

MATLAB EXPO

Going Beyond the Electrical in Modelling Energy Storage Systems

Tom Grimble, MathWorks



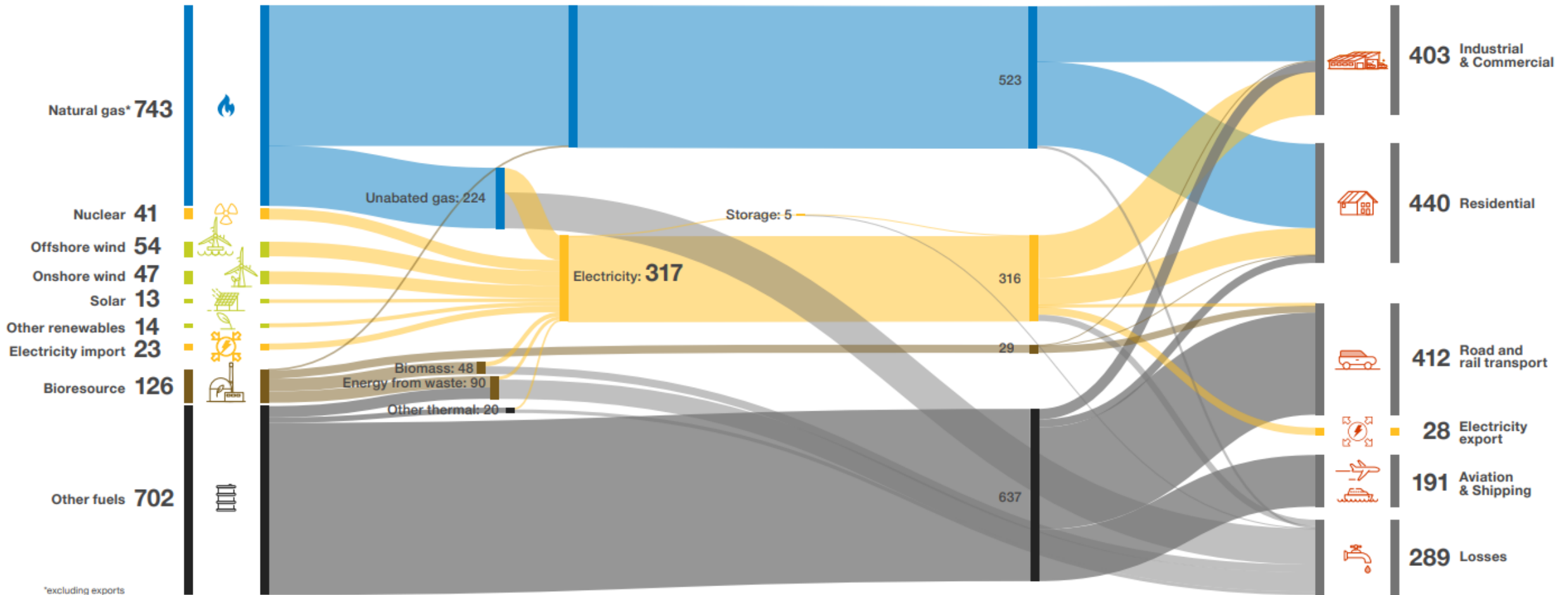
Key Takeaways

- 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



UK Energy Today

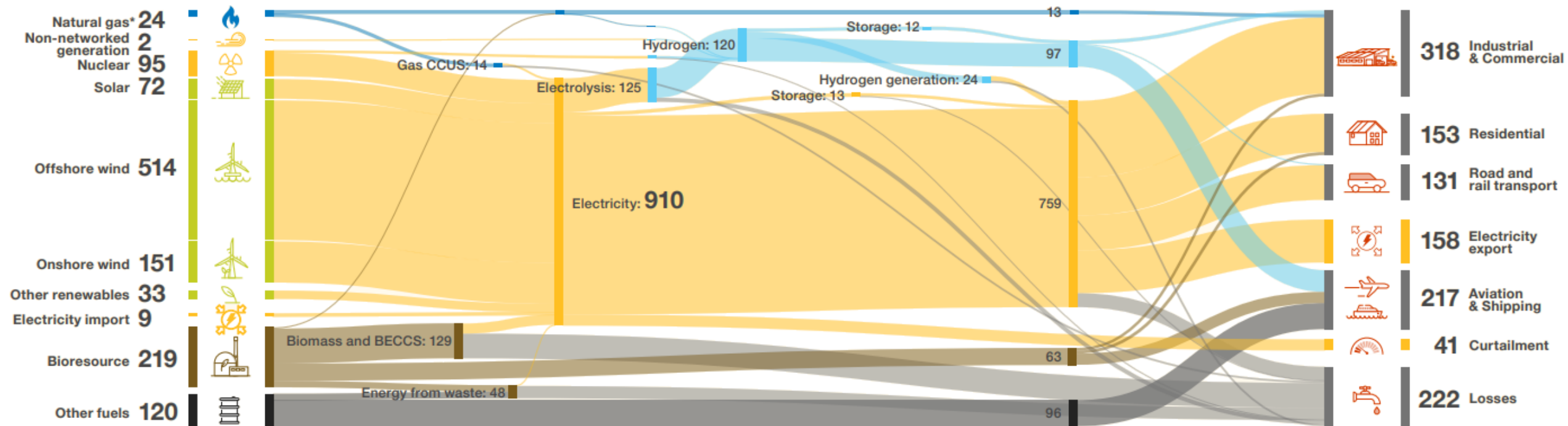
2022 – 1763 TWh



[National Grid ESO Future Energy Scenarios 2023 report](#)

What About Tomorrow?

2050 – 1239 TWh



[National Grid ESO Future Energy Scenarios 2023 report](#)

Growth in Grid Connected Energy Storage

Current UK Capacity

- 2.4 GW

250 million ×



Capacity increase (GW)

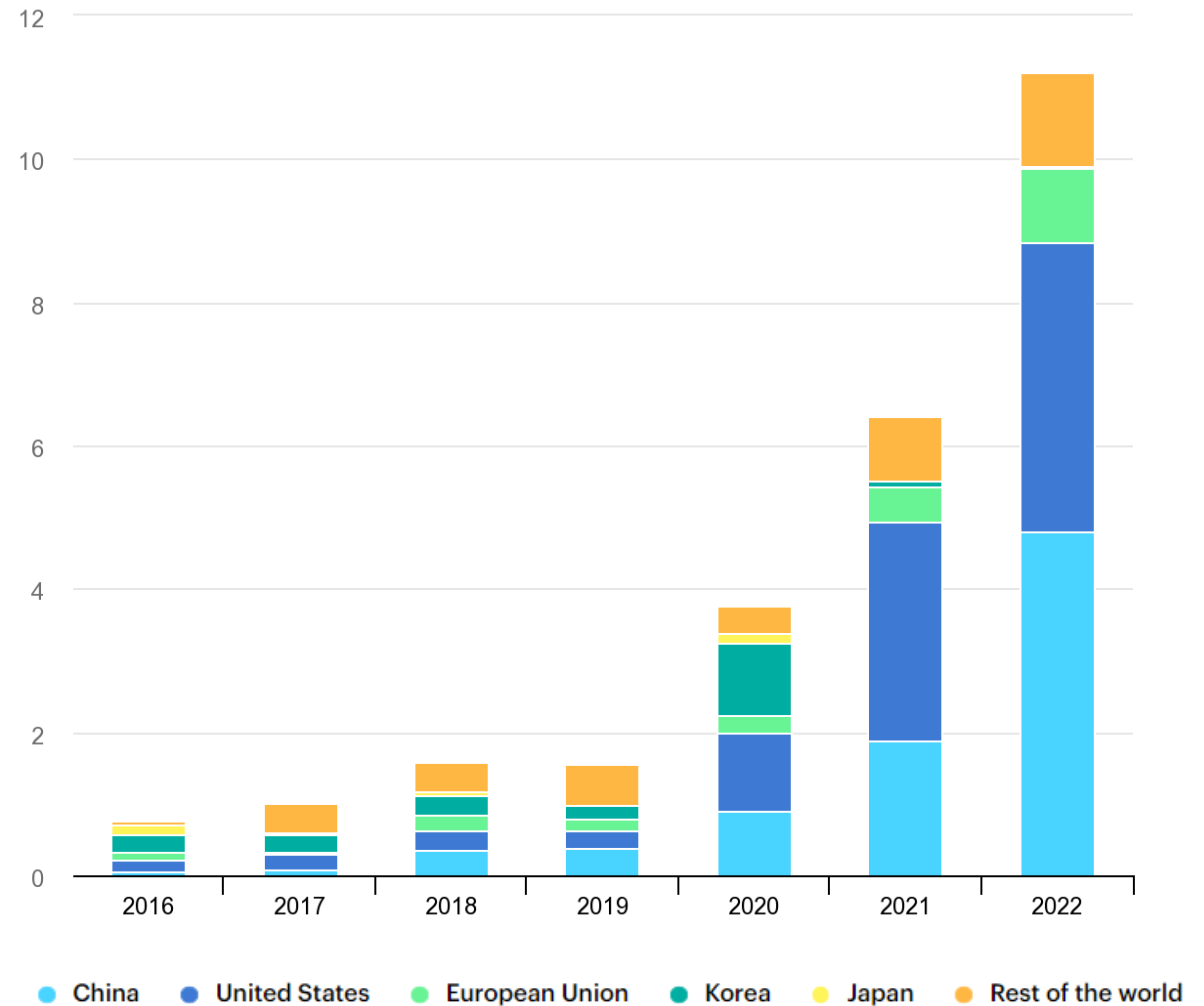
40000 ×



66 GW Additional planned capacity

(2022 Grid generation capacity ~80GW)

Energy Storage Capacity Increase by Year and Region



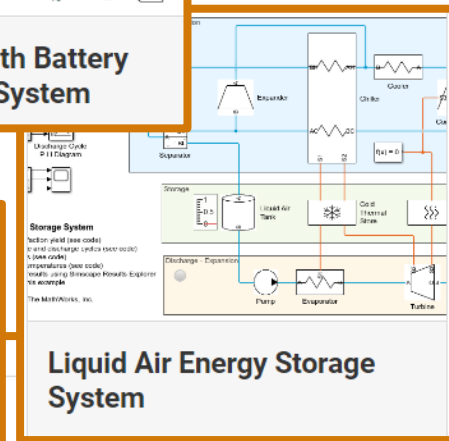
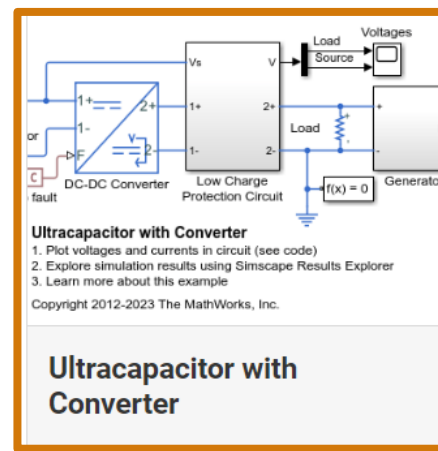
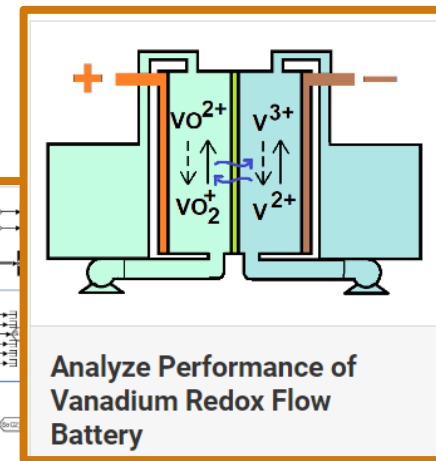
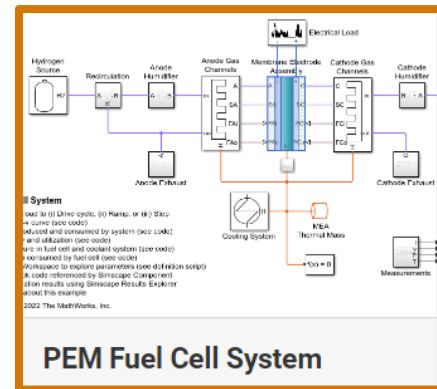
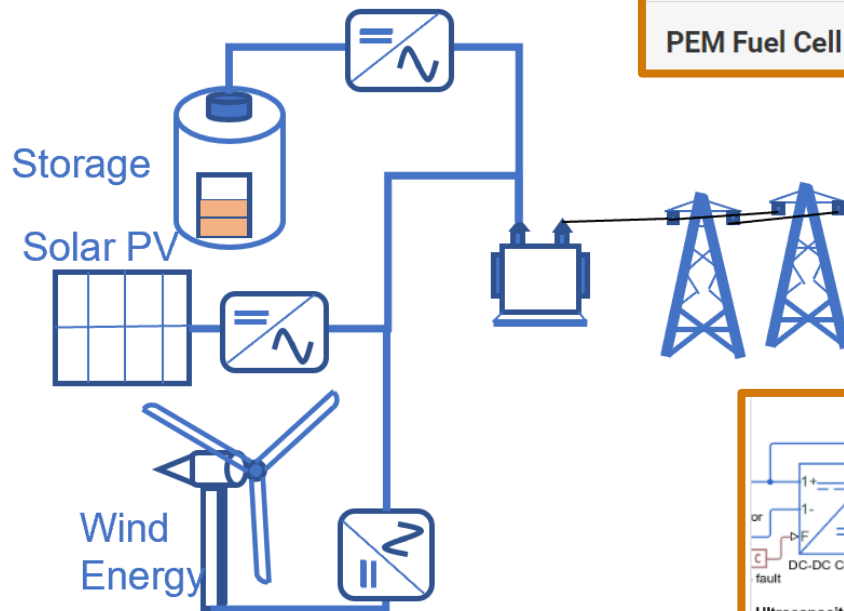
Exploring Technology Options

Three-Phase Grid-Connected Solar Photovoltaic System

Brayton Cycle (Gas Turbine)

Wind Turbine

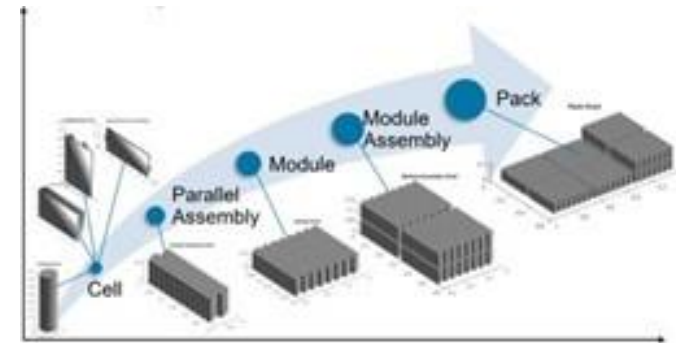
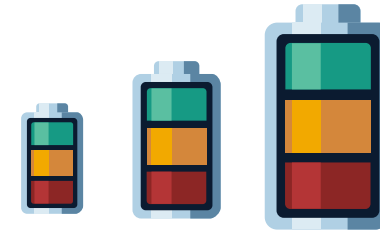
Photovoltaic Thermal (PV/T) Hybrid Solar Panel



