 1-year period. The model includes electrical, thermal liquid and thermal gas domains. Time-step is 1 hour.

Solar Array (ROM)

Electricity Cost

measurements

Electrolyzer

H₂

Energy Storage (ROM)

Grid (ROM)

Ready

Completed 242 simulations

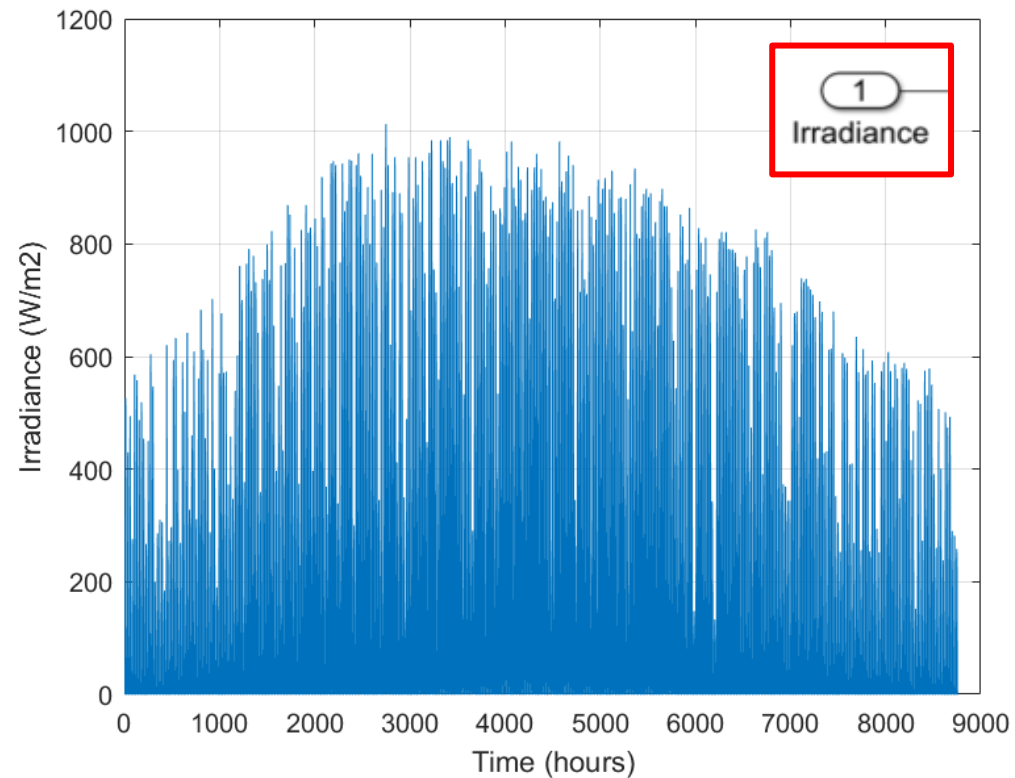
108%

FixedStepAuto

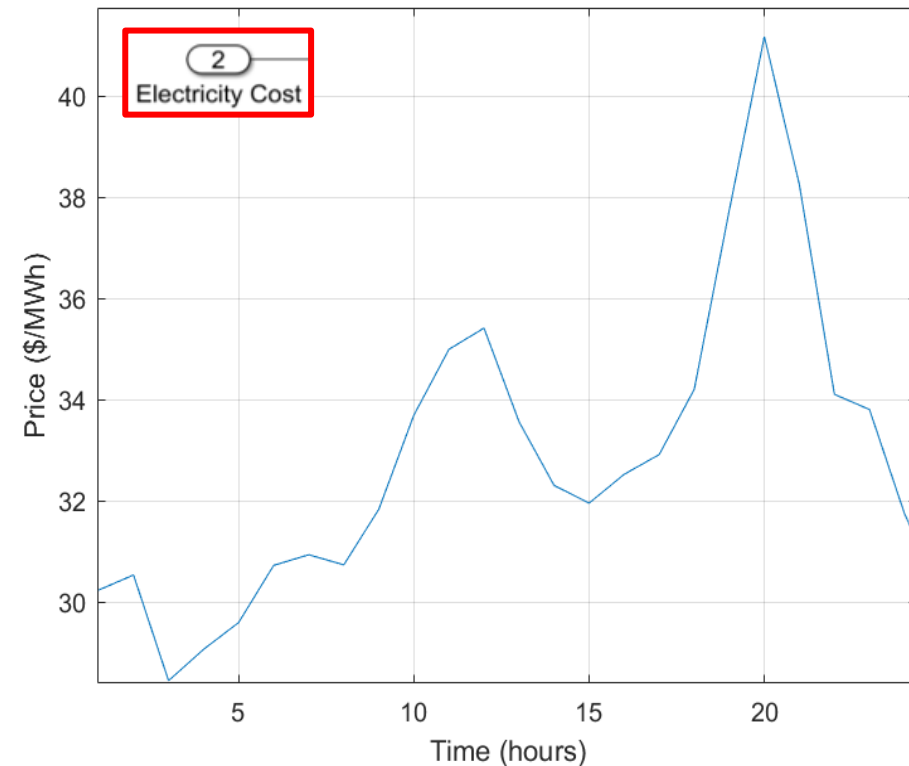
Injecting Real World Data

Load Data to Root-Level Input Ports

The irradiance data is 8760 TMY3 from National Renewable Energy Laboratory.



Electricity price data is averaged one day of data from system operators.



Goal of Simulation / Level of Fidelity

Control Response Dynamics

- Modeling mechanical balance
- Understanding fault scenarios and impacts on performance
- Setting tolerance requirements

High Frequency Power Electronic Switching

- Detailed modelling of semiconductors and converter dynamics
- Optimizing waveforms and losses at component level

Quasi-Steady State

- Energy flow simulation
- Idealized power sources and loads
- Used for sizing & planning purposes (e.g. energy storage)

Thermal dynamics

- Transient thermal response
- Coupling thermal dependency to electrical performance



Detailed component modelling

System level modelling

Techniques for Reduced Order Modelling

Model Based

"model reduction"

Modal Projection

Modal Truncation

Proper Orthogonal Decomposition

Structural Reduction

Balanced Truncation

Data Driven

"model fitting"

Static Model Fitting

Curve Fitting

Lookup tables

Dynamic Model Identification

Local Linear
Models

Linear Parameter
Varying

ARMAX

Box-Jenkins

Linearization

Hammerstein
Wiener Models

Output-Error
Models

Non-Linear
ARX

Machine Learning

Regression
Trees

Support Vector
Machines

Neural ODEs

Ensembles

Gaussian
Process Models

Recurrent
Neural Networks

Shallow
Neural Networks

Convolutional
Neural Networks

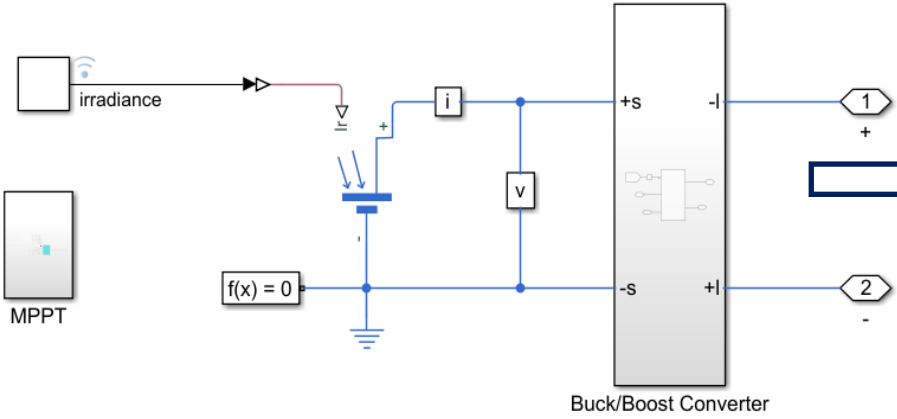
Physically Inspired
Neural Networks

ROM Implementation

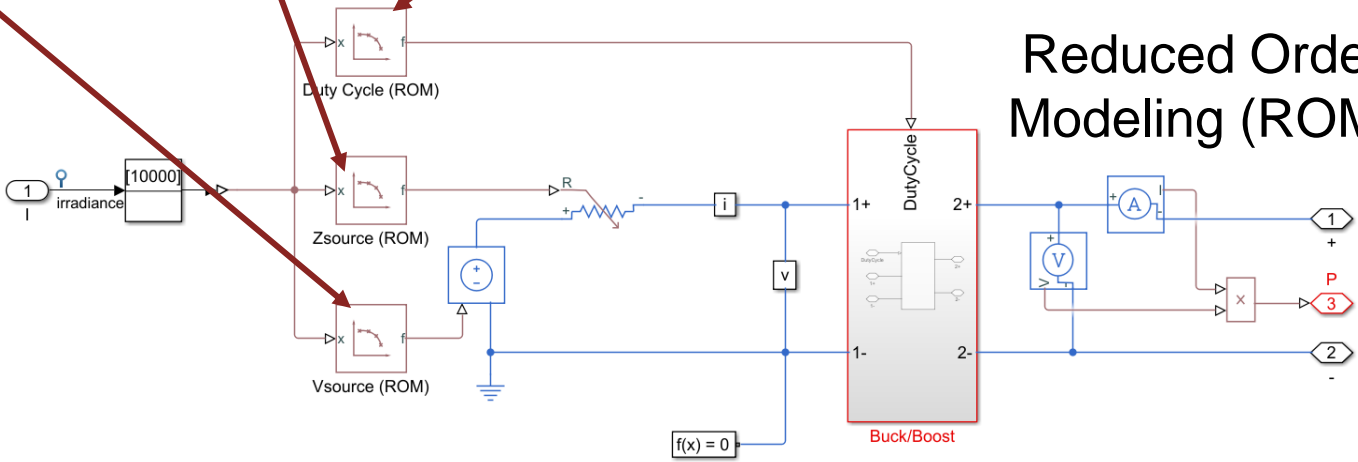
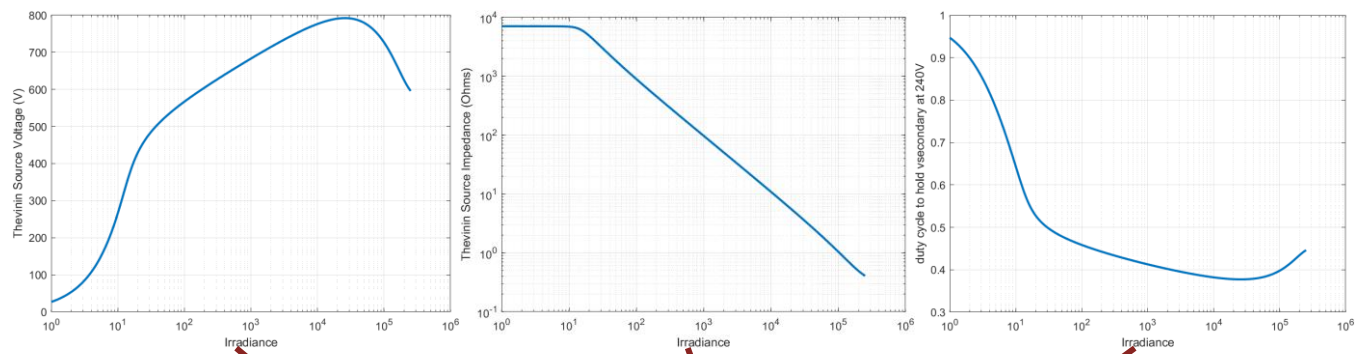
Performance
assessment

Medium
fidelity

Solar cell &
MPPT algorithm



Capture steady state operating point



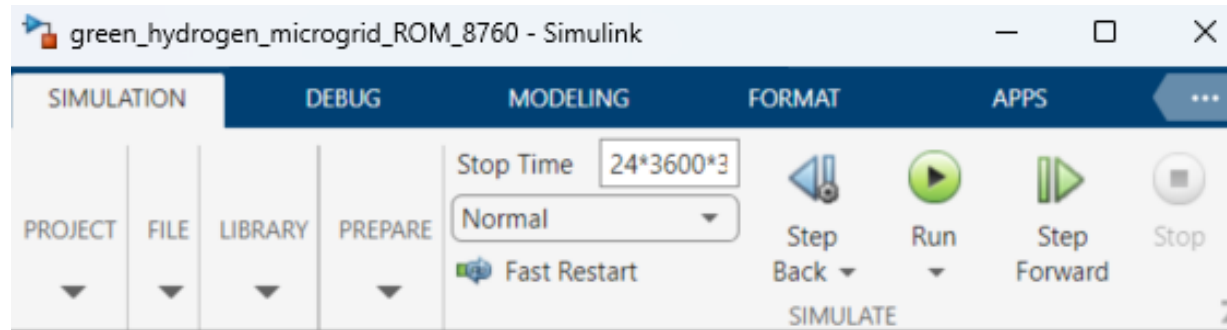
Quasi-steady lookup table model

Techno-economic
analysis

Low
fidelity

Reduced Order
Modeling (ROM)