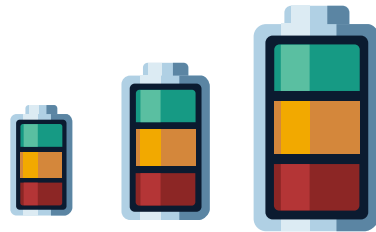
Evaluate Performance of Grid-Forming Battery Energy Storage Systems in Solar PV Plants

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



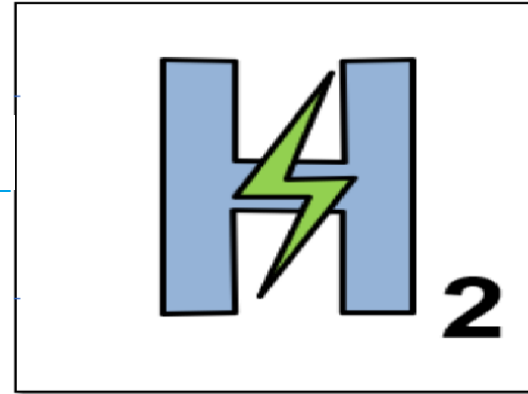
Sun (irradiance)



Solar Array

Electricity

Water



Electrolyzer

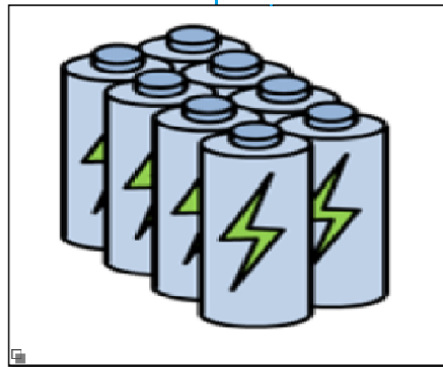
Early design with many assumptions



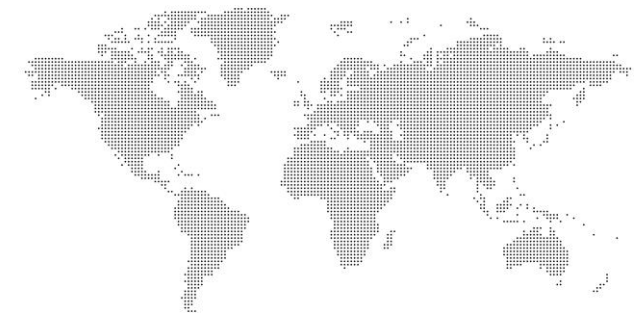
Hydrogen (gas)



Predict performance over a year

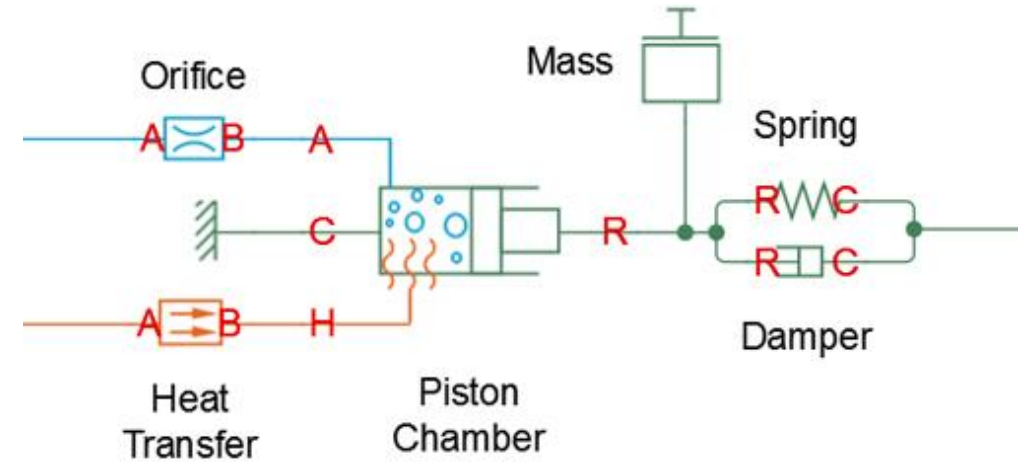
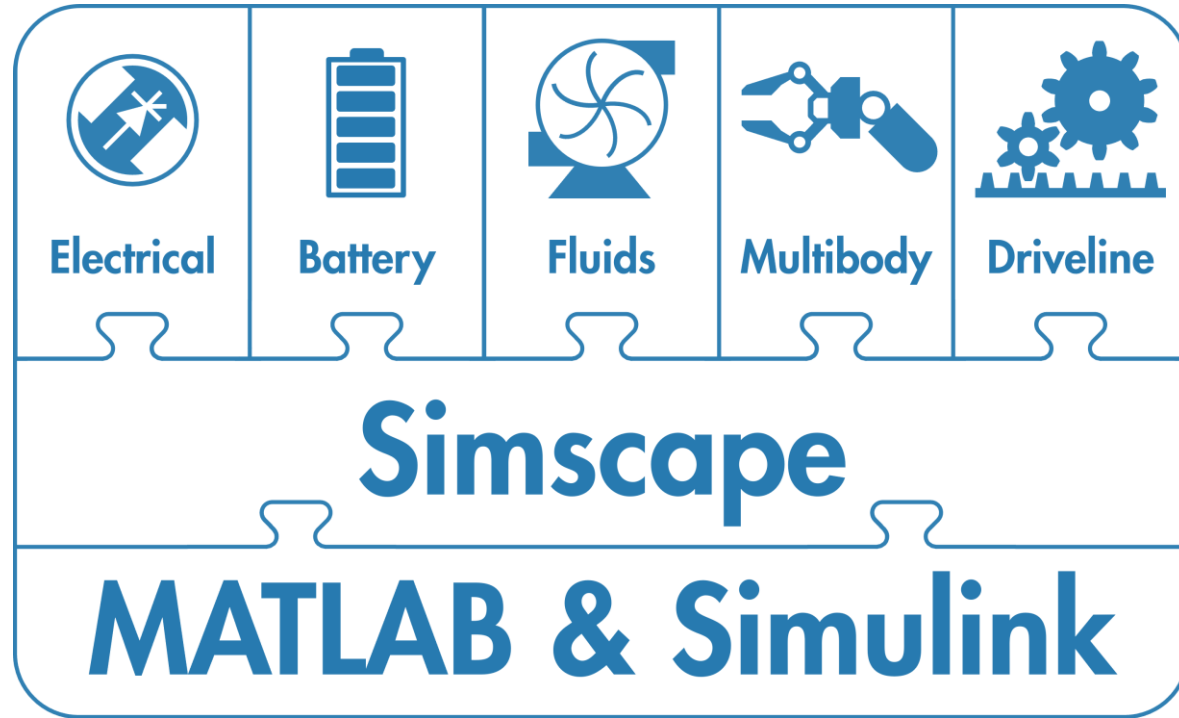


Energy storage



Identify optimal location

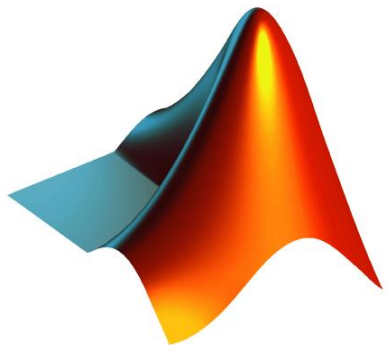
Cost Analysis with MATLAB & Simulink



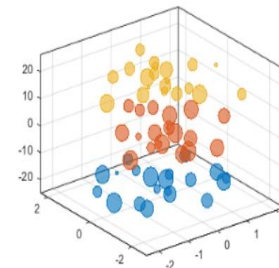
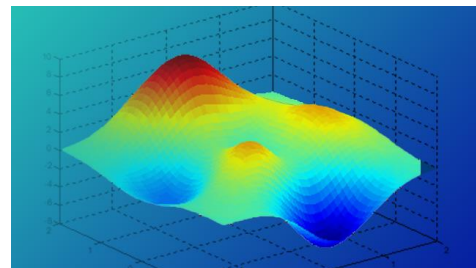
What about



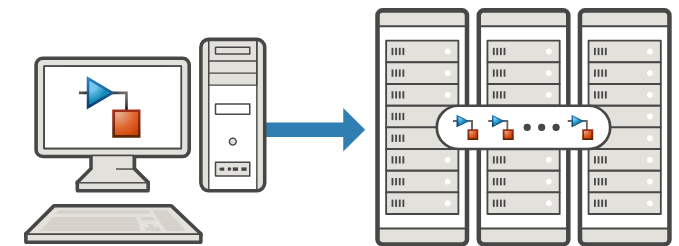
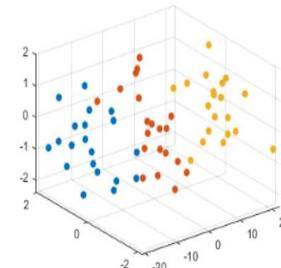
?



Optimization Algorithms



Visualization



Prototype

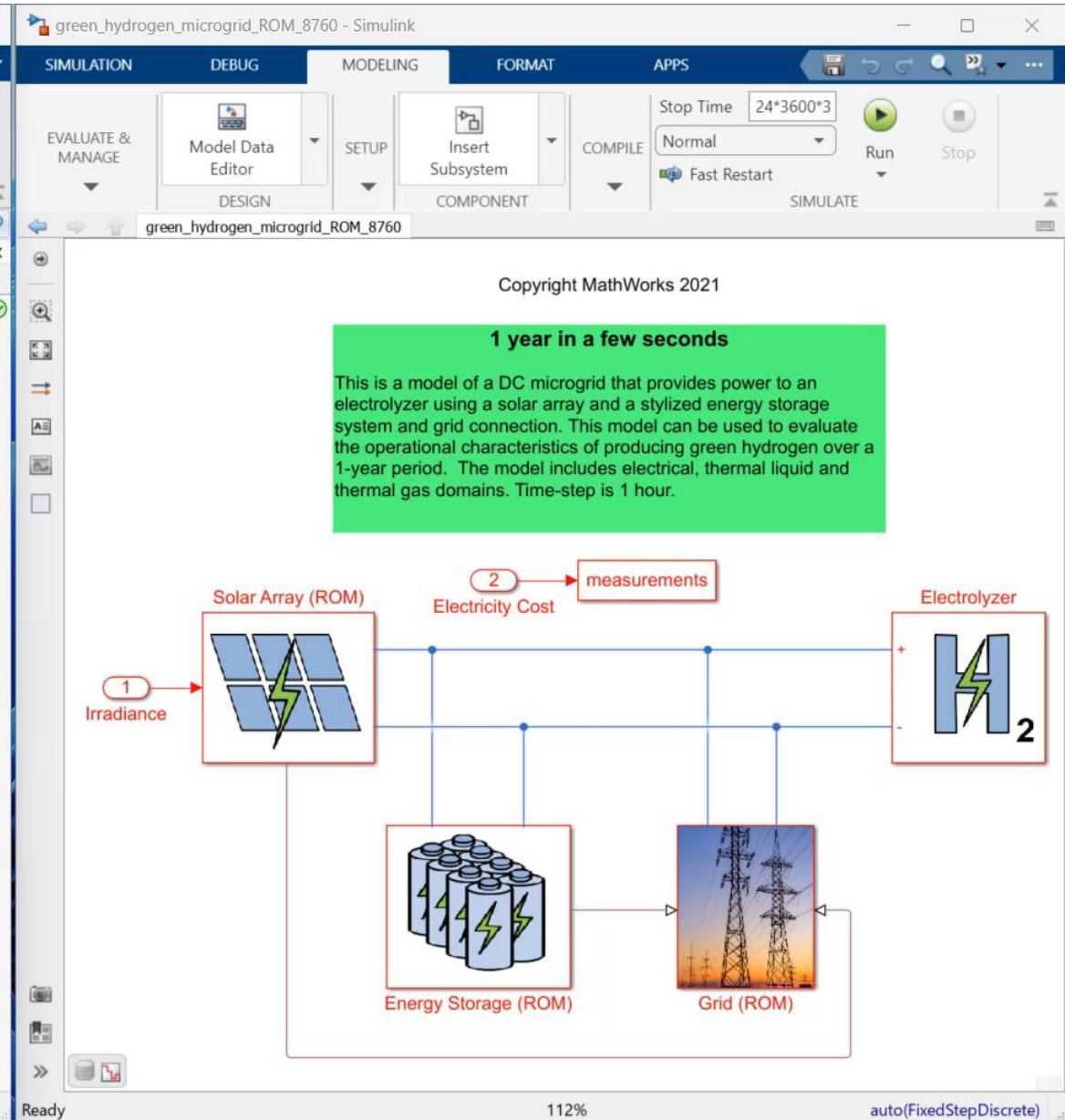
Scale

Parallelization & Scaling

```

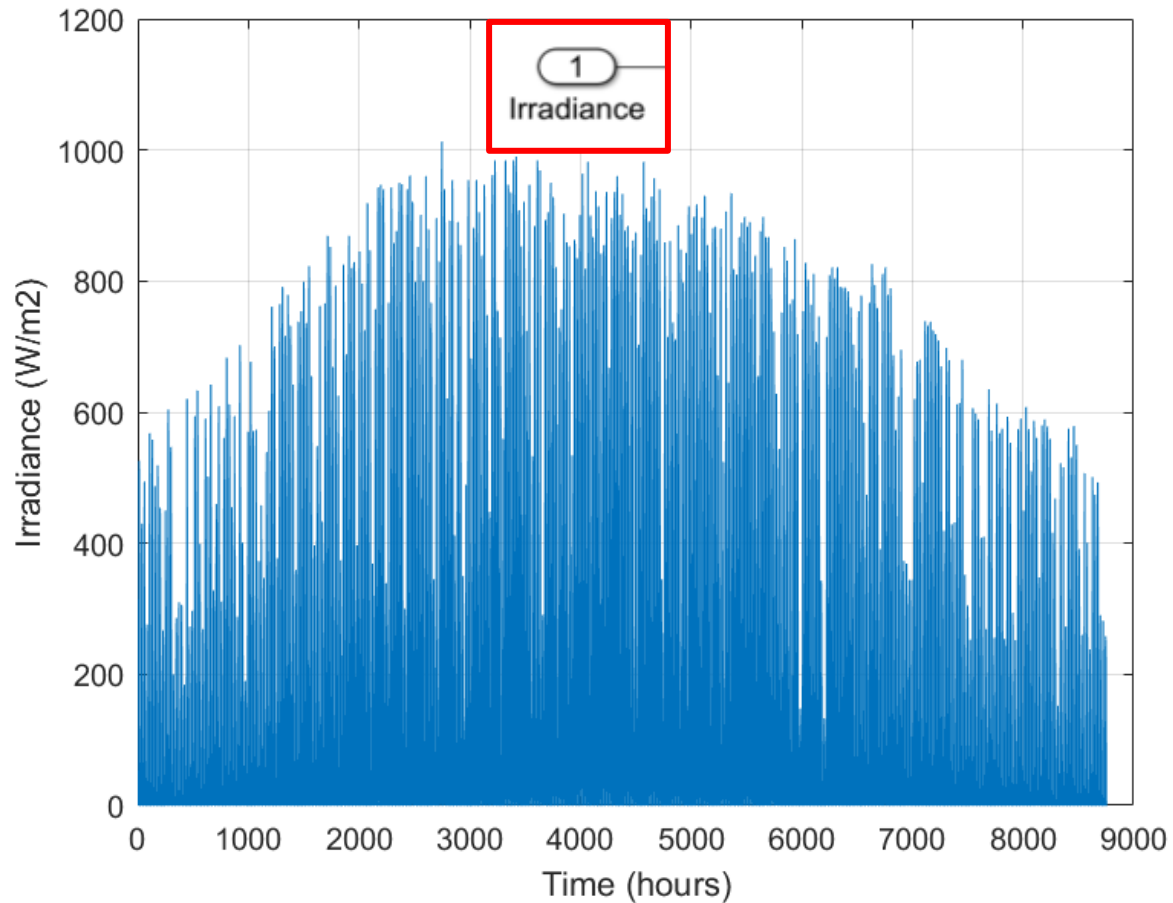
MATLAB R2023a
H... P... A... E... V... Search Documentation Tom
New Open Save Print Compare Refactor ANALYZE SECTION Run Step Stop
FILE CODE RUN
C:\Users\tgrimble\Dev\green-hydrogen-production\8760
Editor - C:\Users\tgrimble\Dev\green-hydrogen-production\8760\parsimScenarios.m
energy_storage_thevenin_equivalent.m parsimScenarios.m Parameter_File.m
1 %% load data
2
3 loadPriceData
4
5 load('StationData_UPDATE')
6
7 %% Define scenario input objects
8
9 for l = 1:numel(StationData)
10
11     irradiance = StationData(l).Irradiance*200+1000;
12     input8760 = [(0:3600:3600*24*365-3600)' irradiance price8760];
13
14     in(l) = Simulink.SimulationInput('green_hydrogen_microgrid_ROM_87
15     in(l) = in(l).setVariable('input8760',input8760);
16 end
17
18 %% Simulate scenarios
19
20 tic
21 out = parsim(in, 'ShowSimulationManager', 'on', 'UseFastRestart', 'or
22 toc
23
24 %%
25
26 grid_cost = zeros(numel(StationData),1);
    
```