Clean Instancing for Model Setup



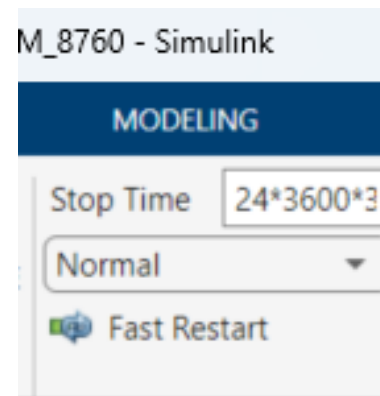
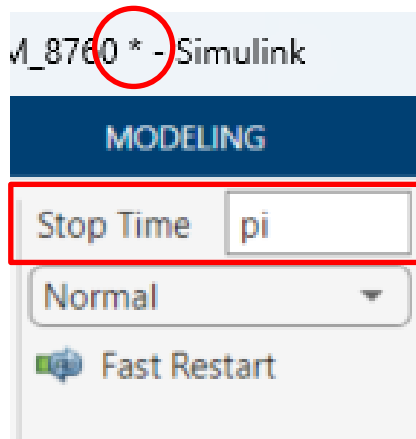
StopTime = "24*3600*365"

To change this via script:

```
set_param(gcs, StopTime = "pi");
```

```
simIn = Simulink.SimulationInput(gcs);
```

```
simIn = simIn.setModelParameter(StopTime = "pi");
```

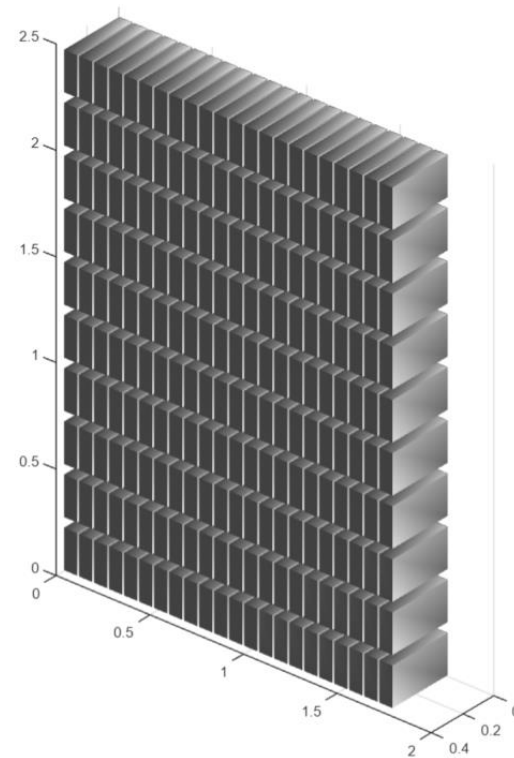


Property ^	Value
ModelName	'green_hydrogen_microgrid_ROM_8760'
InitialState	0x0 ModelOperatingPoint
ExternalInput	[]
ModelParameters	1x1 ModelParameter
BlockParameters	0x0 BlockParameter
Variables	0x0 Variable

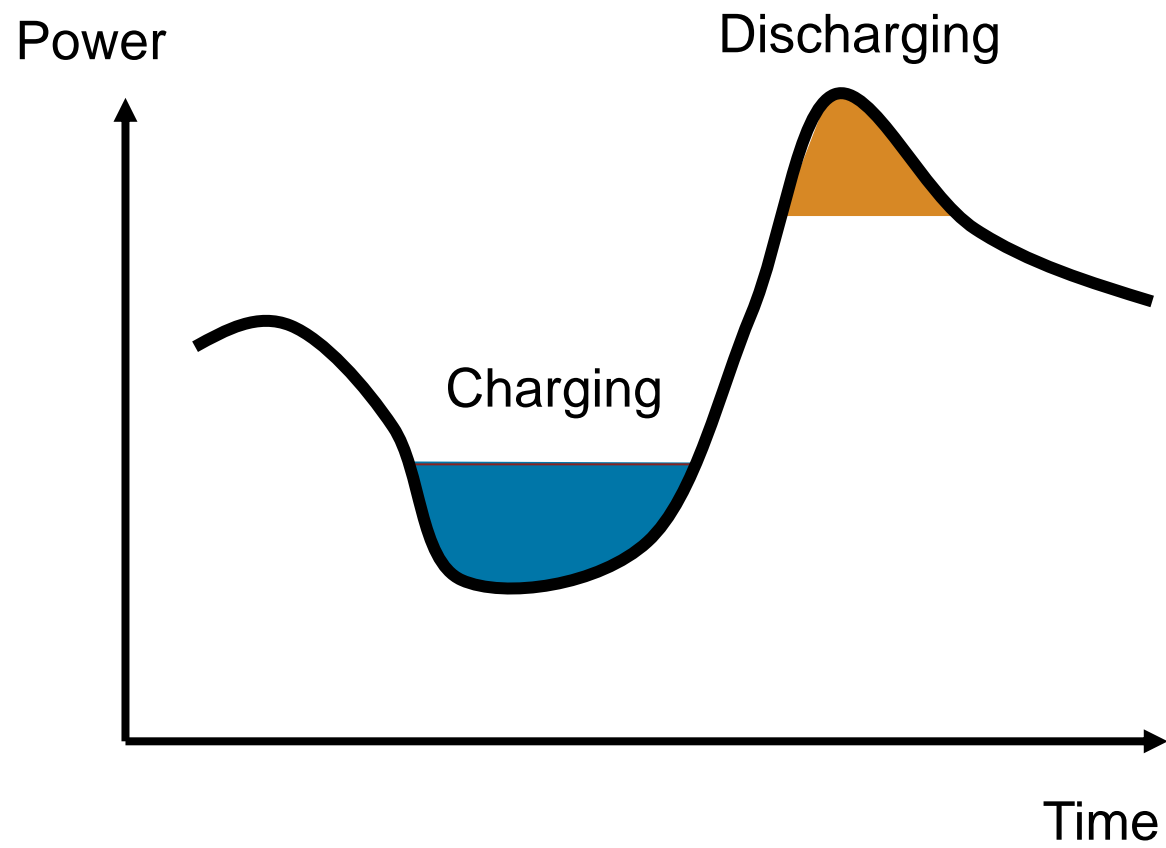
Create Simulink.SimulationInput objects to make changes to model for multiple or individual simulations

```
simOut = parsim(simIn);
```