Zoom: 90% UTF-8 CRLF script Ln 3 Col 14

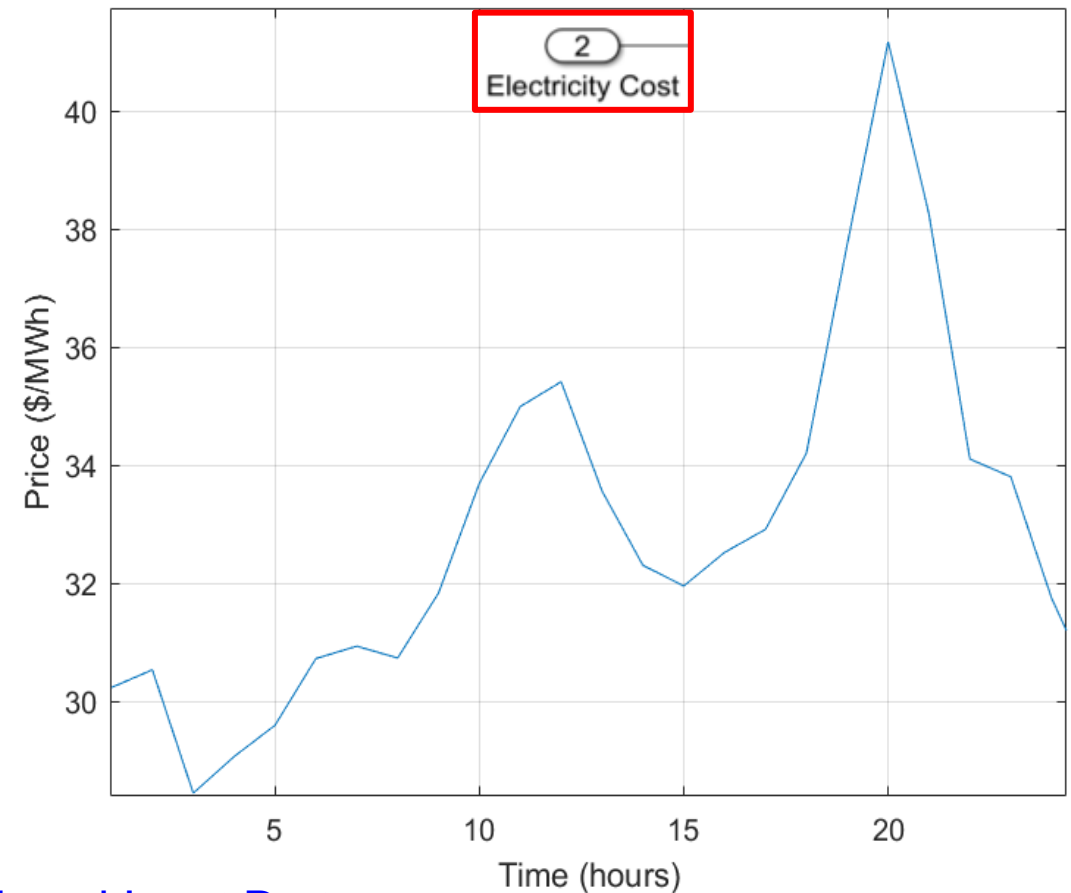


Injecting Real World Data

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



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



[Load Data to Root-Level Input Ports](#)

Goal of Simulation / Level of Fidelity

Detailed component modelling

System level modelling

Control Response Dynamics

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

Quasi-Steady State

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

High Frequency Power Electronic Switching

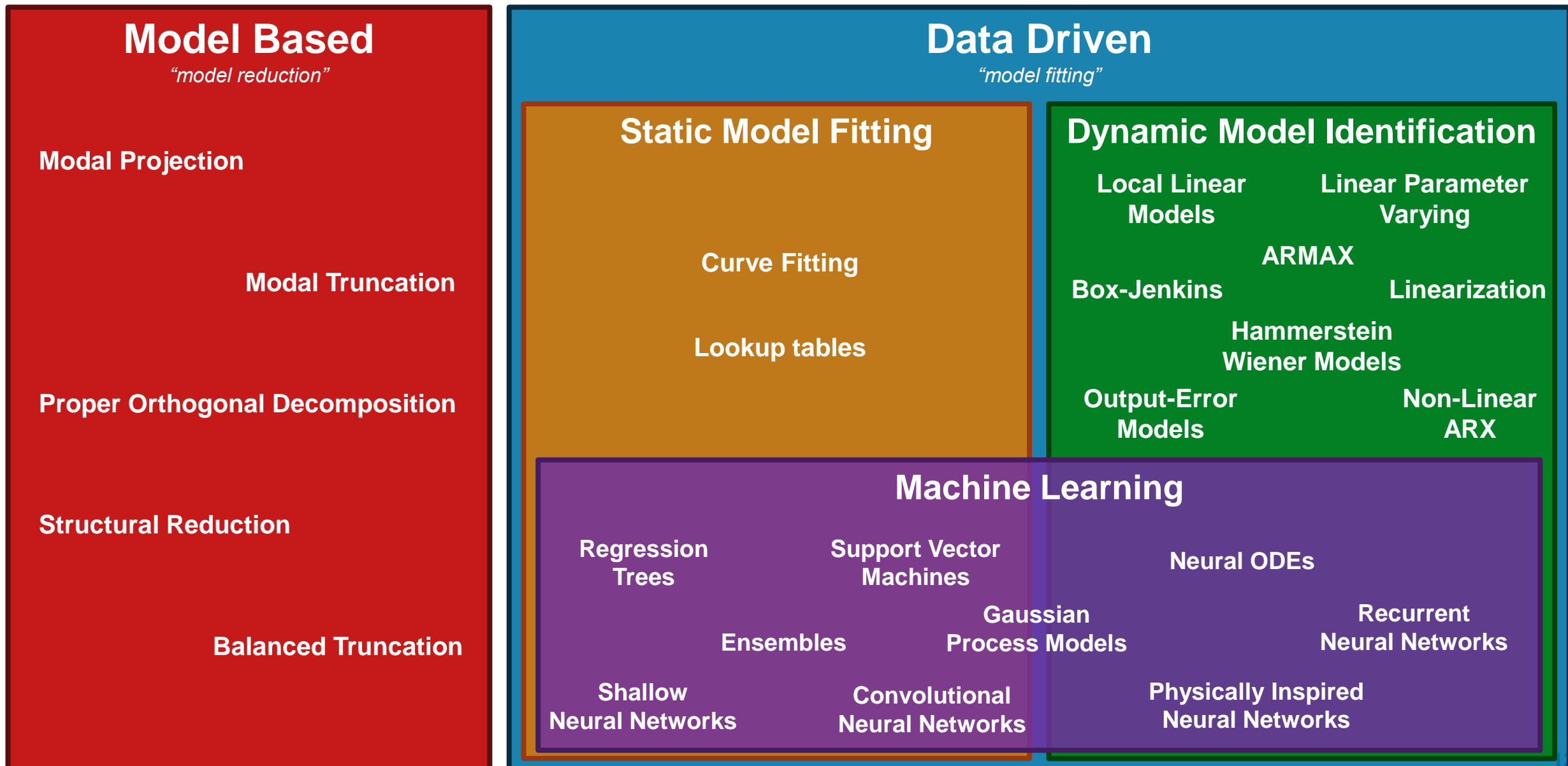
- Detailed modelling of semiconductors and converter dynamics
- Optimizing waveforms and losses at component level

Thermal dynamics

- Transient thermal response
- Coupling thermal dependency to electrical performance



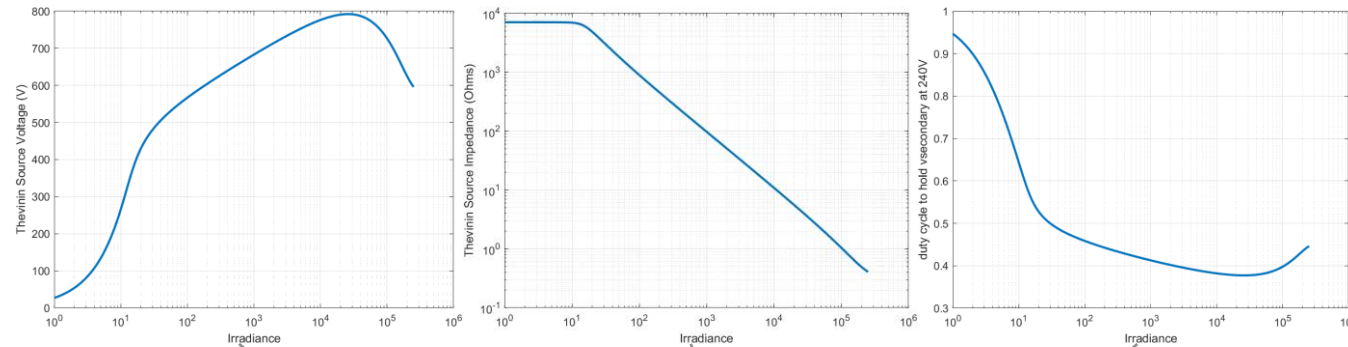
Techniques for Reduced Order Modelling



ROM Implementation

Performance assessment

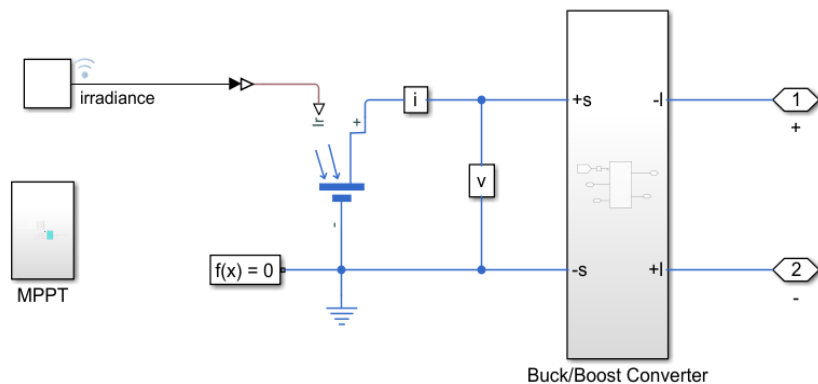
Medium fidelity



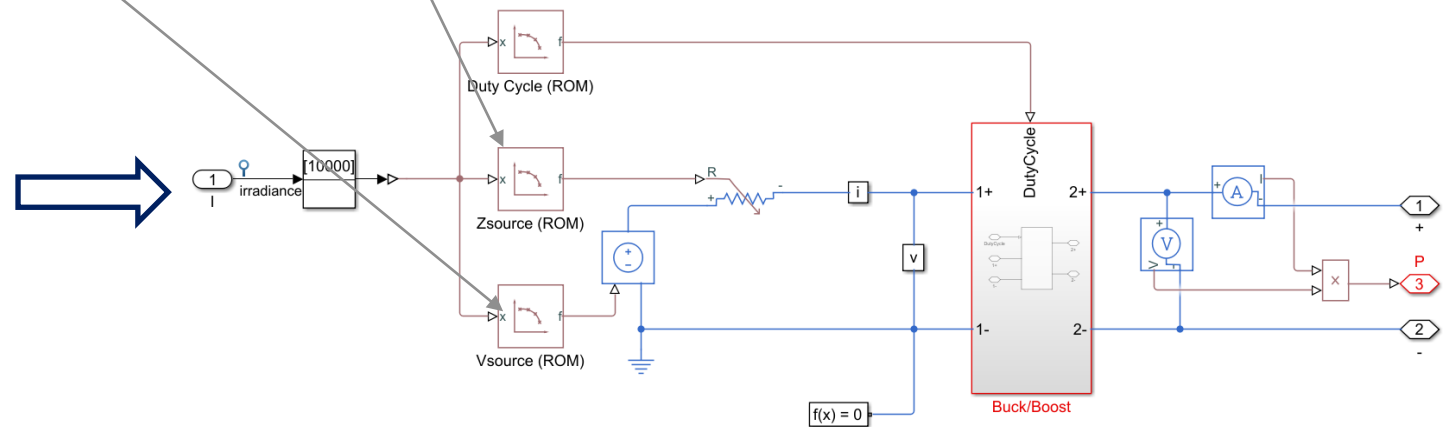
Techno-economic analysis

Low fidelity

Solar cell & MPPT algorithm



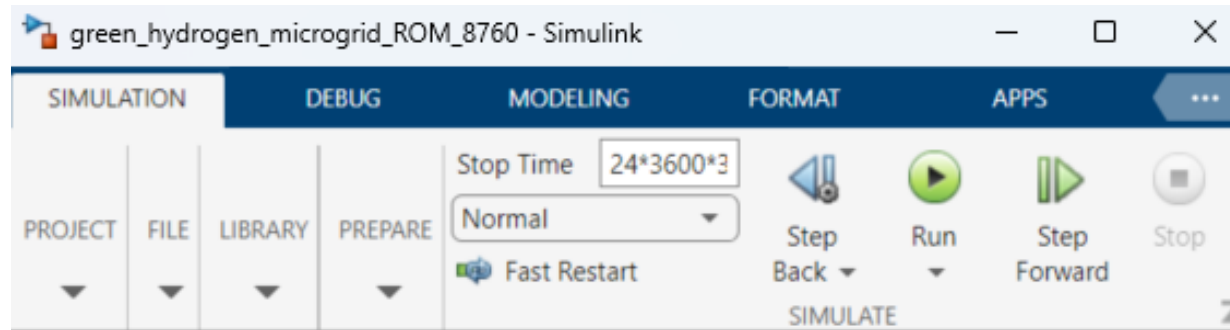
Reduced Order Modeling (ROM)