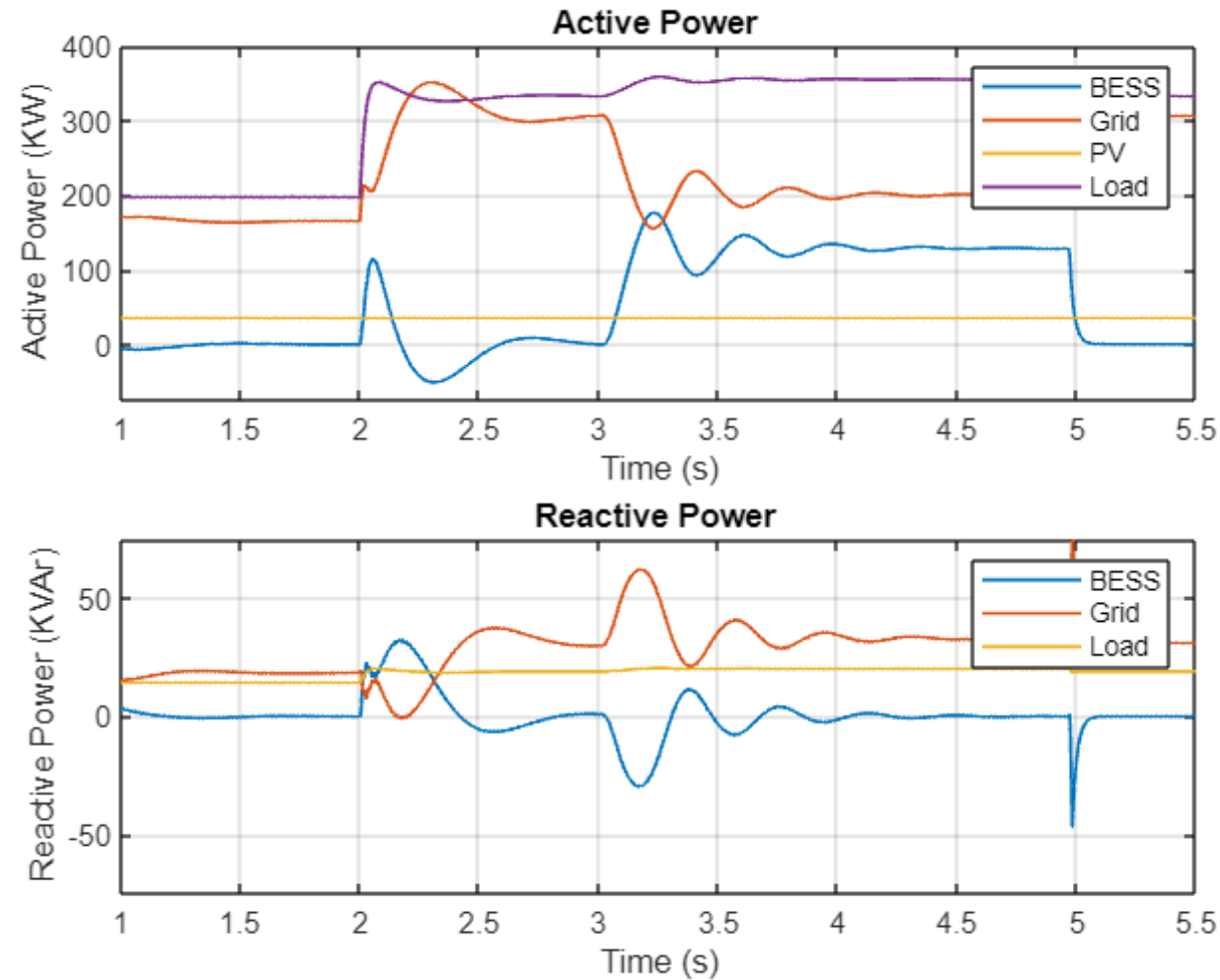

Detailed Design



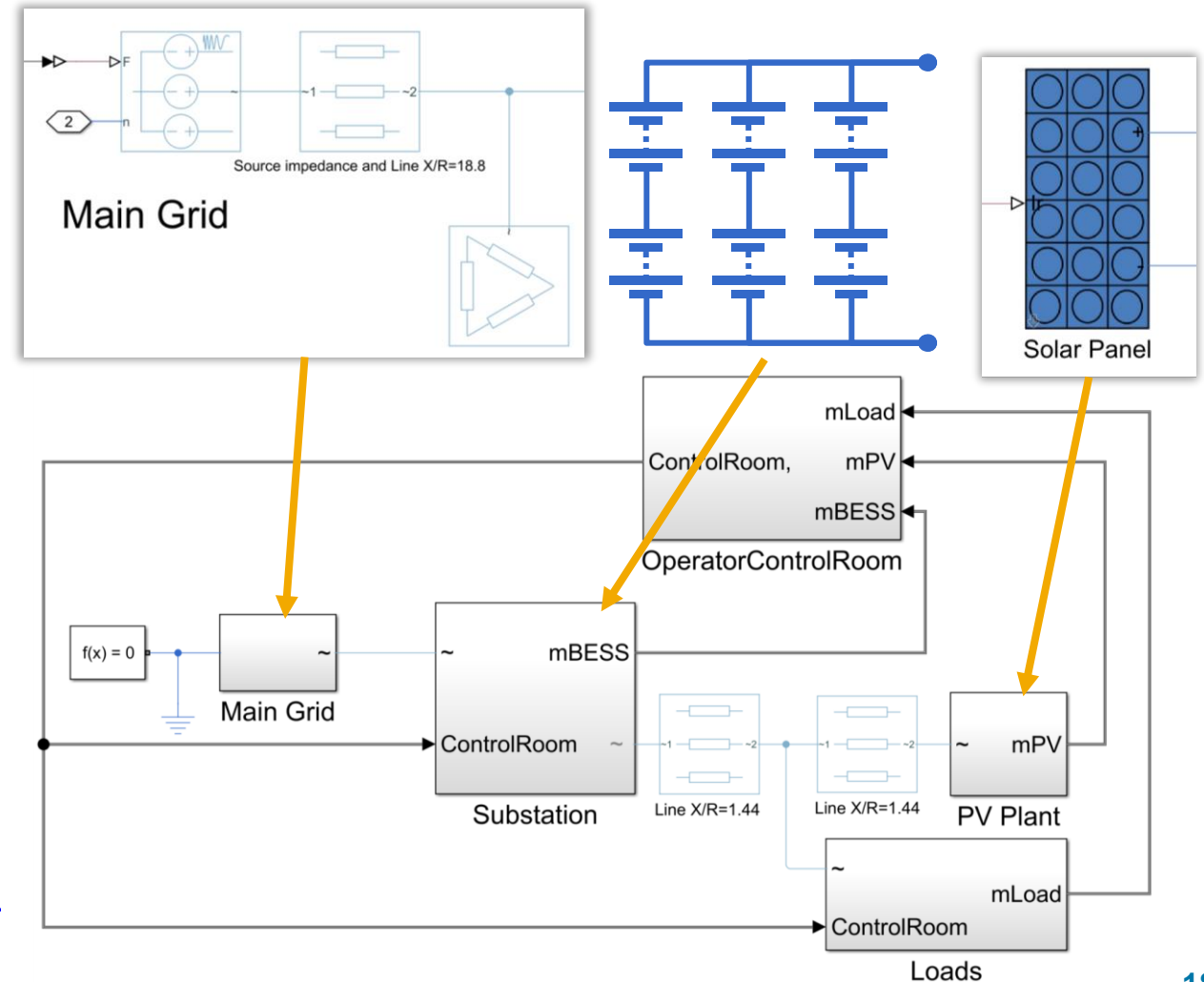
Peak Shaving



Peak Shaving

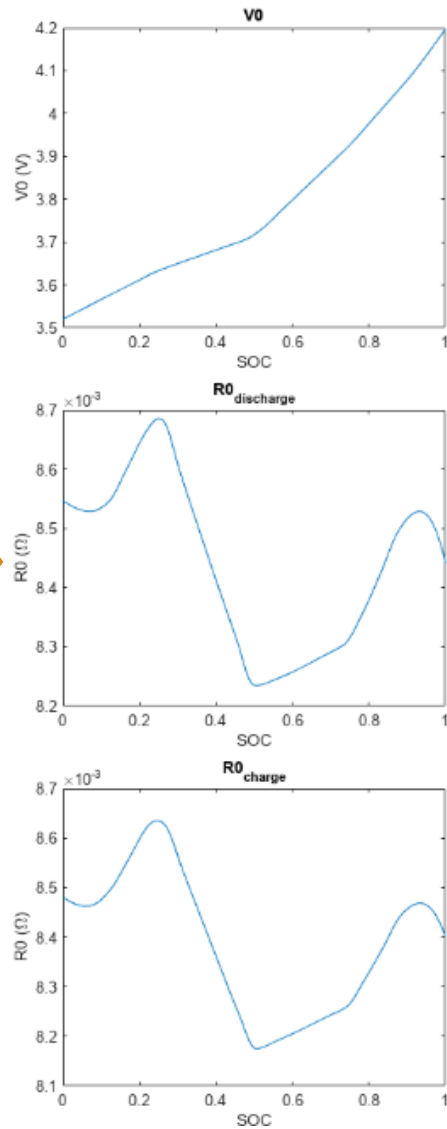
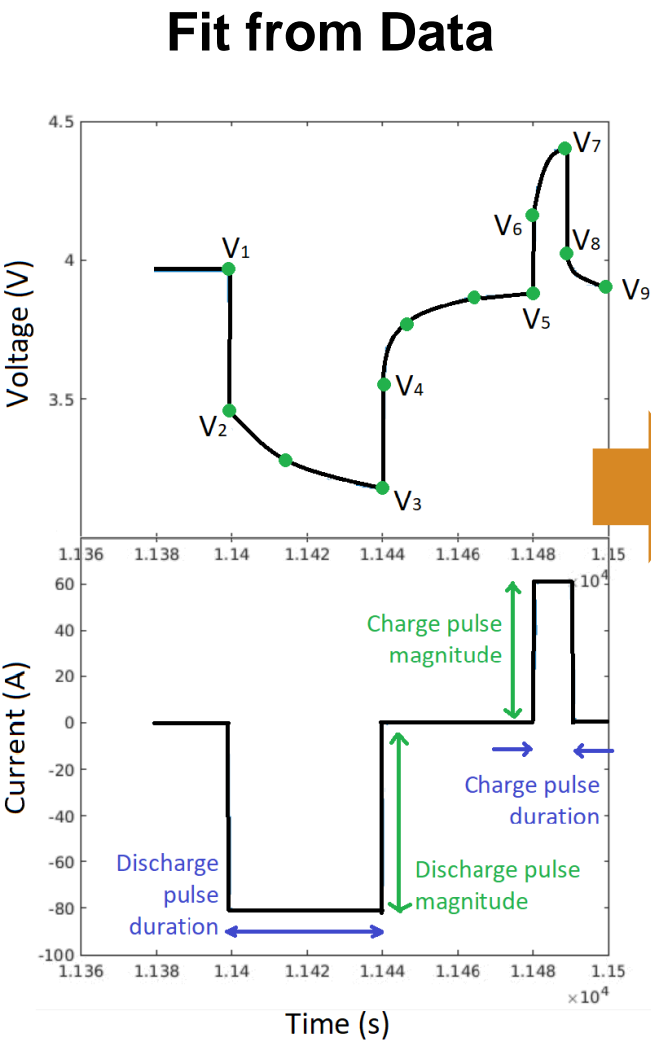


How do we model this detailed battery performance?

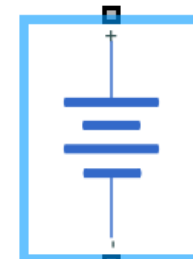


[Peak Shaving with Battery Energy Storage System - MATLAB & Simulink - MathWorks United Kingdom](#)

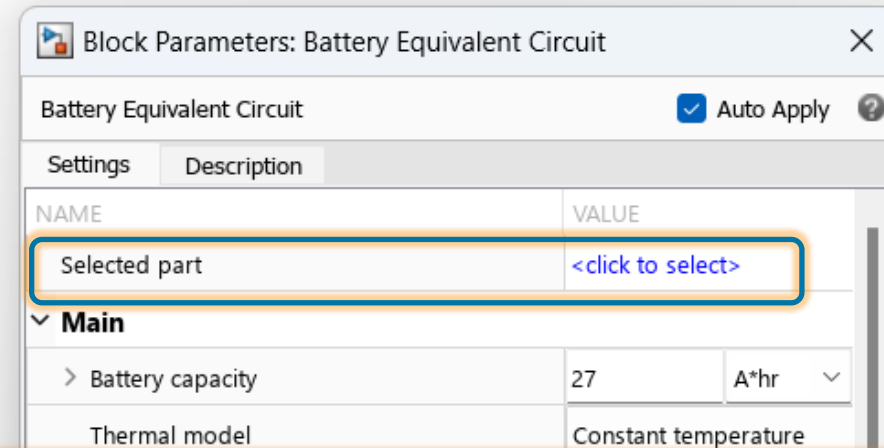
Cell Parameters



Pre-parametrized parts



Battery Equivalent Circuit



The screenshot shows the 'Block Parameterization Manager: Battery Equivalent Circuit' dialog box. It includes a 'SELECT' tab and a 'FORMAT' tab. The 'SELECT' tab is active, showing a table with columns 'Part number', 'Manufacturer', 'BatteryType', 'Geometry', 'Capacity, mA*hr', 'Vnominal, V', and 'Weight, g'. The 'Part specification' section is also visible, showing details for the selected part.

Part number	Manufacturer	BatteryType	Geometry	Capacity, mA*hr	Vnominal, V	Weight, g
ALM12V7	A123	Lithium-ion	Prismatic	4600	13.2000	840.0000
AMP20M1HD	A123	Lithium-ion	Pouch	19600	3.3000	496.0000
ANR26650M1	A123	Lithium-ion	Cylindrical	2300	3.3000	72.0000
PD3032	Korea Powercell	Lithium-ion	Cylindrical	180	3.7000	7.2000

Attribute	Value
Manufacturer	A123
Part number	ALM12V7
Part series	
Web link	http://www.a123systems.com/

Parameter name	Parameterization	Override datasheet value	Part value: ALM12V7	Present block value	Unit
Main>Battery capacity	Datasheet derived	<input checked="" type="checkbox"/>	4.911	27	A*hr
Main>Enable exothermic reactions fault	Parameter not set	<input type="checkbox"/>	false	0	1
Main>Trigger temperature	Parameter not set	<input type="checkbox"/>	350	350	K

Battery Builder

BATTERY CHART

Import

Cell

Parallel Assembly

Module

Module Assembly

Pack

Duplicate

Delete

Export

Create Library

FILE

CREATE

BROWSER

EXPORT

LIBRARY

Battery Browser

Cell

ExampleCell

GridCell

Parallel Assembly

ExampleParallelAssembly

GridParallelAssembly

Module

ExampleModule

GridModule

Module Assembly

ExampleModuleAssembly

GridModuleAssembly

Pack

ExamplePack

Battery Hierarchy

Pack (GridPack)

ModuleAssembly (GridModuleAssembly)

Module (GridModule)

ParallelAssembly (GridParallelAssembly)

Cell (GridCell)

Module (Module2)

ParallelAssembly (ParallelAssembly2)

Cell (GridCell)

Module (Module3)

ParallelAssembly (ParallelAssembly3)

Cell (GridCell)

Module (Module4)

ParallelAssembly (ParallelAssembly4)

Cell (GridCell)

Selected Battery

GridPack (Pack)

z: Vertical direction

2.5

2

1.5

1

0.5

0

0

0.5

1

1.5

2

0.4

0.2

0

y: Lateral direction

x: Forward direction

Simulation Strategy

Pack Properties

Read-Only Properties

Identifier

Name

GridPack

Geometry

Position

x

0

y

0

z

0

StackingAxis

X

Pack Properties

ModuleAssembly

GridModuleAssembly

Select...

InterModuleAssemblyGap

0.001

MassFactor

1

Model Options

Thermal Model Options

Apply

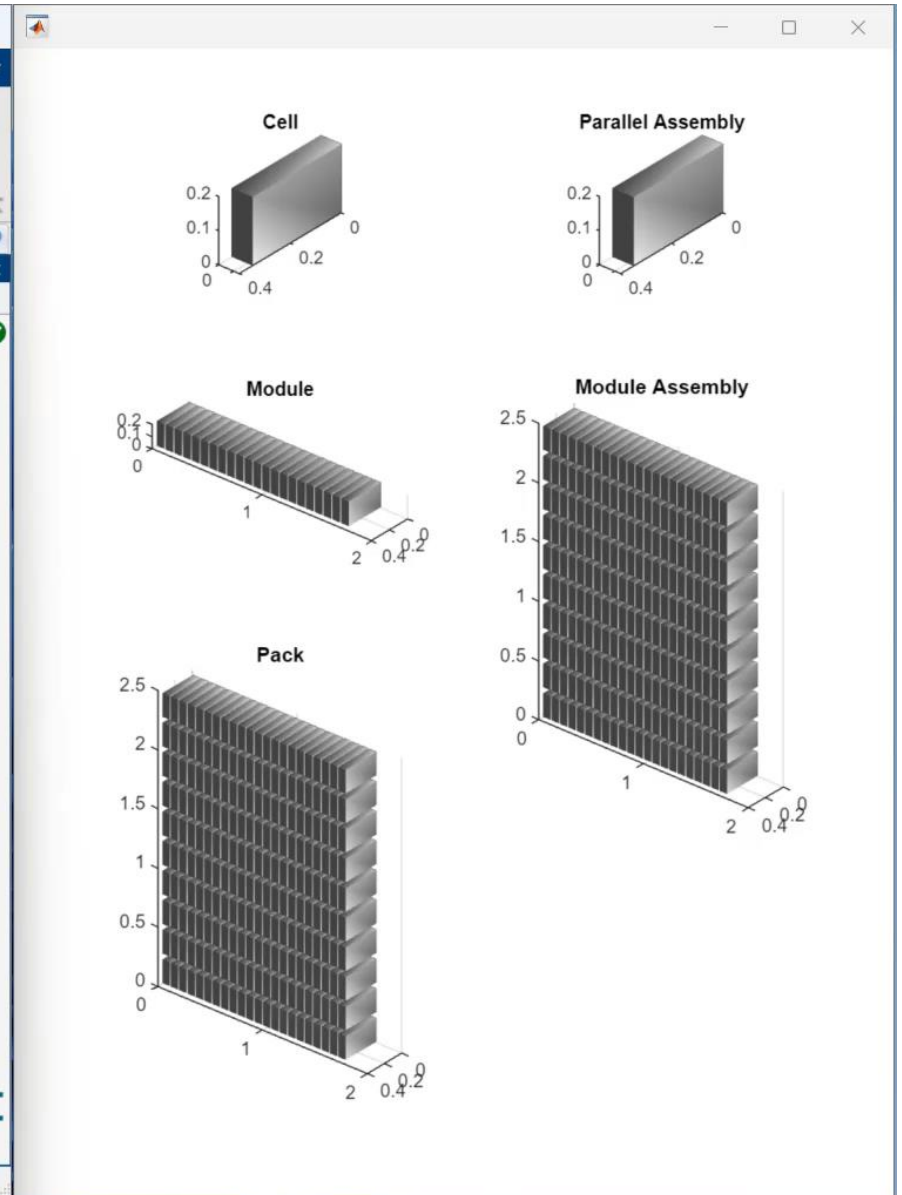
Scripted Battery

```
MATLAB R2023b

H... P... A... E... PU... V... Try the New Desktop Search Documentation Tom
New Open Save Print Compare Go To Find Refactor Analyze Run Section Run and Advance Run Step Stop
FILE NAVIGATE CODE ANALYZE SECTION RUN

C:\Users\tgrimble\Dev\expo-battery-2023\2-Pack
Editor - C:\Users\tgrimble\Dev\expo-battery-2023\2-Pack\packBuildApiPlot.m
packBuildApiPlot.m
52 nexttile(t,[2,1]);
53 assemblyChart = simscape.battery.builder.BatteryChart(...
54     Parent = t, Battery = batteryModuleAssembly);
55 title(assemblyChart,"Module Assembly")
56
57 %% Pack
58 batteryPack = simscape.battery.builder.Pack(...
59     ModuleAssembly = batteryModuleAssembly);
60
61 % Plot
62 nexttile(t,[2,1]);
63 packChart = simscape.battery.builder.BatteryChart(...
64     Parent = t, Battery = batteryPack);
65 title(packChart,"Pack")
66
67 %% Build Battery Library
68 libName = "packLibFromMATLAB";
69 simscape.battery.builder.buildBattery(batteryPack,...
70     LibraryName = libName,...
71     MaskParameters = "VariableNamesByInstance",...
72     MaskInitialTargets = "VariableNamesByInstance");

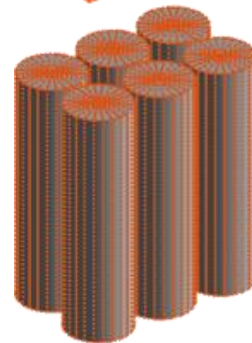
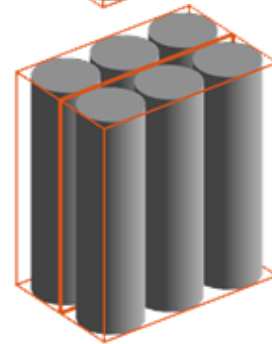
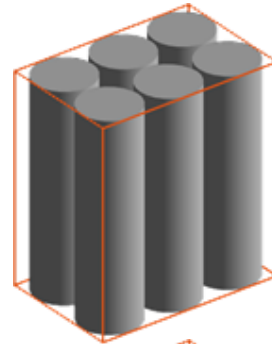
2 usages of "libName" found Zoom: 100% UTF-8 LF script Ln 68 Col 4
```



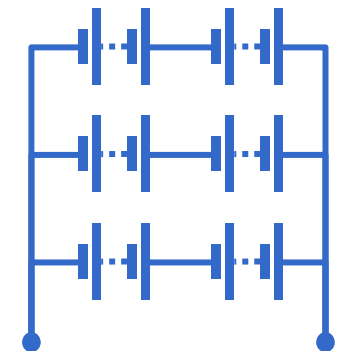
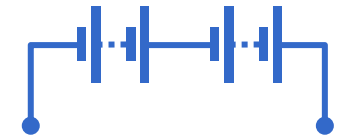
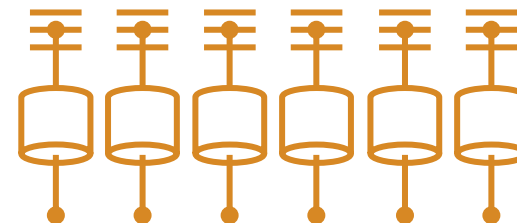
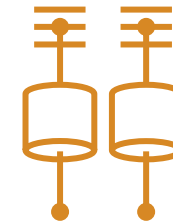
Battery Pack Model Fidelity

- Lumped resolution
 - One electrothermal element
- Grouped resolution
 - Any number of arbitrarily grouped elements
- Detailed resolution
 - Every cell modeled individually

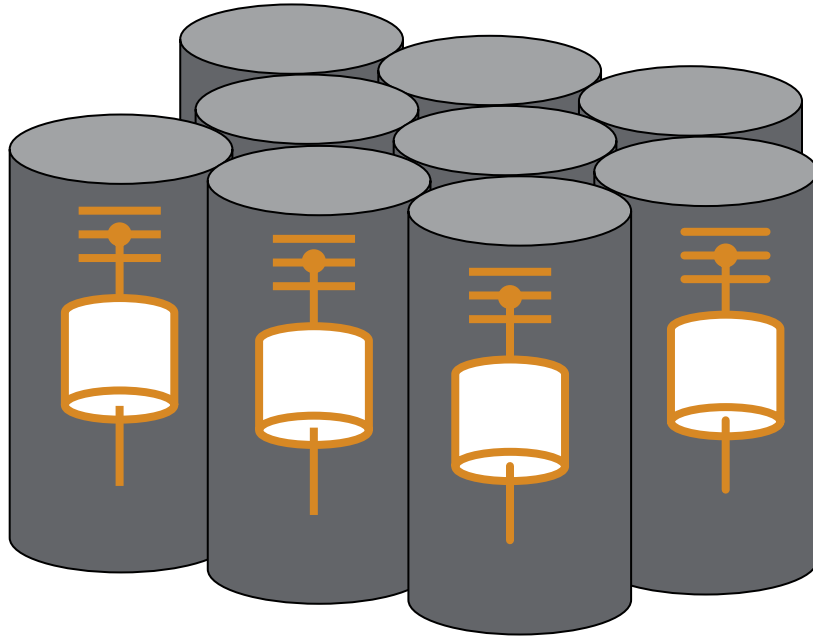
Pack Visualization



Equivalent Thermal Model

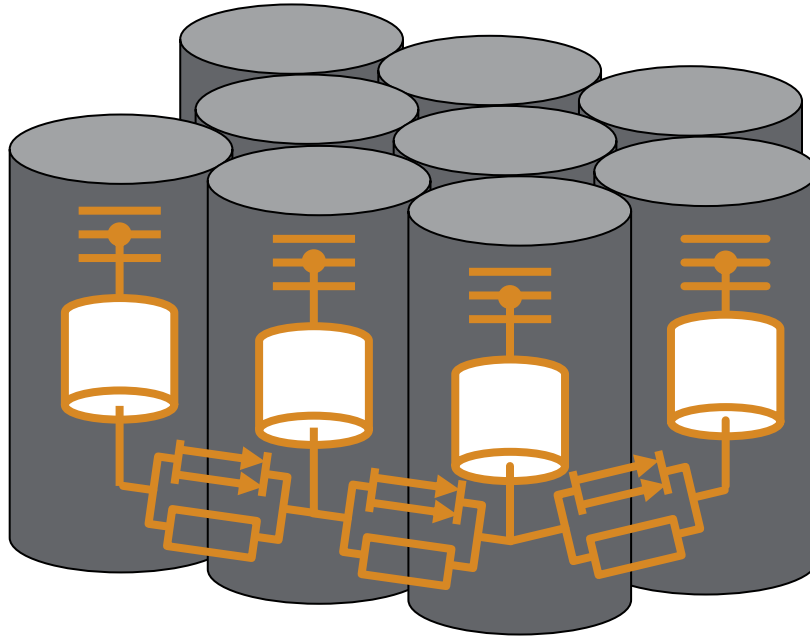


Thermal Connections



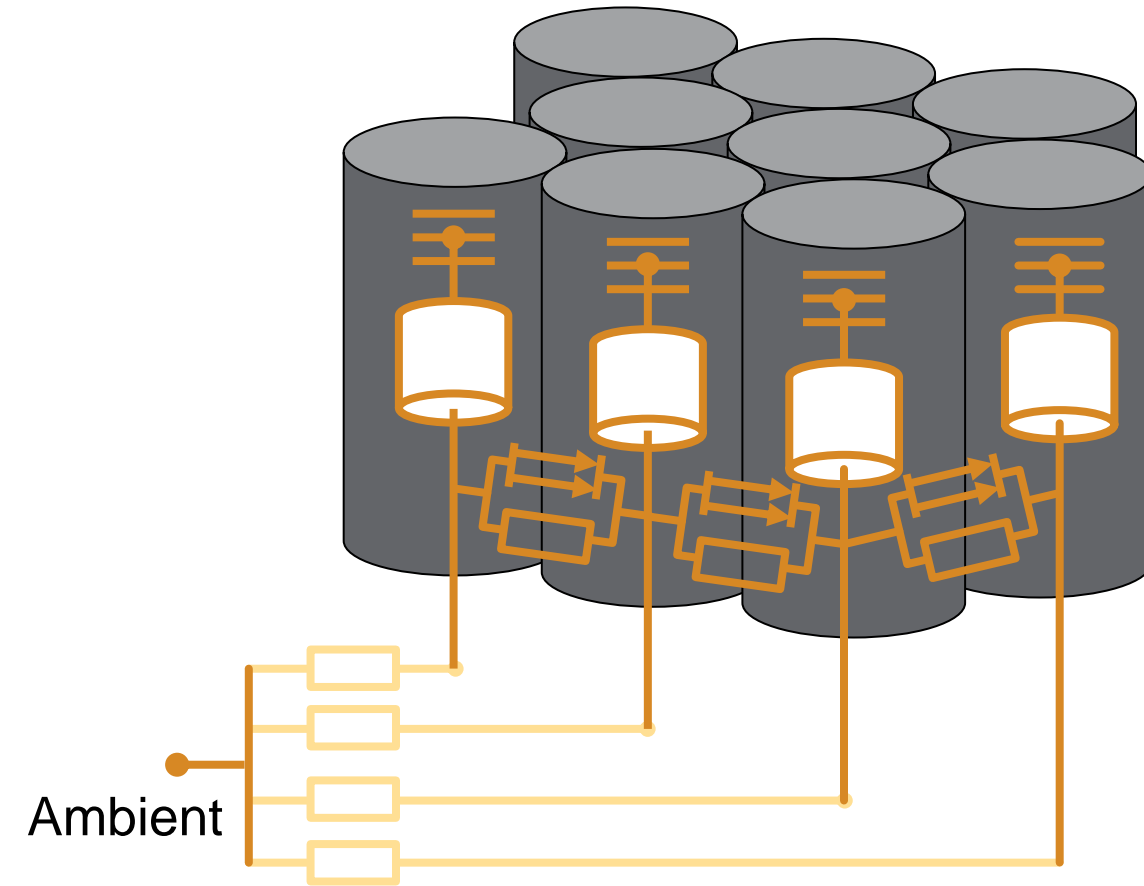
```
batteryModule = Simscape.Battery.Builder.Module(...  
    ParallelAssembly = pAssembly,...  
    NumSeriesAssemblies = 3,...  
    ModelResolution = "Detailed");
```