Capture steady state operating point

Quasi-steady lookup table model

Clean Instancing for Model Setup



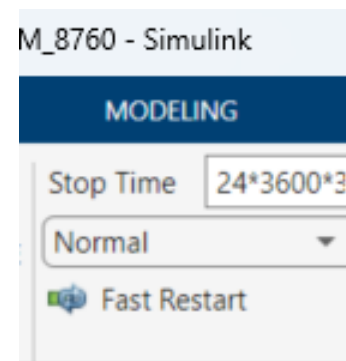
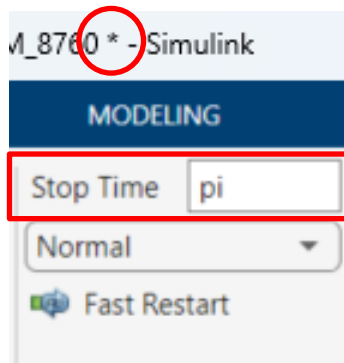
StopTime = "24*3600*365"

To change this via script:

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

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

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

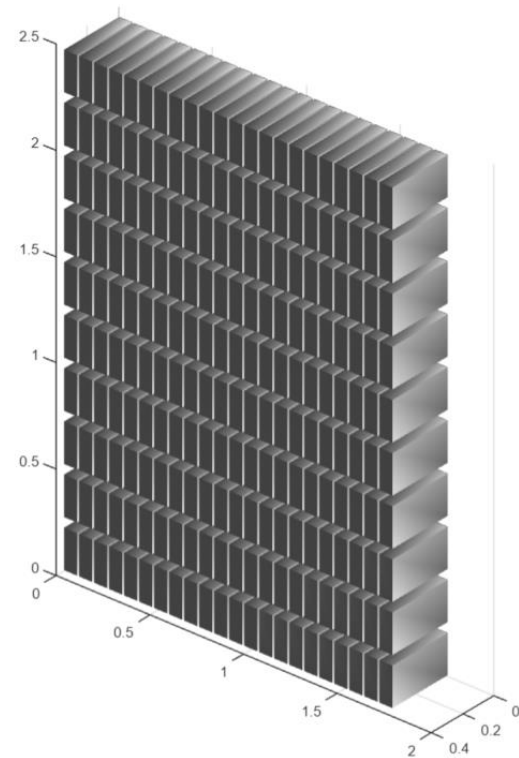


| Property ^ | Value |
|-----------------|-------------------------------------|
| ModelName | 'green_hydrogen_microgrid_ROM_8760' |
| InitialState | 0x0 ModelOperatingPoint |
| ExternalInput | [] |
| ModelParameters | 1x1 ModelParameter |
| BlockParameters | 0x0 BlockParameter |
| Variables | 0x0 Variable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

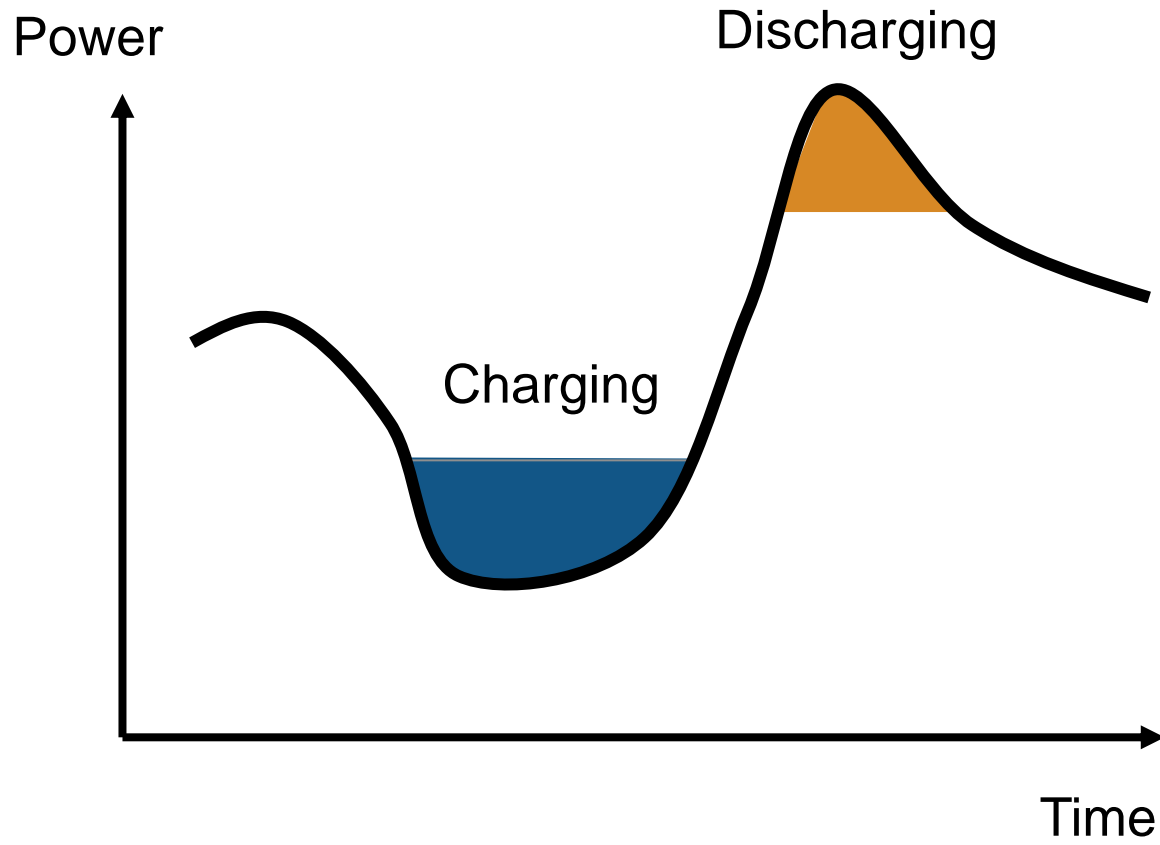
[Create Simulink.SimulationInput objects to make changes to model for multiple or individual simulations](#)

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

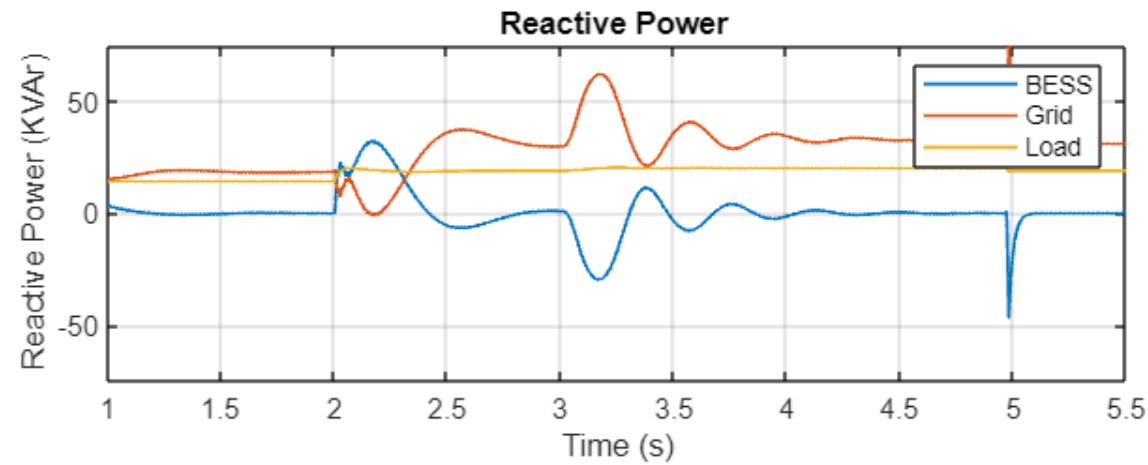
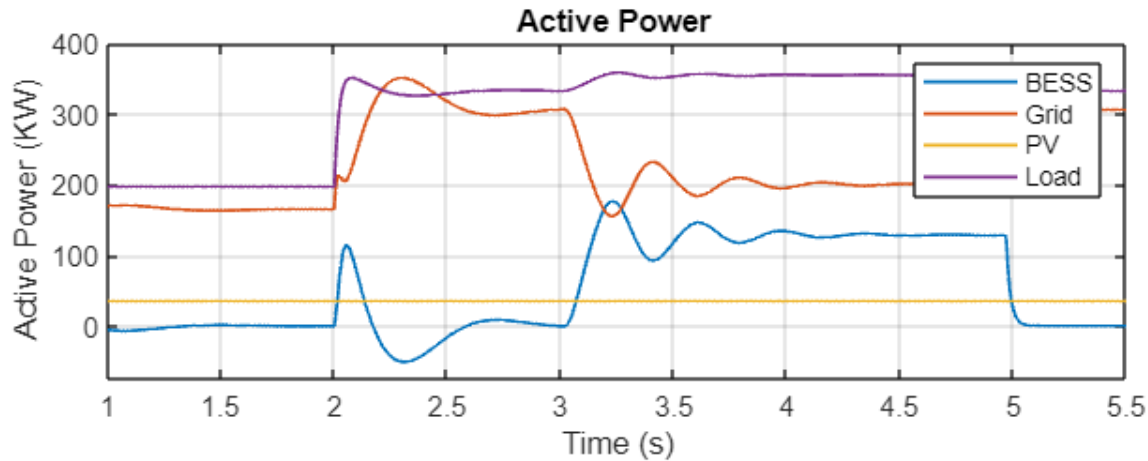
Detailed Design



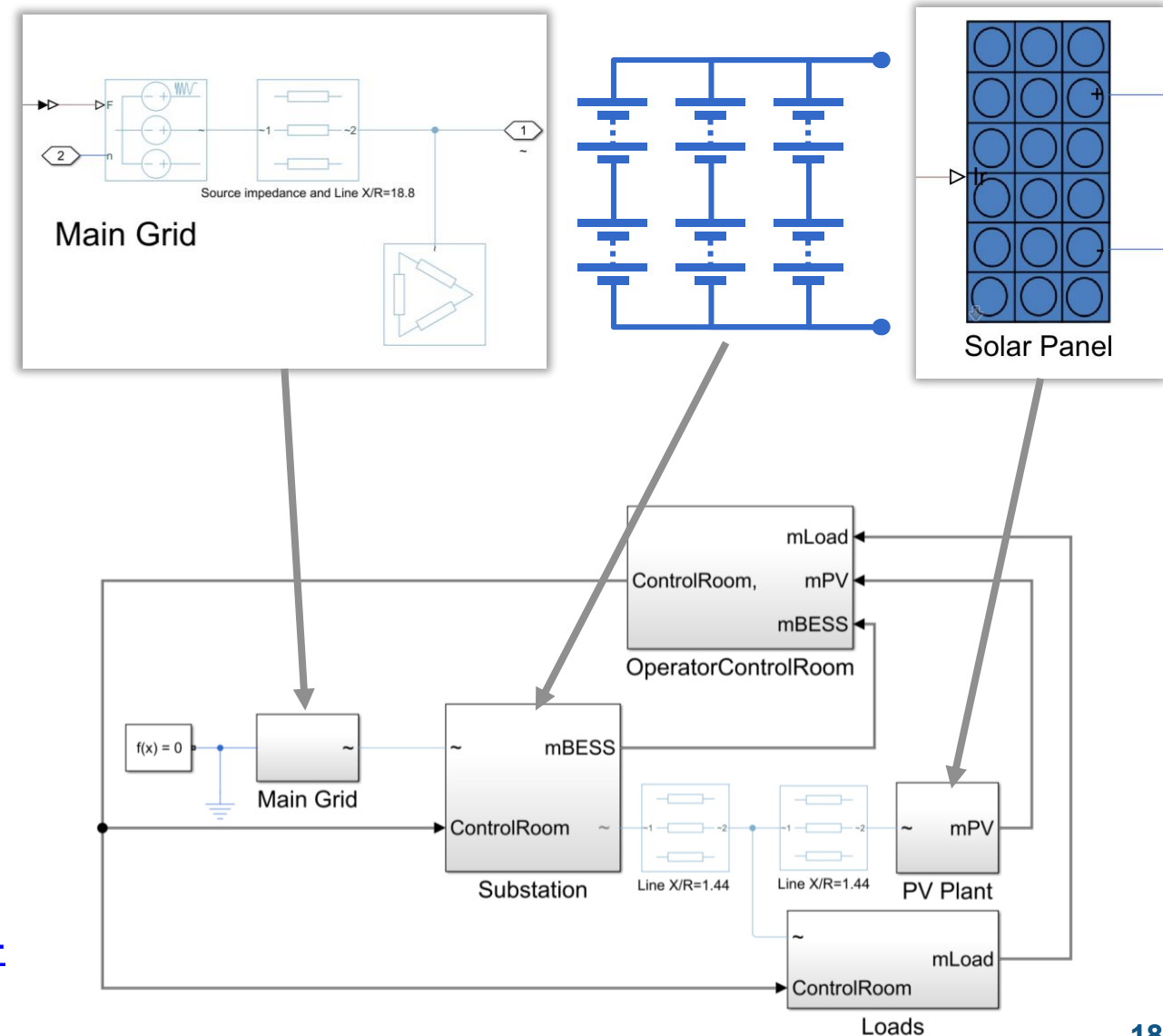
Peak Shaving



Peak Shaving



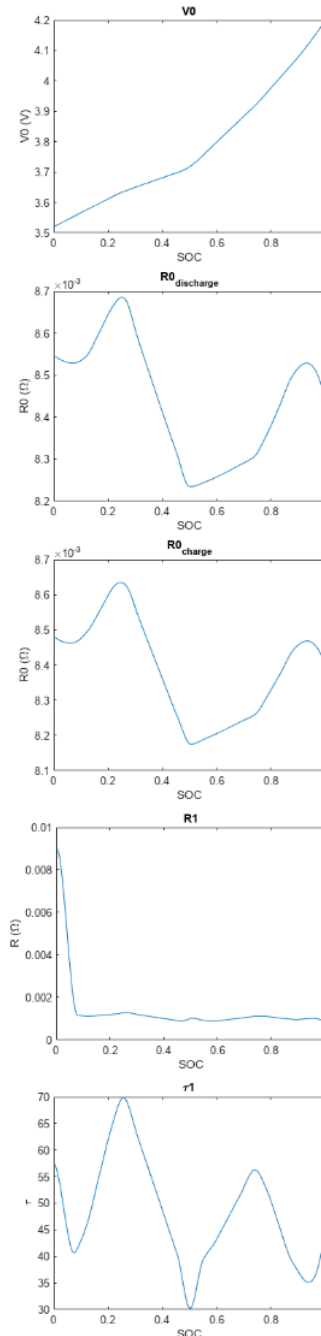
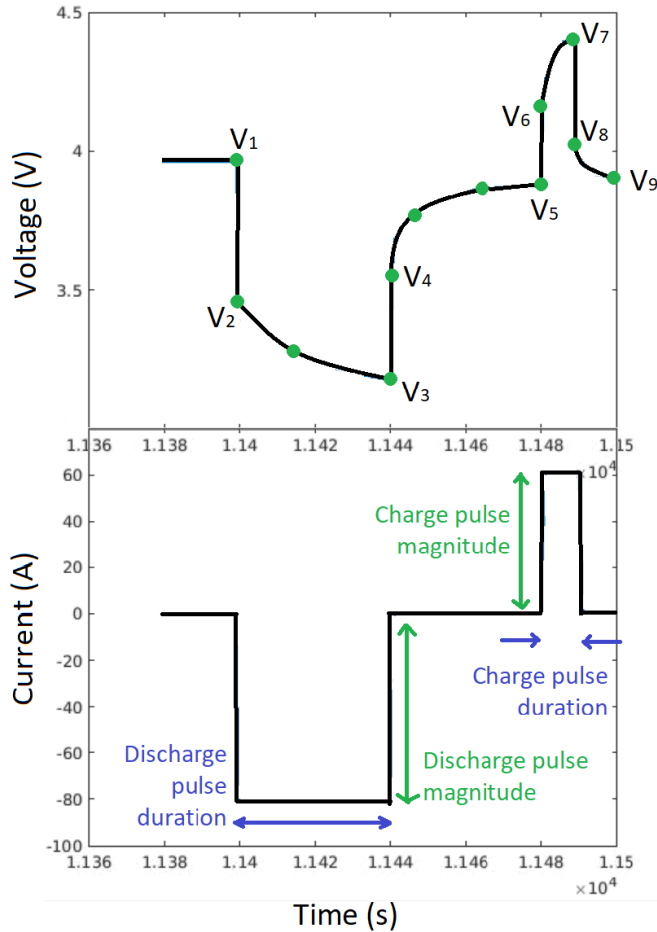
How do we model this complex battery architecture?



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

Battery Parameters

Fit from Data



Pre-parametrized parts



Battery Equivalent Circuit

Block Parameters: Battery Equivalent Circuit

Battery Equivalent Circuit Auto Apply

Settings Description

| NAME | VALUE |
|------------------|----------------------|
| Selected part | <click to select> |
| Main | |
| Battery capacity | 27 A*hr |
| Thermal model | Constant temperature |

Block Parameterization Manager: Battery Equivalent Circuit

| 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 |

| 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 BUILDER BATTERY CHART

Import Cell Module Assembly Duplicate Delete Export Create Library

FILE CREATE BROWSER EXPORT LIBRARY

Battery Browser Selected Battery

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)

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

GridPack (Pack)

z: Vertical direction

y: Lateral direction

x: Forward direction

Simulation Strategy

Scripted Battery

The image displays the MATLAB R2023b environment with a script editor on the left and a plot window on the right. The script, named `packBuildApiPlot.m`, defines a battery library and generates 3D plots for its components.

```

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");
  
```

The plot window displays four 3D visualizations of battery components:

- Cell:** A single rectangular cell with dimensions approximately 0.4 x 0.2 x 0.2.
- Parallel Assembly:** A single rectangular cell, identical to the Cell plot.
- Module:** A stack of 2 cells, with a height of 0.4.
- Module Assembly:** A stack of 2 modules, with a height of 0.8.
- Pack:** A stack of 2 module assemblies, with a height of 1.6.

The status bar at the bottom indicates "2 usages of 'libName' found", "Zoom: 100%", "UTF-8", "LF", "script", "Ln 68", and "Col 4".

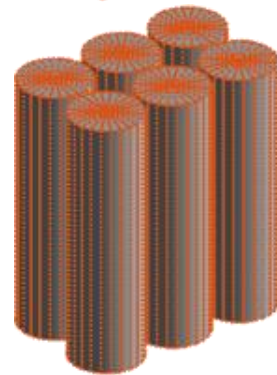
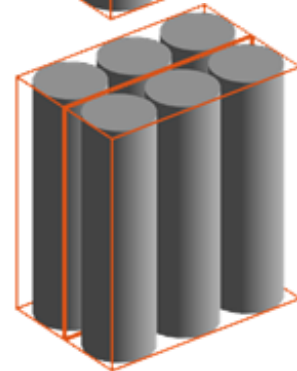
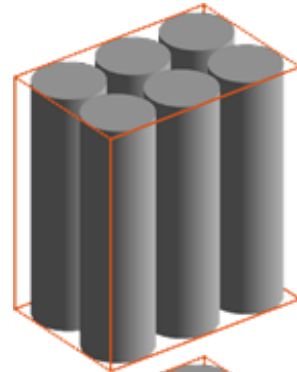
Battery Pack Model Fidelity

- Lumped resolution
 - One electrothermal element

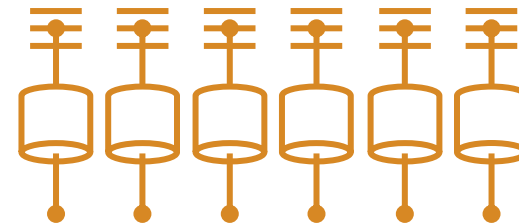
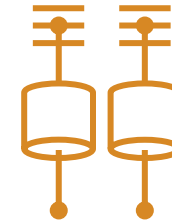
- Grouped resolution
 - Any number of arbitrarily grouped elements

- Detailed resolution
 - Every cell modeled individually

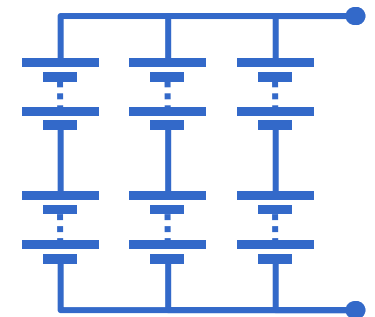
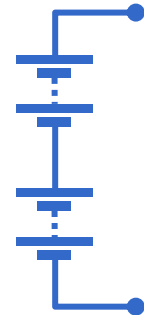
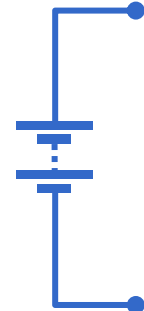
Pack Visualization



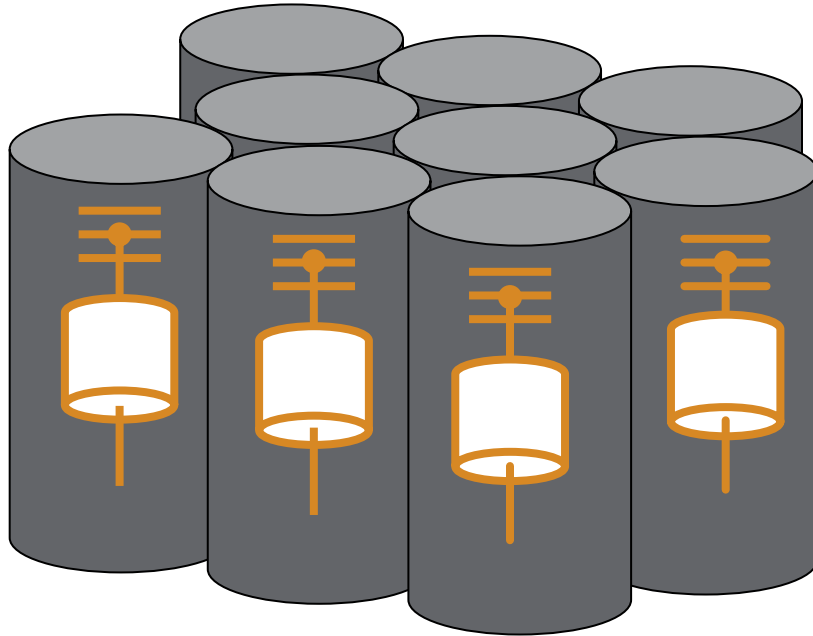
Equivalent Thermal Model



Equivalent Electrical Model

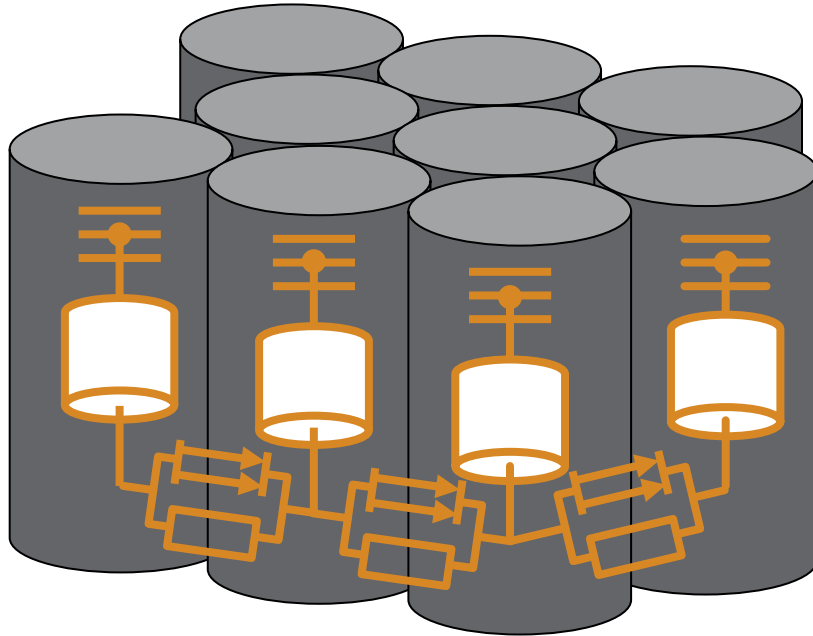


Thermal Connections



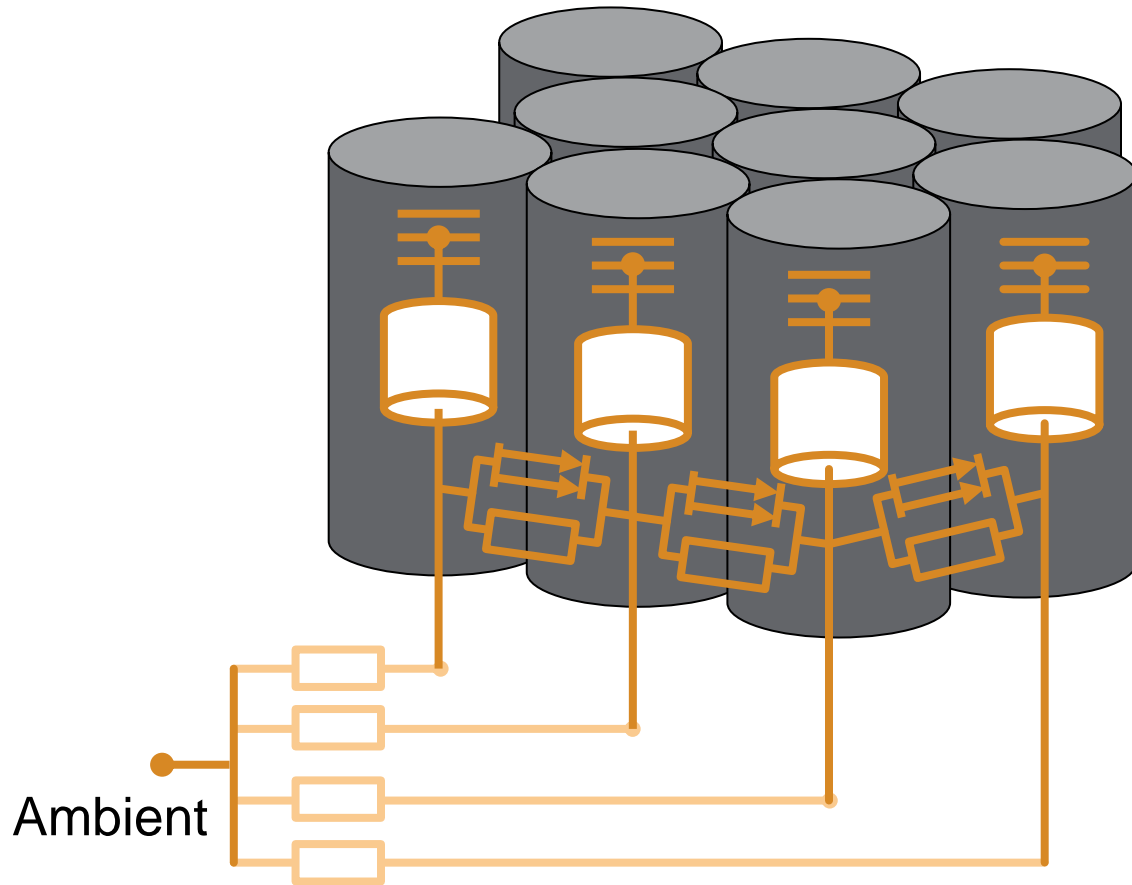
```
batteryModule = Simscape.Battery.Builder.Module(...  
    ParallelAssembly = pAssembly,...  
    NumSeriesAssemblies = 3,...  
    ModelResolution = "Detailed");
```

Thermal Connections



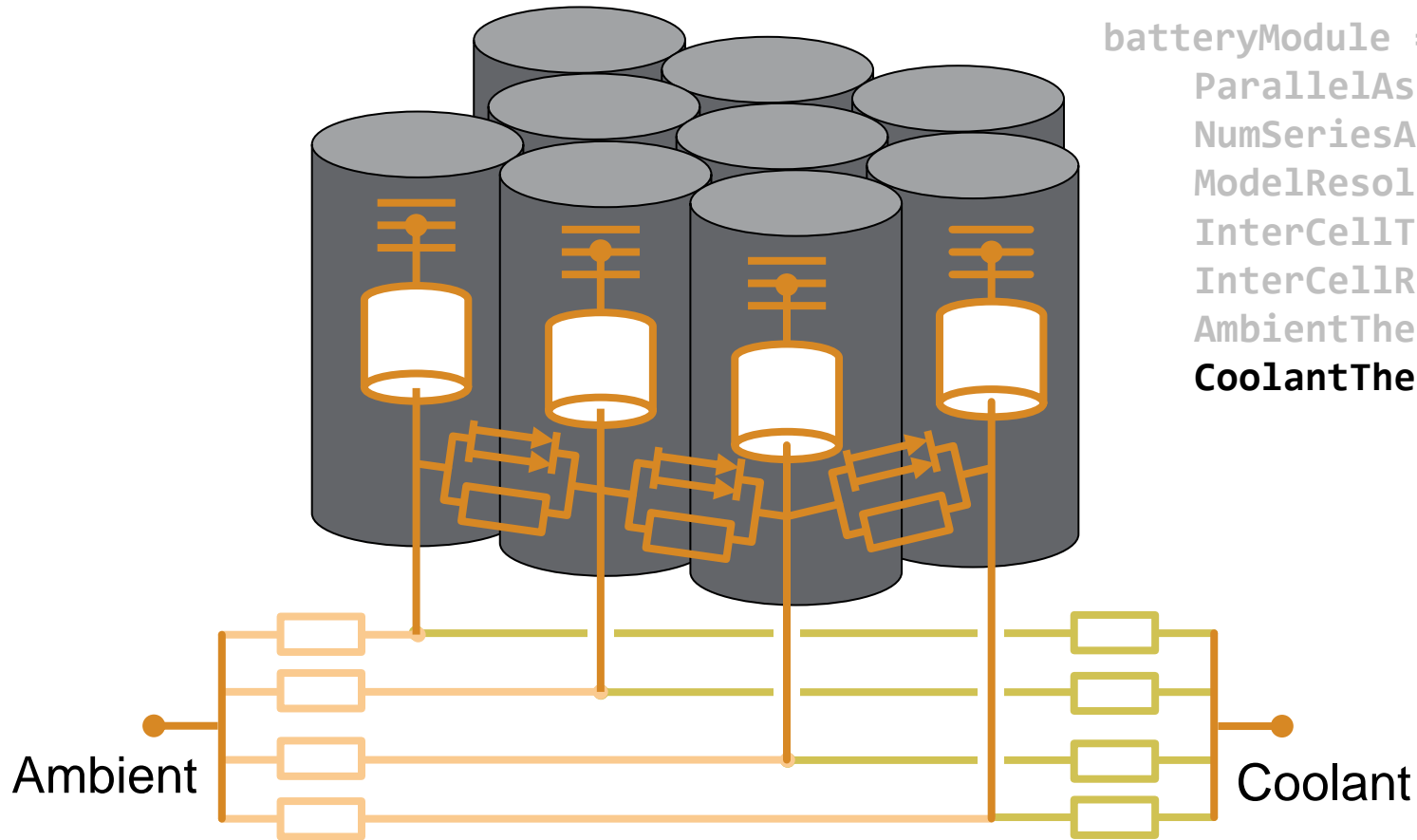
```
batteryModule = Simscape.Battery.Builder.Module(...  
    ParallelAssembly = pAssembly,...  
    NumSeriesAssemblies = 3,...  
    ModelResolution = "Detailed",...  
    InterCellThermalPath = "on",...  
    InterCellRadiativeThermalPath = "on");
```