Thermal Connections



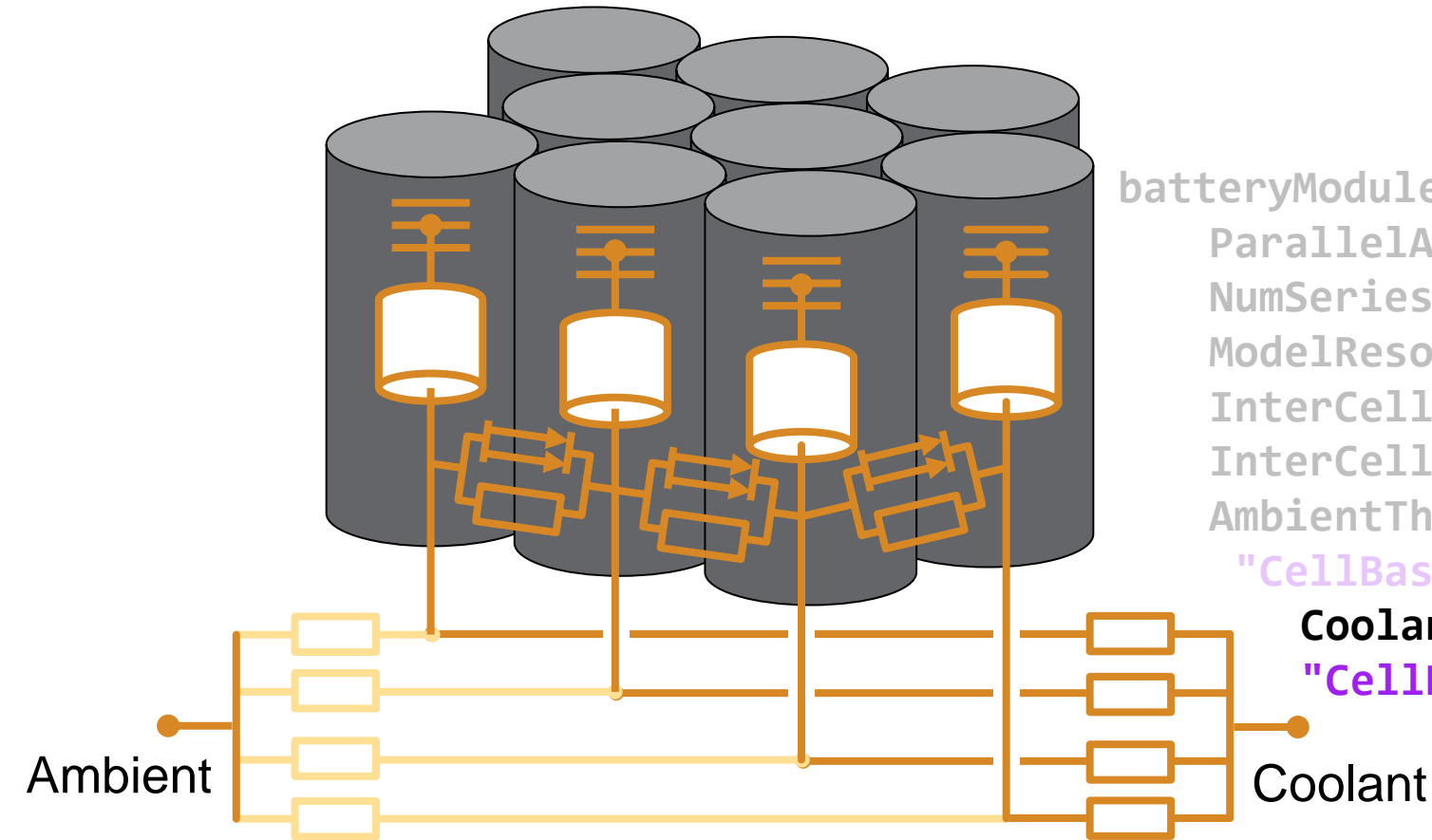
```
batteryModule = simscape.battery.builder.Module(...  
    ParallelAssembly = pAssembly,...  
    NumSeriesAssemblies = 3,...  
    ModelResolution = "Detailed",...  
    InterCellThermalPath = "on",...  
    InterCellRadiativeThermalPath = "on");
```

Thermal Connections



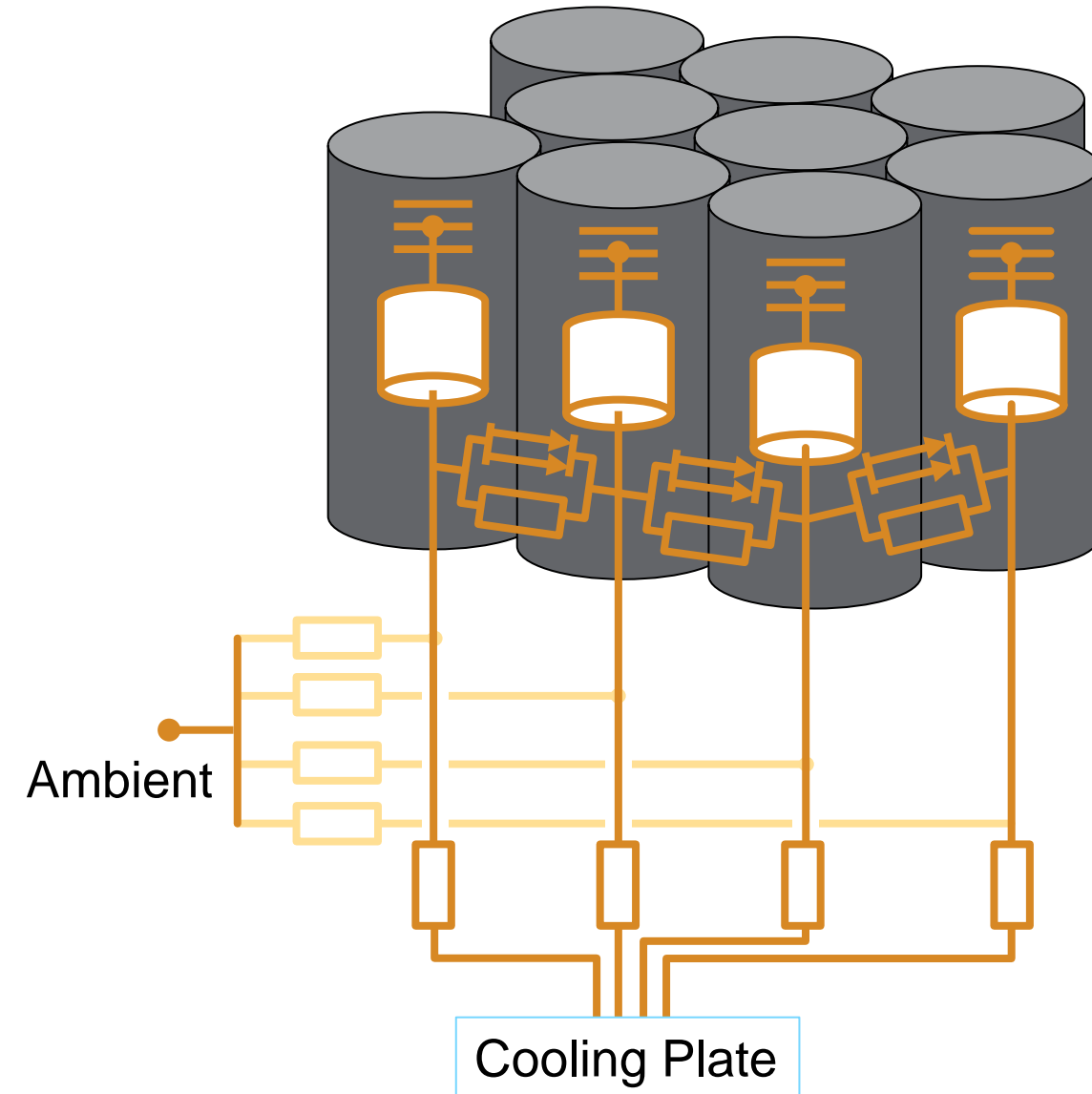
```
batteryModule = simscape.battery.builder.Module(...  
    ParallelAssembly = pAssembly,...  
    NumSeriesAssemblies = 3,...  
    ModelResolution = "Detailed",...  
    InterCellThermalPath = "on",...  
    InterCellRadiativeThermalPath = "on",...  
    AmbientThermalPath = ...  
    "CellBasedThermalResistance");
```

Thermal Connections



```
batteryModule = simscape.battery.builder.Module(...  
    ParallelAssembly = pAssembly,...  
    NumSeriesAssemblies = 3,...  
    ModelResolution = "Detailed",...  
    InterCellThermalPath = "on",...  
    InterCellRadiativeThermalPath = "on",...  
    AmbientThermalPath = ...  
        "CellBasedThermalResistance",...  
        CoolantThermalPath = ...  
        "CellBasedThermalResistance");
```

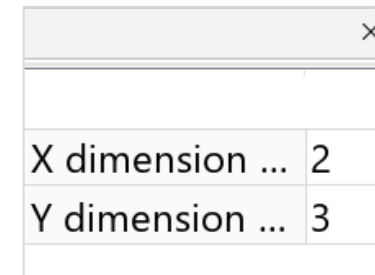
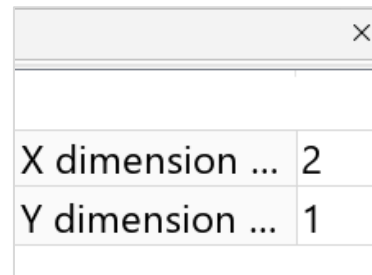
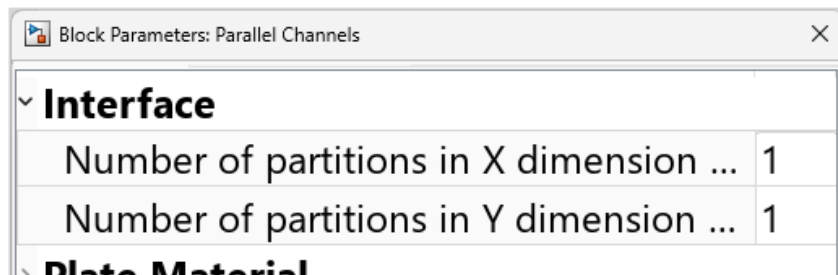
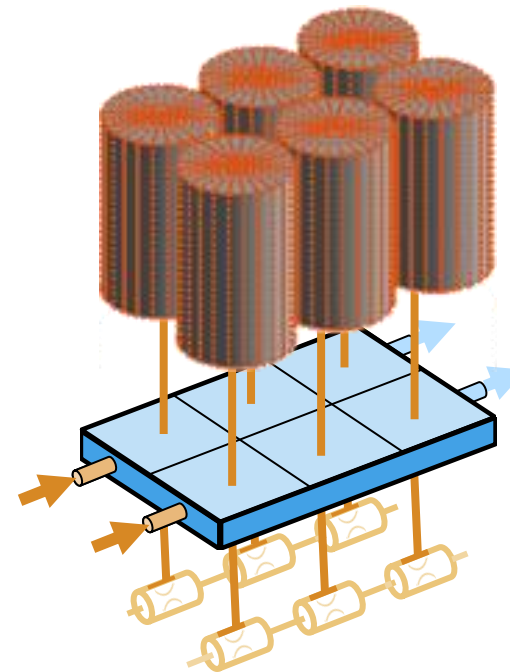
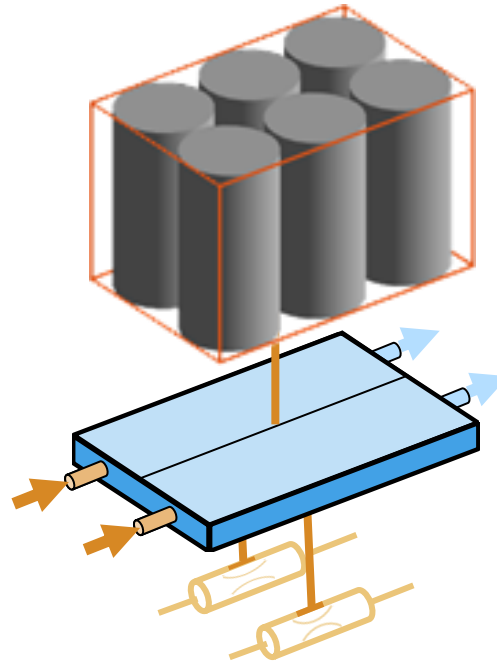
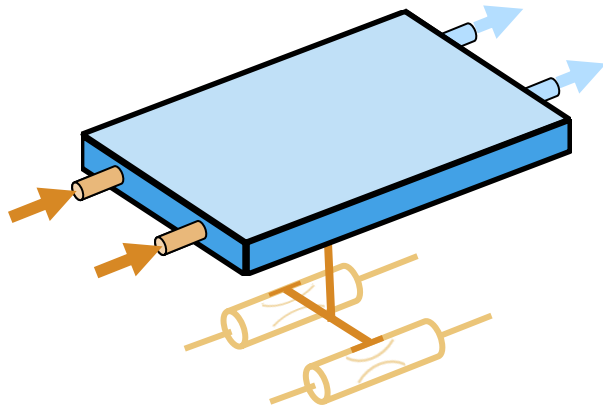
Thermal Connections