Thermal Connections



```
batteryModule = Simscape.Battery.Builder.Module(...  
    ParallelAssembly = pAssembly,...  
    NumSeriesAssemblies = 3,...  
    ModelResolution = "Detailed",...  
    InterCellThermalPath = "on",...  
    InterCellRadiativeThermalPath = "on",...  
    AmbientThermalPath = "CellBasedThermalResistance");
```

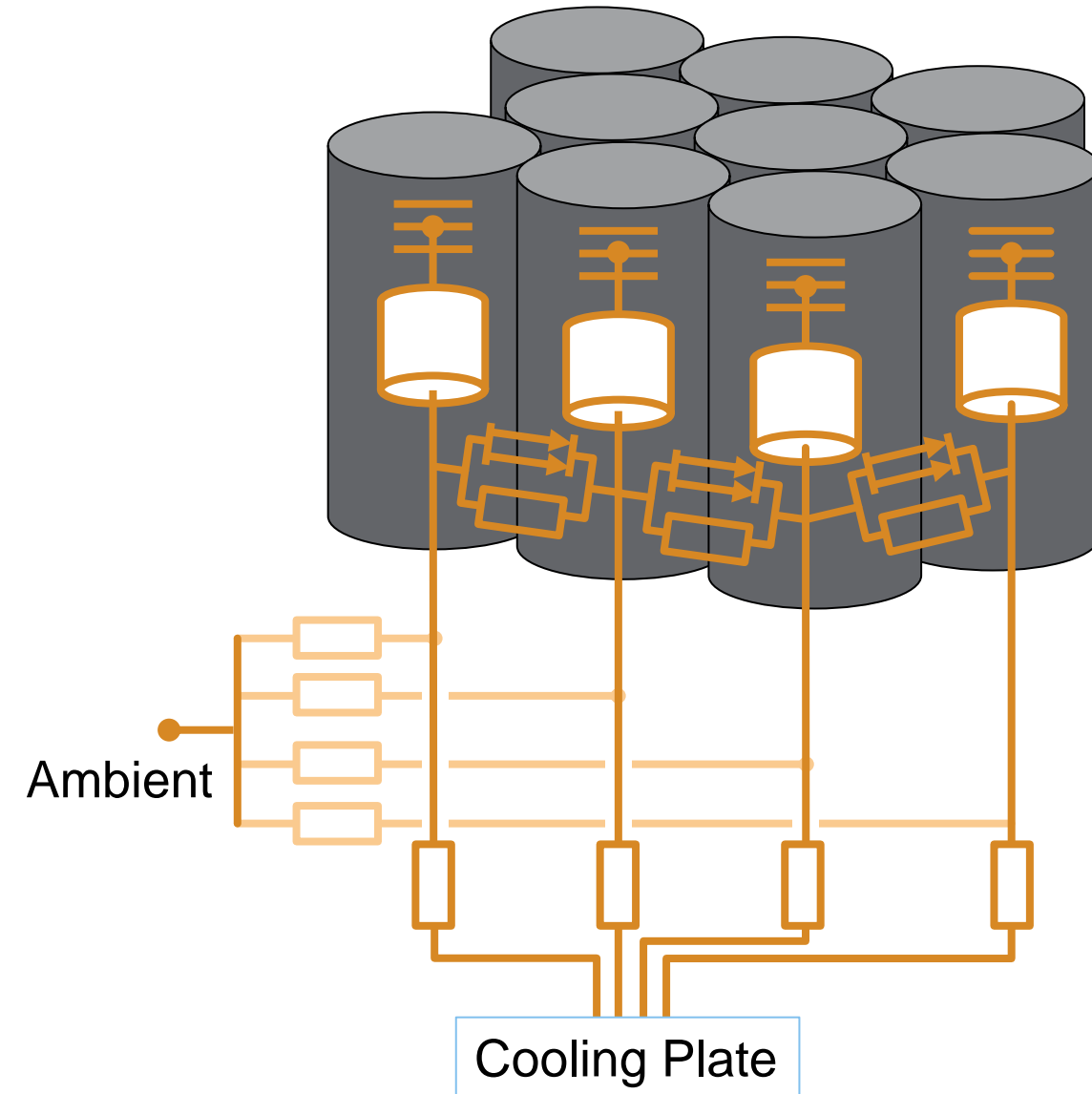
Thermal Connections



```

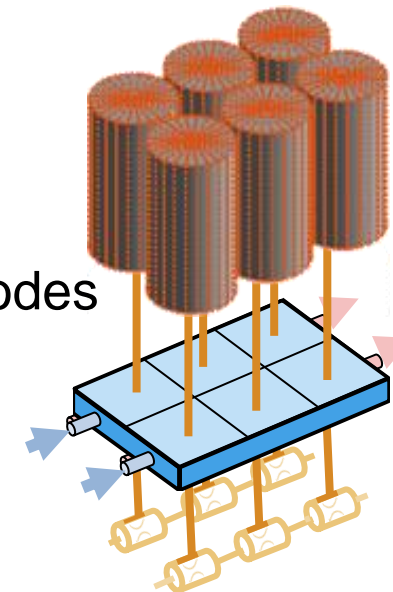
batteryModule = Simscape.Battery.Builder.Module(...
    ParallelAssembly = pAssembly,...
    NumSeriesAssemblies = 3,...
    ModelResolution = "Detailed",...
    InterCellThermalPath = "on",...
    InterCellRadiativeThermalPath = "on",...
    AmbientThermalPath = "CellBasedThermalResistance",...
    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");
```

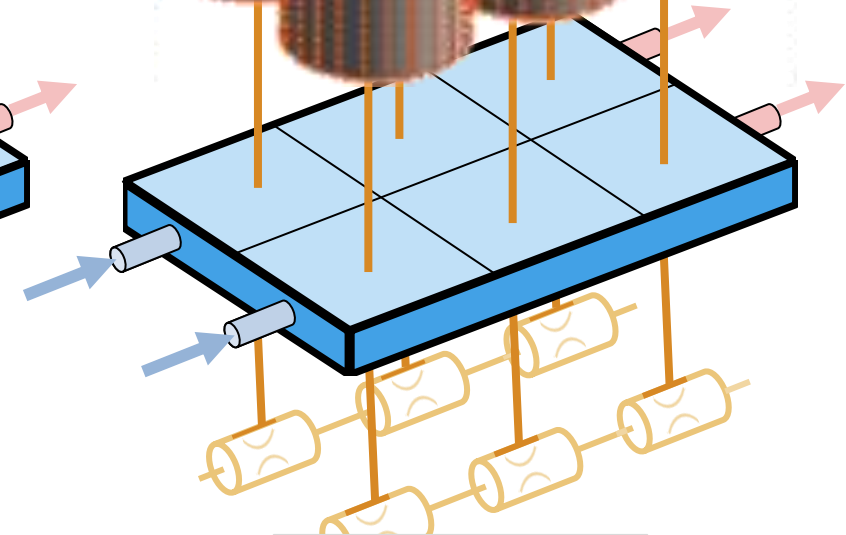
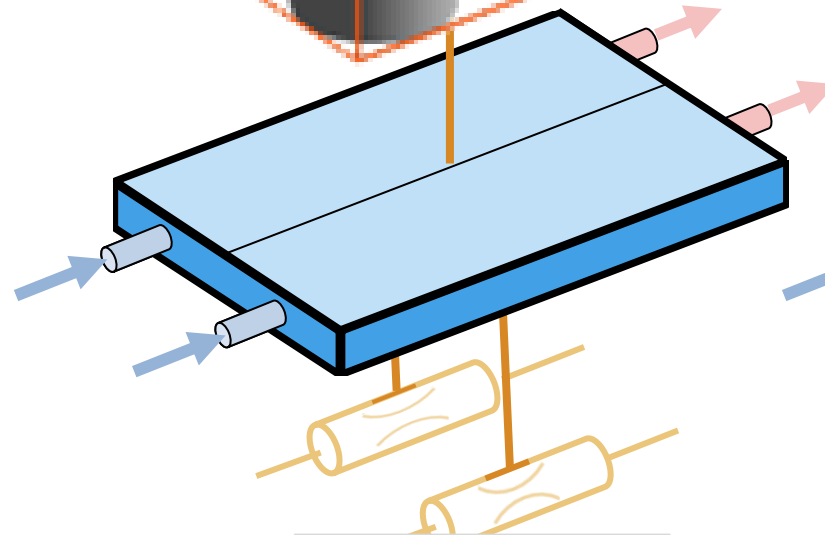
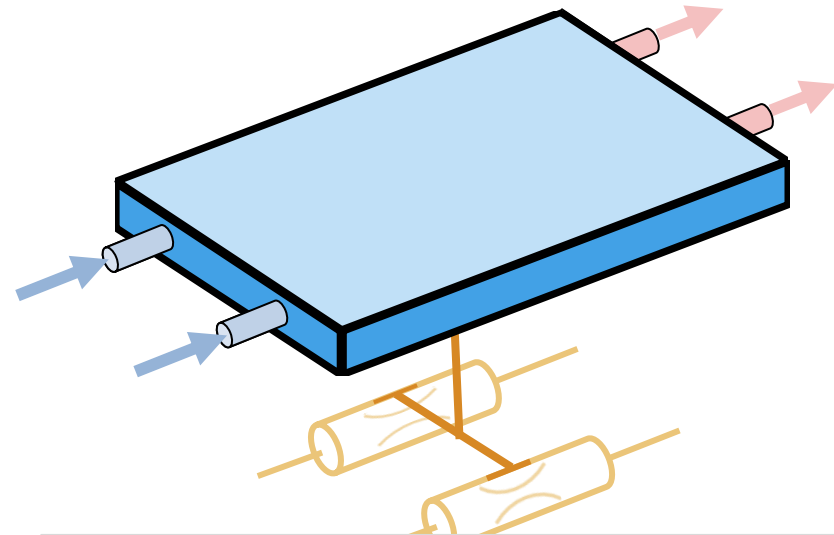
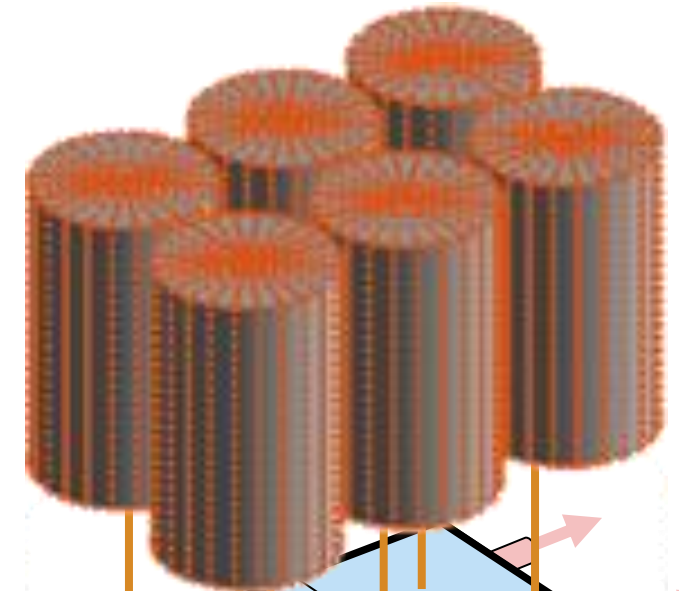
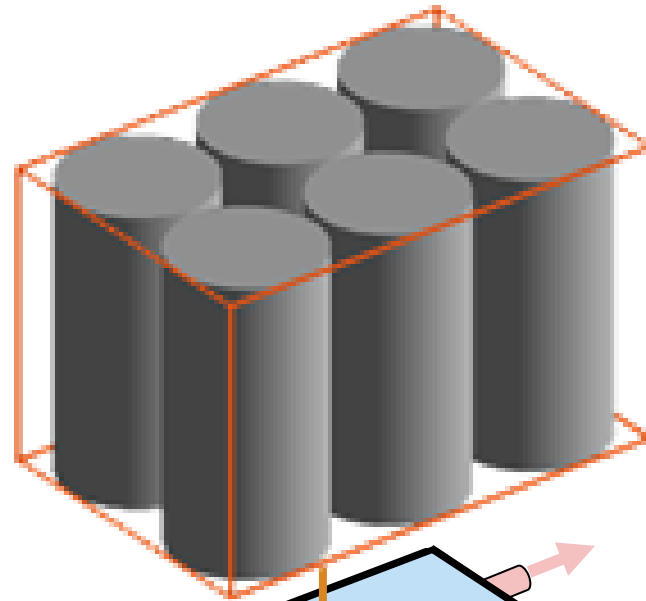
Array of
thermal nodes



Discretized plate and
cooling channels

Cooling Plate Connection

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

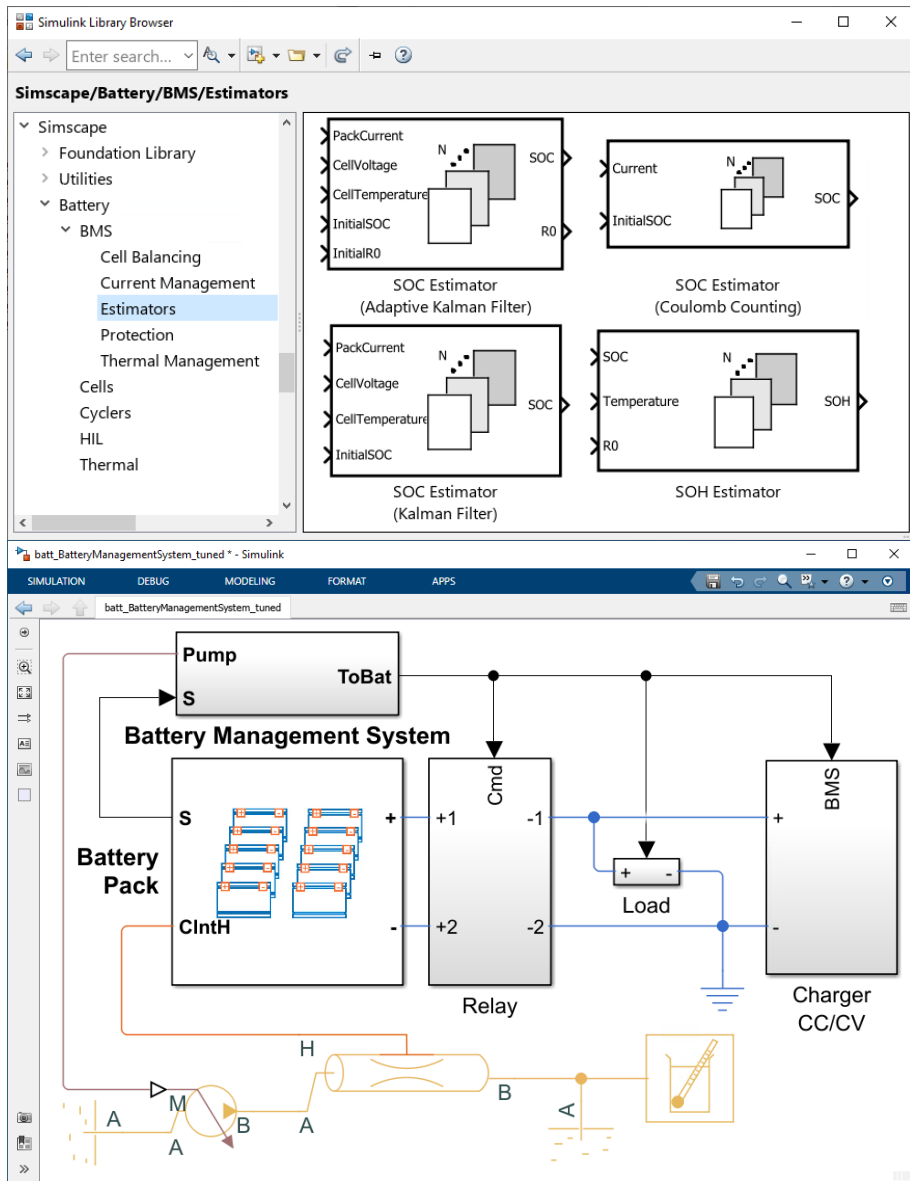


| Block Parameters: Parallel Channels | |
|---|---|
| Interface | |
| Number of partitions in X dimension ... | 1 |
| Number of partitions in Y dimension ... | 1 |
| Plate Material | |

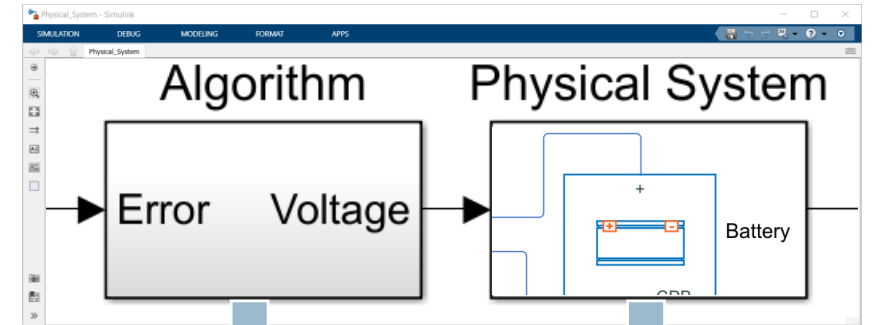
| | |
|-----------------|---|
| X dimension ... | 2 |
| Y dimension ... | 1 |

| | |
|-----------------|---|
| X dimension ... | 2 |
| Y dimension ... | 3 |

Control Algorithms & Deployment

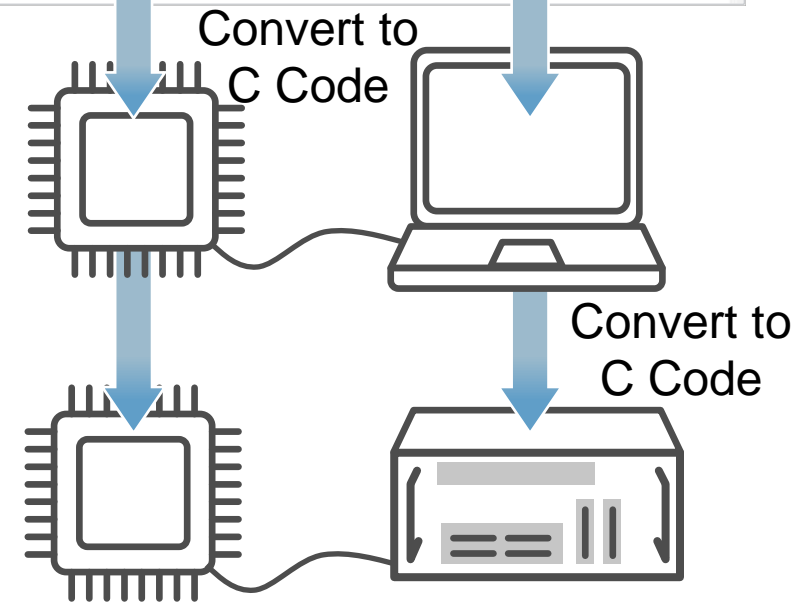


Battery Management Systems In Simscape Battery



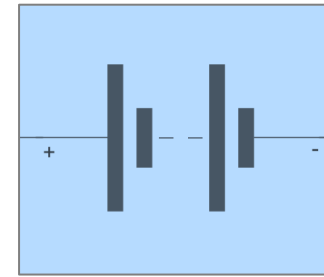
Processor-in-the-Loop (PIL)

Hardware-in-the-Loop (HIL)

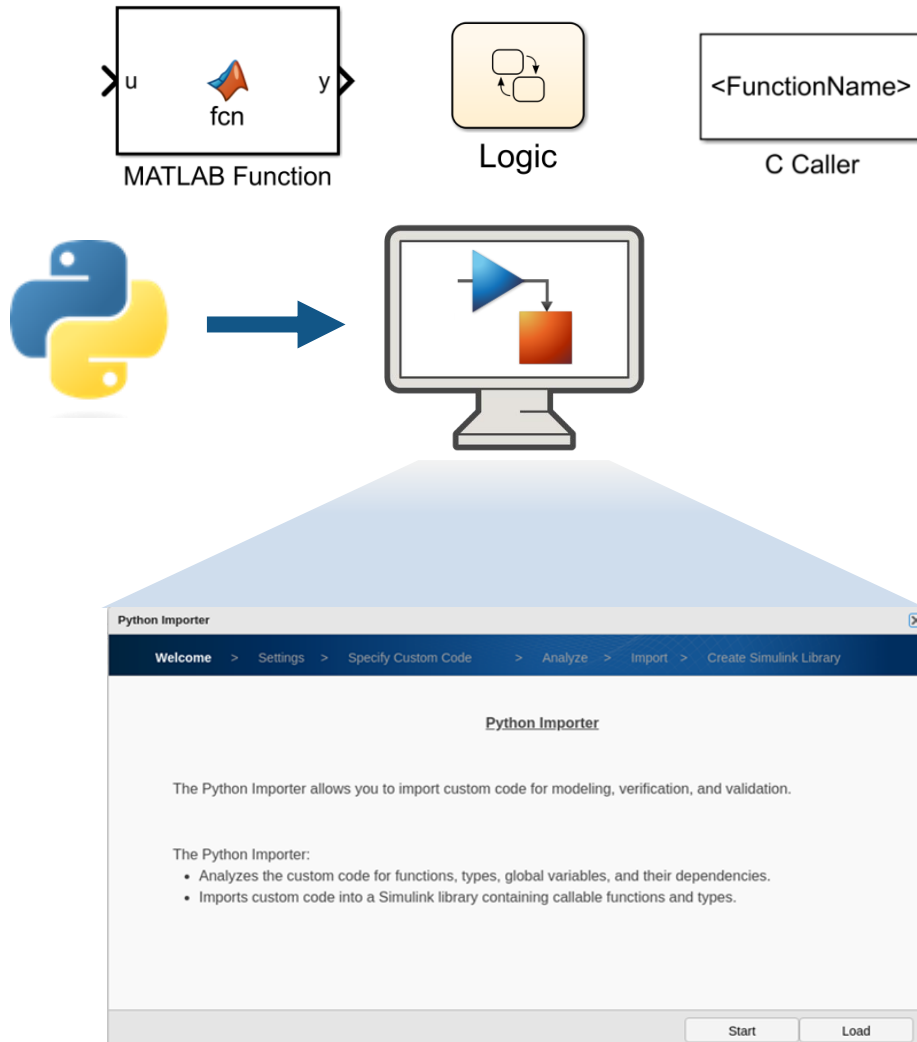


Customization

Customization and flexibility are at the core of MATLAB & Simulink



Custom cell



$$i = (C_0 + C_v v) \frac{dv}{dt} + \frac{v}{r_d}$$



Lossy Ultracapacitor









```

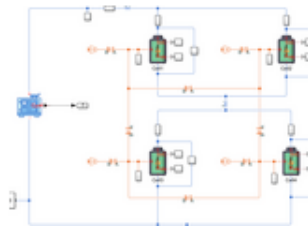
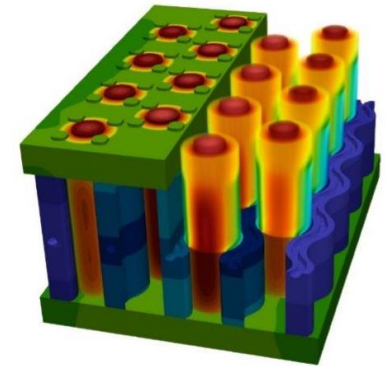
34 equations
35     i == (C0 + Cv*vc)*vc.der + vc/Rd;
36     v == vc + i*R;
37 end
    
```

Customize physical models with Simscape language

Extensions and Partners



| | | | |
|--|---|---|--|
|  Gen1 Demo About:Energy |  INR18650-M01 LG Chem |  US21700VTC6A Murata |  INR-18650-P28A Molicel |
|  N18650CNP BAK |  Tesla Model 3 Panasonic |  Model Y, Generation 1 Tesla |  US18650VTC6 Sony |



A Simscape-Battery-Library

Version 2.0.0.0 (4.15 MB) by W. Dhammika Widanage

A Li-ion battery library written in Matlab Simscape language. Battery models include electrochemical models with ageing and ECMs.

<https://github.com/WDWidanage/Simscape-Battery-Library>

Fault Robustness



Faults & System Protection

- ▼ Simscape
 - ▶ Foundation Library
 - ▶ Utilities
 - ▼ Battery
 - ▼ BMS
 - ▶ Cell Balancing
 - ▶ Current Management
 - ▶ Estimators
 - ▼ Protection
 - ▶ Thermal Management



Battery Current Monitoring



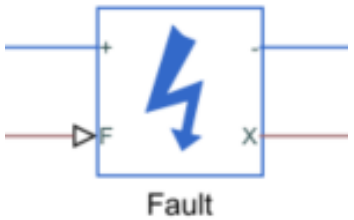
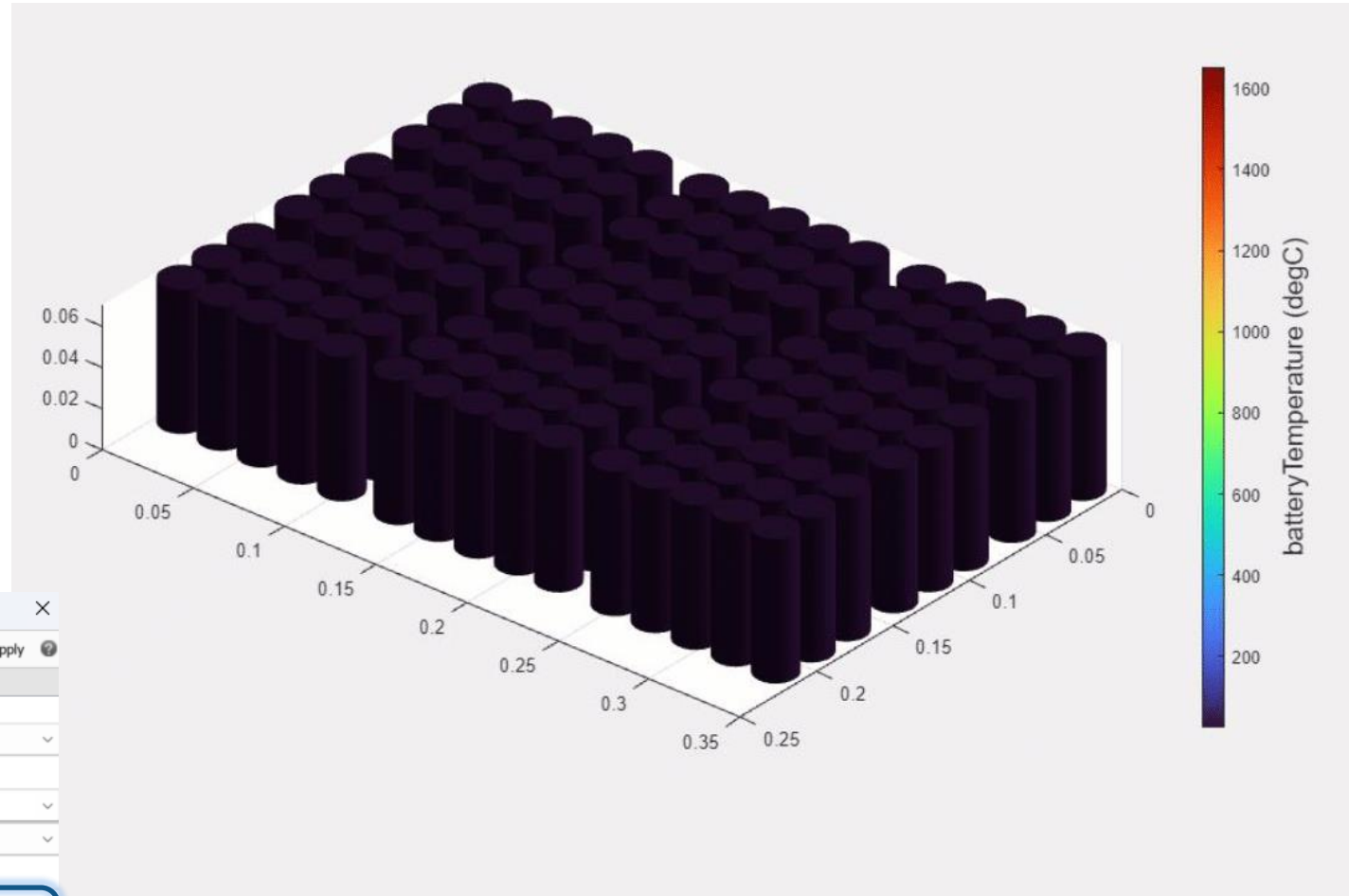
Battery Temperature Monitoring



Battery Voltage Monitoring



Fault Qualification



Block Parameters: Resistor

Resistor Auto Apply

| Settings | Description |
|-------------------------------|--------------------------|
| NAME | VALUE |
| Modeling option | No thermal port |
| Main | |
| > Resistance | 1 Ohm |
| Tolerance application | None - use nominal value |
| Operating Limits | |
| Faults | |
| Enable faults | Yes |
| Reporting when a fault occurs | None |

fault_test - Simulink prerelease use

SIMULATION DEBUG MODELING FORMAT APPS SIMSCAPE BLOCK

+ New Open Save Print Library Browser Log Signals Add Viewer Signal Table Stop Time: 20 Normal Step Back Pause Step Forward Stop Data Inspector Logic Analyzer Bird's-Eye Scope Simulation Manager

Model 'fault_test' is being compiled or simulated and Fault Simulation is ON.