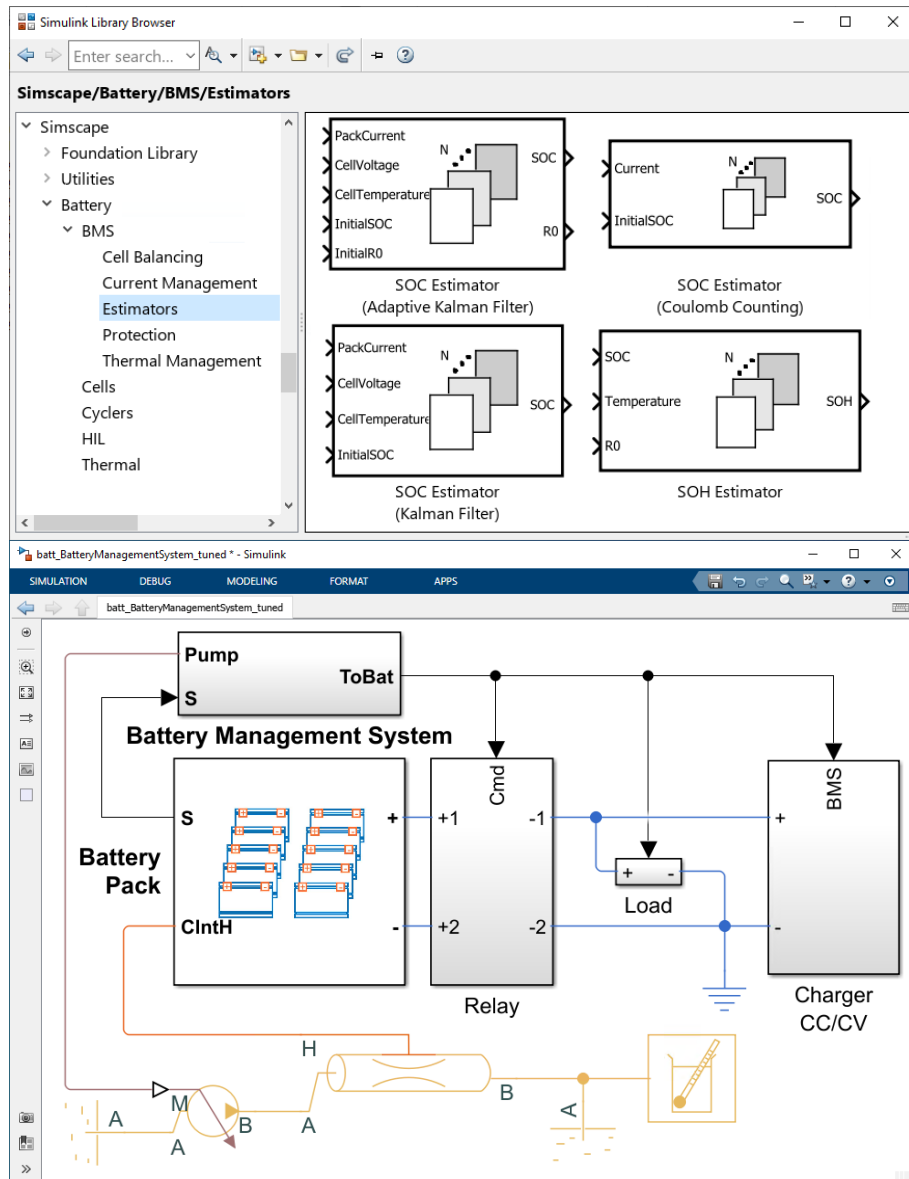
```
batteryModule = simscape.battery.builder.Module(...  
    ParallelAssembly = pAssembly,...  
    NumSeriesAssemblies = 3,...  
    ModelResolution = "Detailed",...  
    InterCellThermalPath = "on",...  
    InterCellRadiativeThermalPath = "on",...  
    AmbientThermalPath = ...  
        "CellBasedThermalResistance",...  
    CoolantThermalPath =...  
        "CellBasedThermalResistance",...  
    CoolingPlate = "Bottom",...  
    CoolingPlateBlockPath = ...  
        "batt_lib/Thermal/Parallel Channels");
```

Cooling Plate Connection

- Adjust granularity of plate
- Connect to pack of any resolution

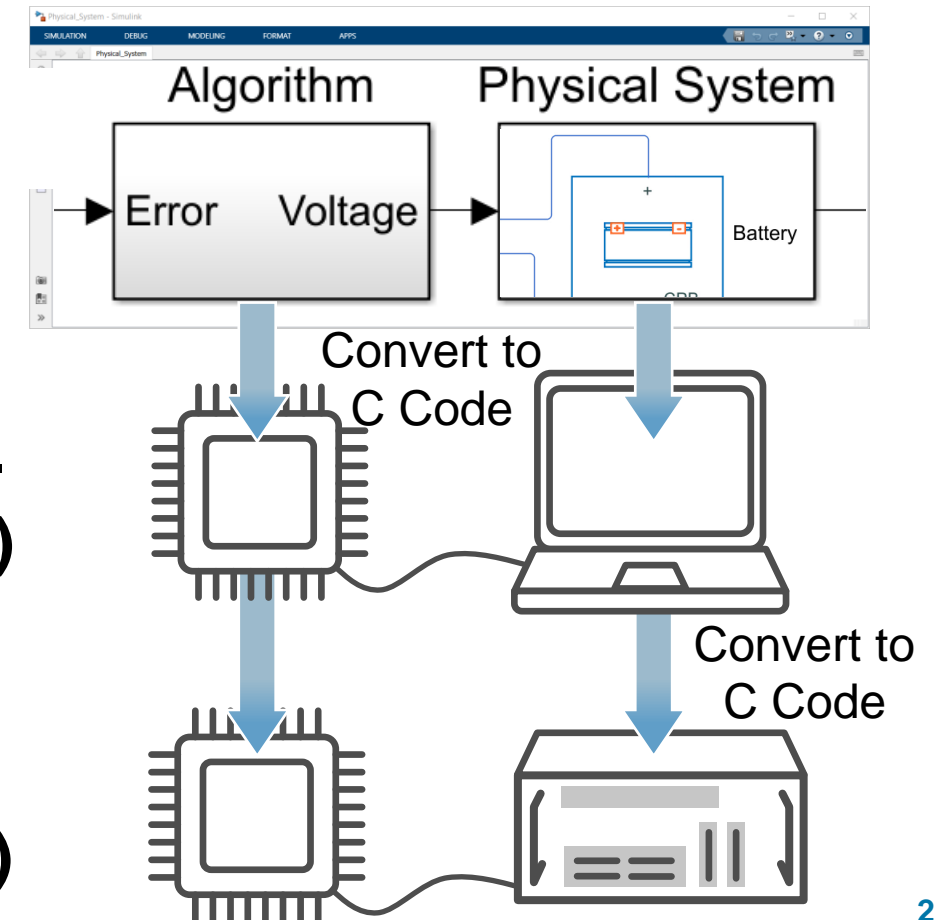


Control Algorithms & Deployment



Battery Management Systems In Simscape Battery

C/C++ Code
HIL Code

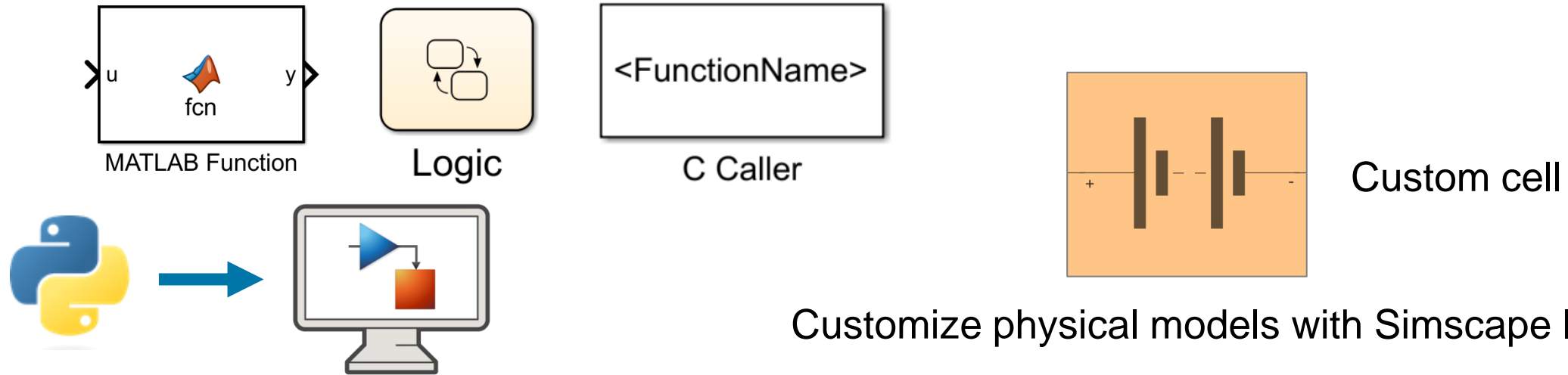


Processor-in-the-Loop (PIL)

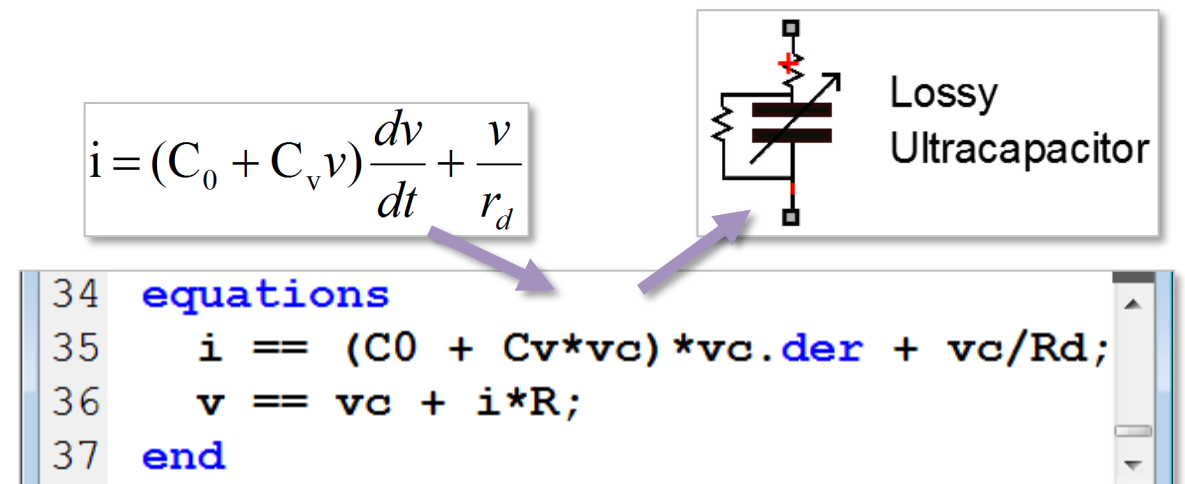
Hardware-in-the-Loop (HIL)

Customization

Customization and flexibility are at the core of MATLAB & Simulink



Customize physical models with Simscape language



[Simscape Customization](#)

Fault Robustness



Faults & System Protection

▼ Battery

▼ BMS

- ▶ Cell Balancing
- ▶ Current Management
- ▶ Estimators
- ▼ Protection



Battery Current Monitoring



Battery Temperature Monitoring

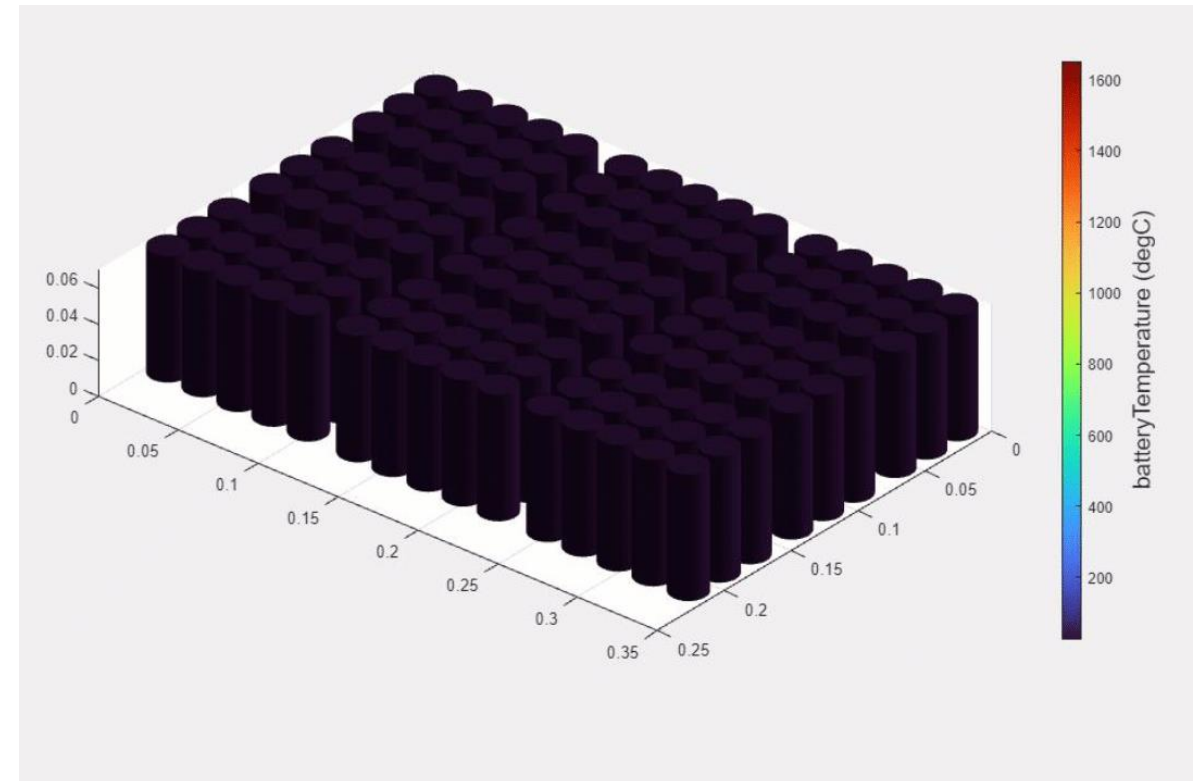
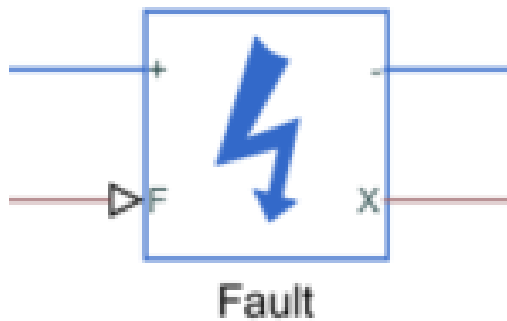


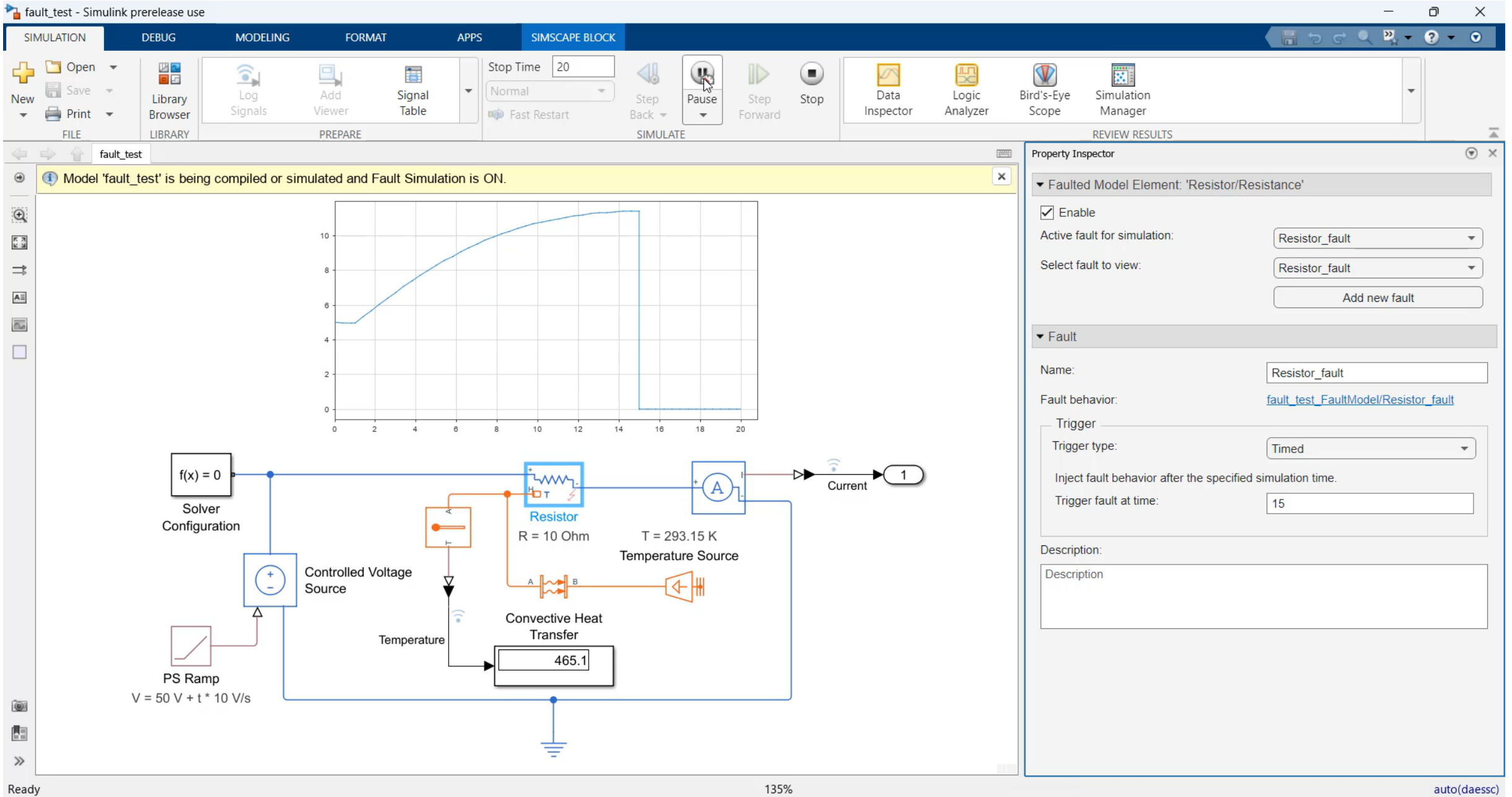
Battery Voltage Monitoring

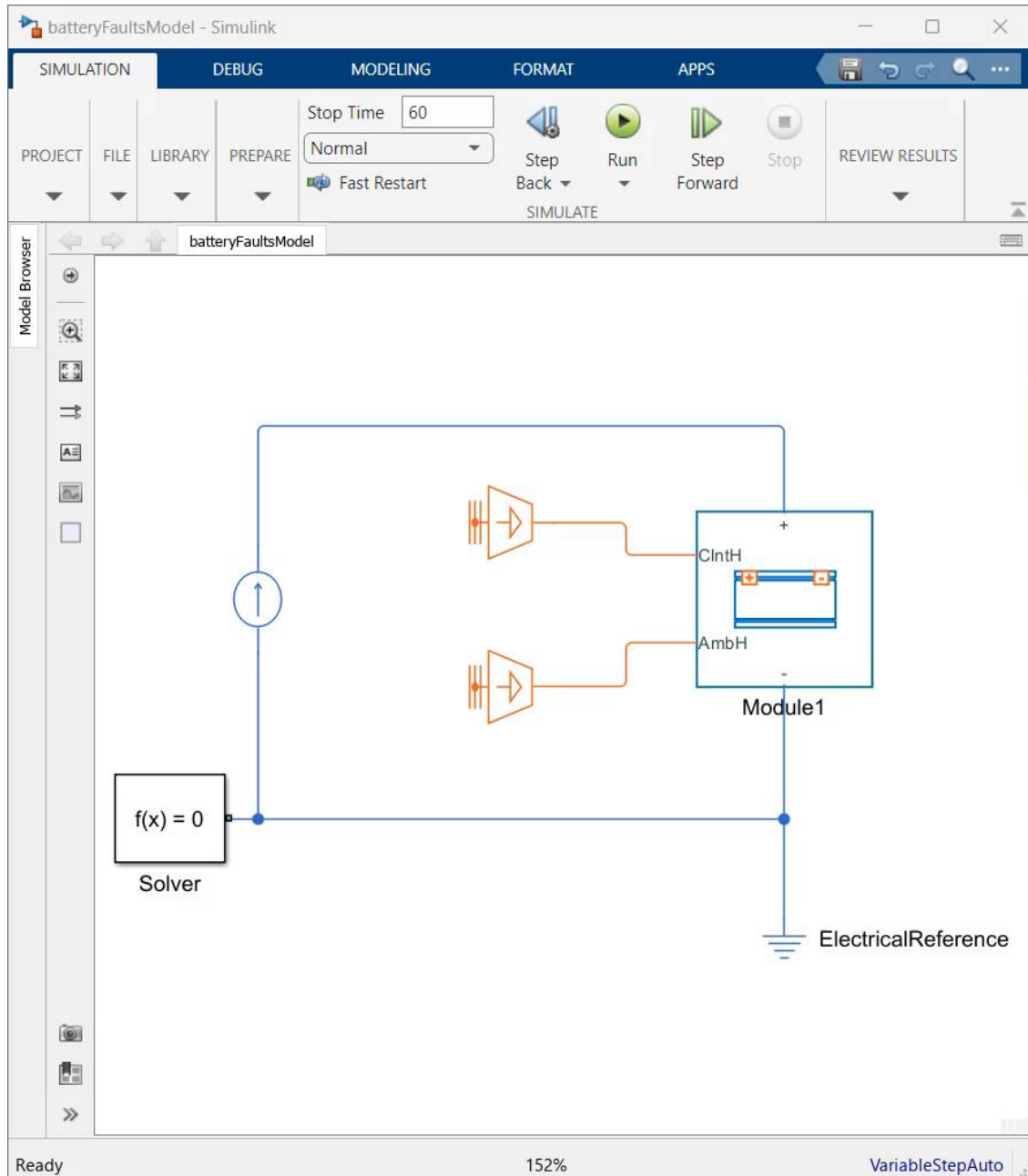


Fault Qualification

- ▶ Thermal Management







MATLAB R2023b

Try the New Desktop

Search Documentation

FILE CODE SECTION RUN

Live Editor - C:\Users\tgrimble\Dev\expo-battery-2023\programmaticFaults.mlx

Load our previously generated battery module

```
1 load("faultModuleData.mat","batteryModule");
2
3 batteryModule
```

Visualise the module

```
4 f = uifigure;
5 packChart = simscape.battery.builder.BatteryChart(...
6     Parent = f, Battery = batteryModule,SimulationStrategyVisible = "on");
```

Fault APIs for Simulink and Simscape

```
7 modelname = "batteryFaultsModel";
8
9 faulttableBlocks = simscape.findFaulttableBlocks(modelname)
```

Add a single fault

```
10 InternalShortFault = Simulink.fault.addFault(...
11     strcat(faulttableBlocks(1),"/ParallelAssembly1(10)/Cell1(1)/Internal short"));
12 InternalShortFault.addBehavior(strcat(modelname, "_FaultModel"));
```

Setup fault triggers programmatically

```
13 InternalShortFault.TriggerType = "Timed";
14 InternalShortFault.StartTime = 30;
15 InternalShortFault.activate;
```

Zoom: 100% UTF-8 LF script

Battery Cell Fault Modeling



Battery Equivalent Circuit

Property Inspector

▼ Faulted Model Element: 'Battery Equivalent Circuit/Exothermic reactions'

☒ Enable

Active fault for simulation: ExothermicReactionFault

Select fault to view: ExothermicReactionFault

Add new fault

▼ Fault

Name: ExothermicReactionFault

Fault behavior: ExothermicReactionFaultModel/BatteryEquivalentCircuit_fault

Trigger

Trigger type: Always On

Inject fault behavior throughout the simulation.

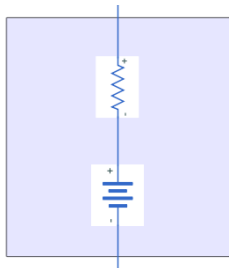
Block Parameters: BatteryEquivalentCircuit_fault

Battery Equivalent Circuit ☒ Auto Apply

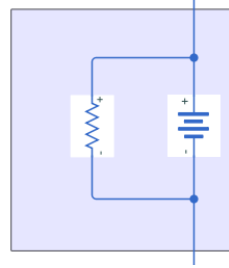
Settings Description

NAME	VALUE
▼ Faults	
Modeling fidelity	Analytical
<input type="checkbox"/> Tabulate with state of charge	
▶ Current interruption temperature	420 K
▶ Total heat of reaction	23e3 J
▶ Exotherm onset temperature	350 K
▶ Exotherm onset temperature rate	0.02 K/min
▶ Activation energy	160e3 J/mol
▶ Order of reaction	1
▶ Percent of thermal mass vented	40

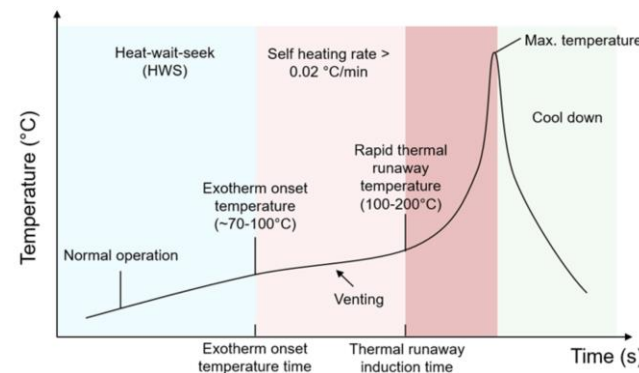
Additional Resistance Fault



Internal Short Fault



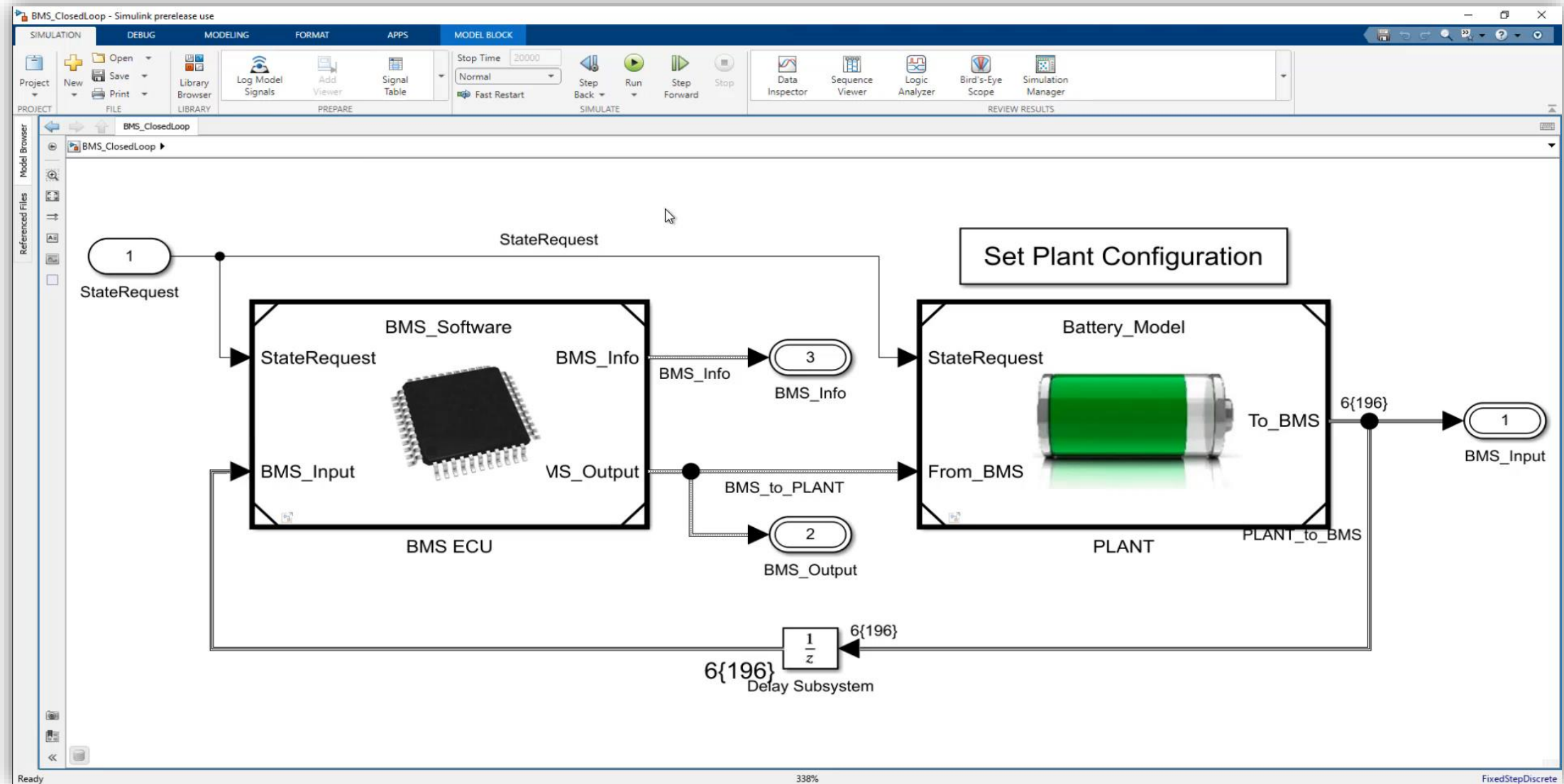
Exothermic Reaction Fault



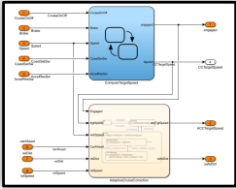
- ✓ Definition of time or condition dependent faults.
- ✓ Support modeling of thermal runaway events.

Inject Faults in Battery Models

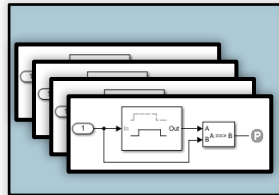
Unified Fault Framework



Design Logic



Fault Logic








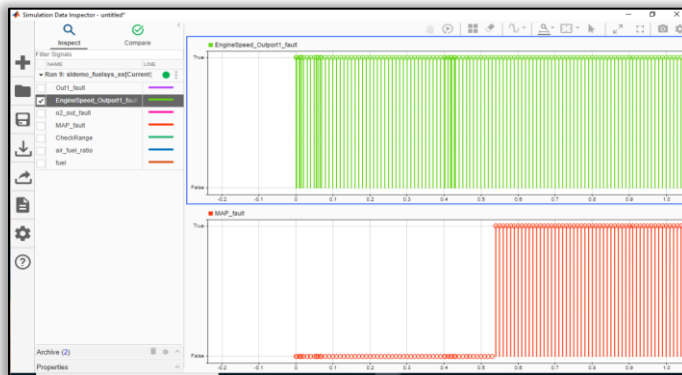
Model faults without
modifying the design

Simulink Fault Analyzer™

Manage faults across
multiple domains

Fault Table			
Fault		Conditional	
Enable	Model Element/Fault Name	Active Fault	Trigger
<input checked="" type="checkbox"/>	Environment/Constant6/Output/1 HighTemperatureFault	<input type="checkbox"/>	Conditional: highSpeedCondition
<input checked="" type="checkbox"/>	Environment/Constant7/Output/1 LowTemperatureFault	<input checked="" type="checkbox"/>	Conditional: SampleConditional
<input checked="" type="checkbox"/>	Environment/Constant7/Output/1 HighPressureFault	<input checked="" type="checkbox"/>	Timed: 20
<input checked="" type="checkbox"/>	Environment/Constant2/Output/1 LowPressureFault	<input type="checkbox"/>	Always On
<input checked="" type="checkbox"/>	Environment/Constant2/Output/1 Grade_fault	<input checked="" type="checkbox"/>	Always On
<input checked="" type="checkbox"/>	Environment/Constant2/Output/1 Grade_fault_1	<input type="checkbox"/>	Always On
<input checked="" type="checkbox"/>	Environment/Constant3/Output/1 wind_x_fault	<input checked="" type="checkbox"/>	Always On
<input checked="" type="checkbox"/>	Passenger Car/Electric Plant/Simscape/Inductor1/Inductor Inductor1_fault	<input checked="" type="checkbox"/>	Behavioral

Details: Design Study		
Specification	Run Options	
    		
Root Parameter Set		
Fault Set_1		



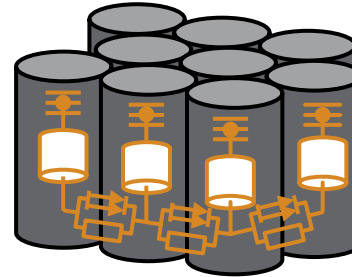
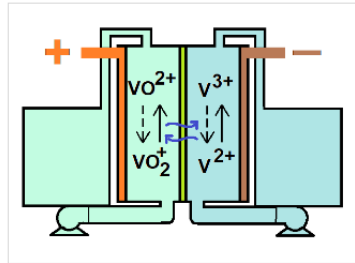
Simulate, explore and
analyze fault effects

Safety Analysis Manager				
HOME				
New	Open	Paste	Cut	Copy
Save	Import	Delete	Add Row	Add Column
FILE	EDIT	SPREADSHEET	LINKS	SEARCH
RobotFMEA				
	Failure Mode	Failure Rate (E-06)	Failure Effect	Detection Method
1	Angular Velocity Invalid After 50 seconds	1	Robot spins	Safety Lock
2	Angular Velocity Invalid at Maximum Pose	1	Robot spins	Safety Lock
1 warning Simulation errored out without Detection Method working.				

Perform systematic safety
analysis using simulation

Conclusions

- Energy Storage can extend far beyond just electrical modelling



- Critical to simulate real world power storage challenges



2
Electricity Cost



- Use MATLAB & Simulink to accelerate your design and problem solving throughout the design cycle

Learn More with MathWorks Onramps and Instructor-Led Training



Power Systems Simulation Onramp

5 modules | 1.5 hours | [Languages](#)

Learn how to progressively build and validate power systems using Simscape Electrical.



Power Electronics Simulation Onramp

5 modules | 1 hour | [Languages](#)

Learn the basics of simulating power electronics converters in Simscape.



Simscape Onramp

9 modules | 1.5 hours | [Languages](#)

Learn the basics of simulating physical systems in Simscape.



Simscape Battery Onramp

5 modules | 1 hour | [Languages](#)

Learn the basics of simulating battery systems in Simscape.



Circuit Simulation Onramp

7 modules | 2 hours | [Languages](#)

Learn the basics of simulating electrical circuits in Simscape.

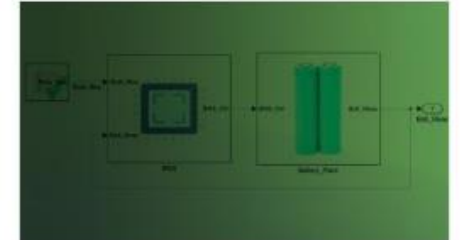
[Training – Courses in MATLAB, Simulink, Stateflow and Simscape](#)



Modeling Electrical Power Systems with Simscape

Model three-phase systems, analyze and control electrical power systems, model power electronic components, and speed up simulation of electrical models.

INTERMEDIATE



Battery Modeling and Algorithm Development with Simulink

In this course, you will learn how to use Simscape and Stateflow to model battery packs and develop supervisory controls for battery management systems.

INTERMEDIATE

[Self-Paced Online Courses - Physical Modeling](#)