10
8
6
4
2
0
0 2 4 6 8 10 12 14 16 18 20

f(x) = 0 Solver Configuration Controlled Voltage Source PS Ramp V = 50 V + t * 10 V/s Resistor R = 10 Ohm Temperature Source T = 293.15 K Convective Heat Transfer 465.1 Current 1

Property Inspector

Faulted Model Element: 'Resistor/Resistance'
 Enable
 Active fault for simulation: Resistor_fault
 Select fault to view: Resistor_fault
 Add new fault

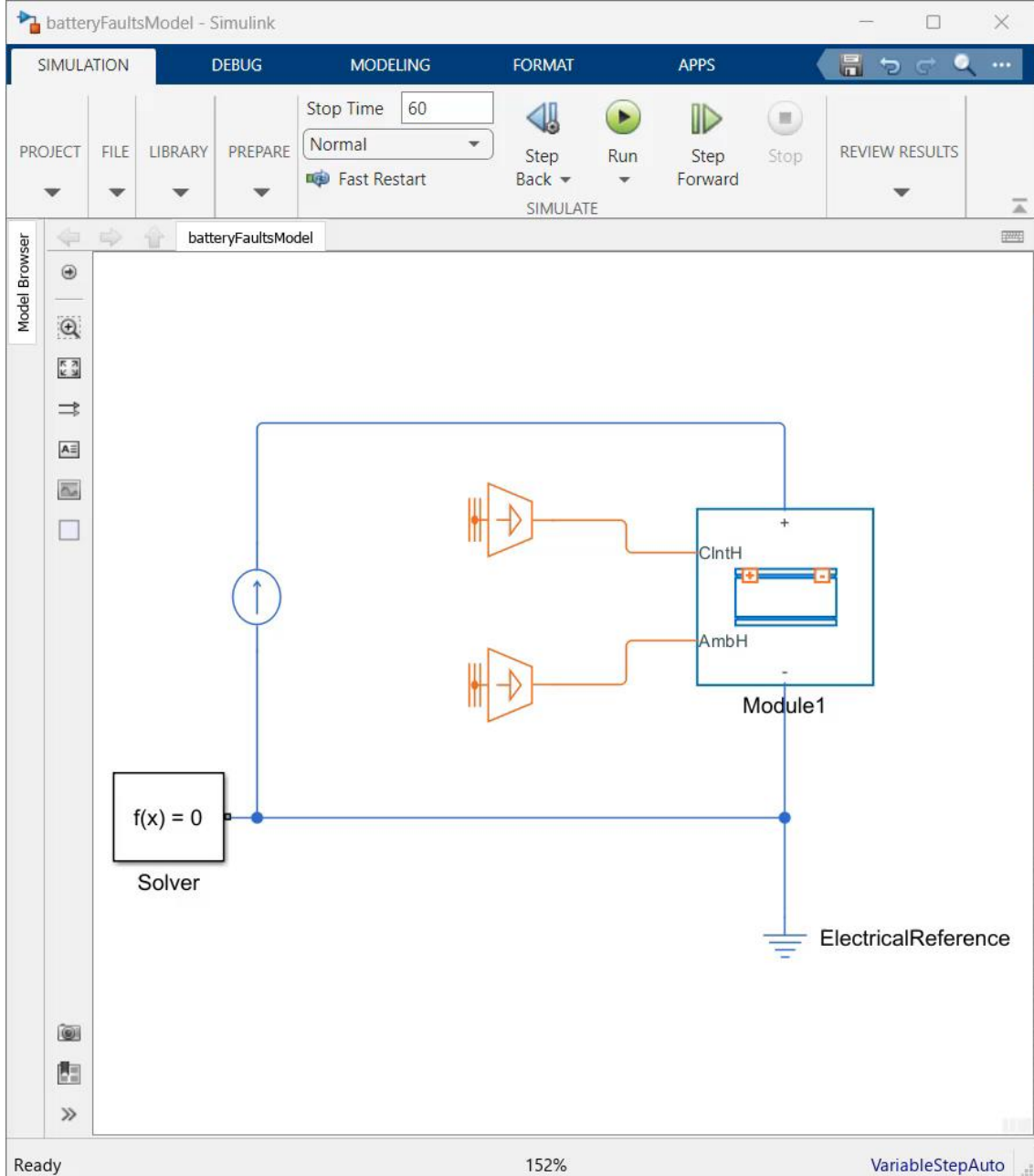
Fault
 Name: Resistor_fault
 Fault behavior: fault_test_FaultModel/Resistor_fault

Trigger
 Trigger type: Timed
 Inject fault behavior after the specified simulation time.
 Trigger fault at time: 15

Description:

Description

Ready 135% auto(daessc)



MATLAB R2023b

Try the New Desktop

Search Documentation

File: New, Open, Save, Print, Export

Code: Run, Step, Stop

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

```

1  Load our previously generated battery module
2
3  load("faultModuleData.mat","batteryModule");
4
5  Visualise the module
6  f = uifigure;
7  packChart = simscape.battery.builder.BatteryChart(...
8      Parent = f, Battery = batteryModule,SimulationStrategyVisible = "on");
9
10 Fault APIs for Simulink and Simscape
11
12  modelname = "batteryFaultsModel";
13  faulttableBlocks = simscape.findFaulttableBlocks(modelname)
14
15  Add a single fault
16  InternalShortFault = Simulink.fault.addFault(...
17      strcat(faulttableBlocks(1),"/ParallelAssembly1(10)/Cell1(1)/Internal short"));
18  InternalShortFault.addBehavior(strcat(modelname, "_FaultModel"));
19
20  Setup fault triggers programmatically
21  InternalShortFault.TriggerType = "Timed";
22  InternalShortFault.StartTime = 30;
23  InternalShortFault.activate;
    
```

Ready 152% VariableStepAuto 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.

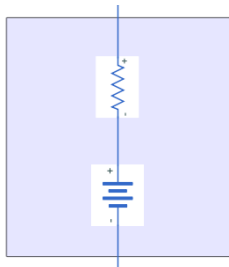
Block Parameters: BatteryEquivalentCircuit_fault

Battery Equivalent Circuit Auto Apply

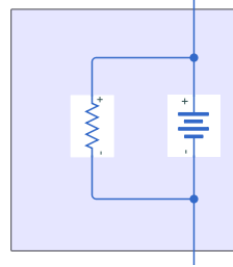
Settings Description

| 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 |

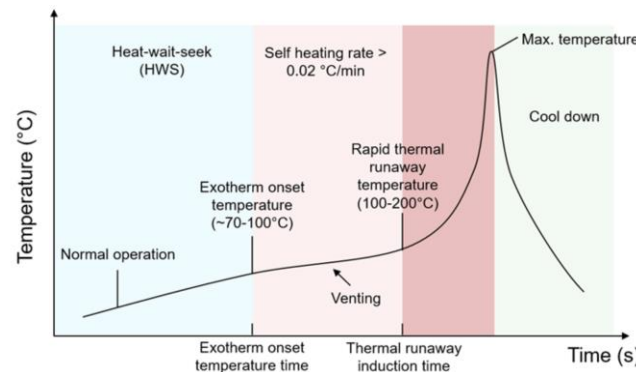
Additional Resistance Fault



Internal Short Fault



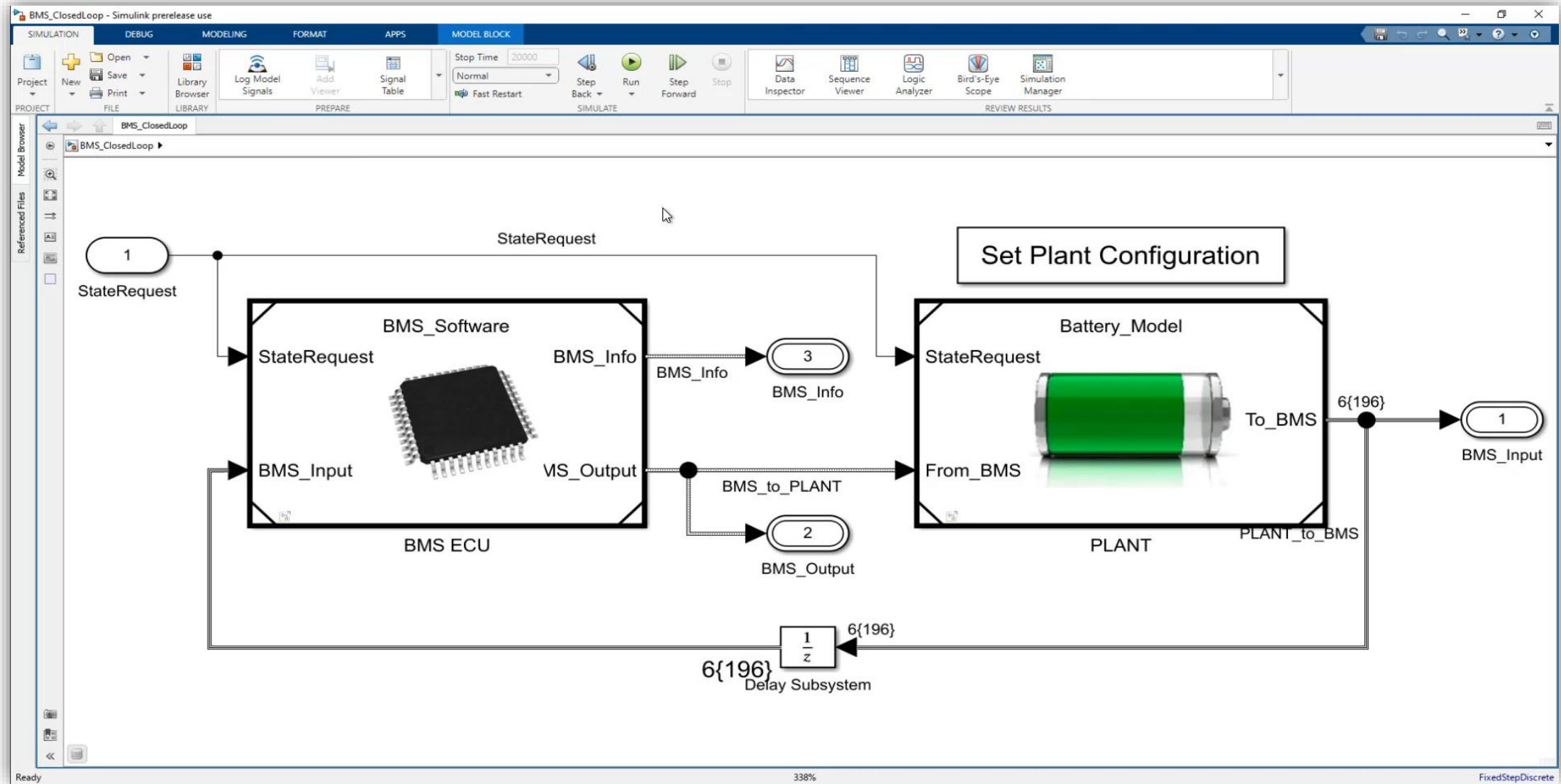
Exothermic Reaction Fault



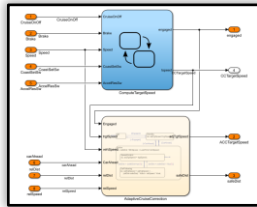
- ✓ Definition of time or condition dependent faults.
- ✓ Support modeling of thermal runaway events.

[Inject Faults in Battery Models](#)

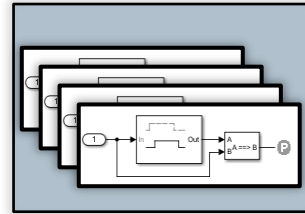
Unified Fault Framework



Design Logic



Fault Logic



Model faults without modifying the design

Simulink Fault Analyzer™

Fault Table

| 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 LowTemperaturFault | <input checked="" type="checkbox"/> | Conditional: SampleConditional |
| <input checked="" type="checkbox"/> | Environment/Constant2/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 |

Manage faults across multiple domains

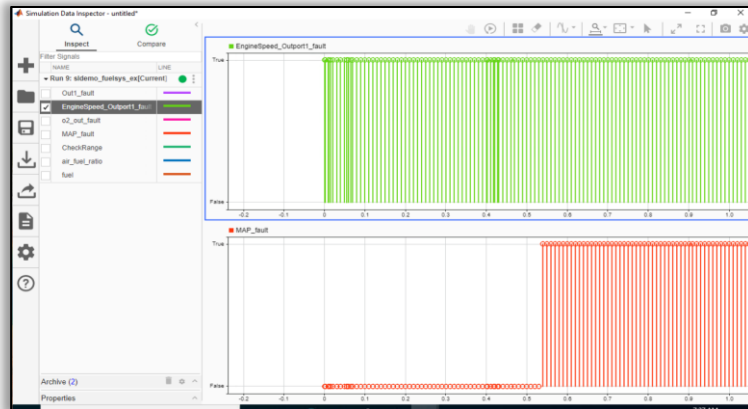
Details: Design Study

Specification Run Options

Root Parameter Set

Fault Set_1

| | Fault | Component |
|-------------------------------------|----------------------|----------------------|
| <input checked="" type="checkbox"/> | HighTemperatureFault | EvReferenceApplic... |
| <input checked="" type="checkbox"/> | HighPressureFault | EvReferenceApplic... |
| <input checked="" type="checkbox"/> | LowTemperaturFault | EvReferenceApplic... |
| <input checked="" type="checkbox"/> | LowPressureFault | EvReferenceApplic... |
| <input checked="" type="checkbox"/> | Grade_fault | EvReferenceApplic... |
| <input checked="" type="checkbox"/> | Grade_fault_1 | EvReferenceApplic... |
| <input checked="" type="checkbox"/> | wind_x_fault | EvReferenceApplic... |



Simulate, explore and analyze fault effects

Safety Analysis Manager

HOME

RobotFMEA x

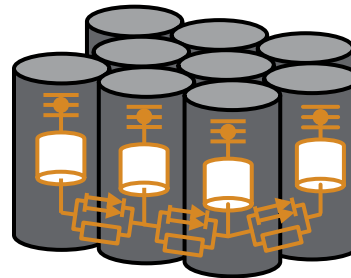
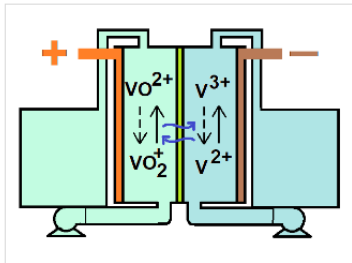
| | Failure Mode | Failure Rate (E-06) | Failure Effect | Detection Method |
|---|---|---------------------|----------------|------------------|
| 1 | Angular Velocity Invalid After 50 seconds | 1 | Robot spins | Safety Lock |
| 2 | Angular Velocity Invalid at Maximum Pose | 1 | Robot spins | Safety Lock |

1 warning
Simulation errored out without Detection Method working.

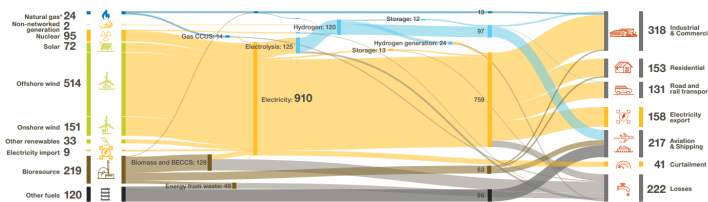
Perform systematic safety analysis using simulation

Conclusions

- Energy Storage is far more than just electrical systems



- 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

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



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Simscape Onramp

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Circuit Simulation Onramp

7 modules | 2 hours | Languages

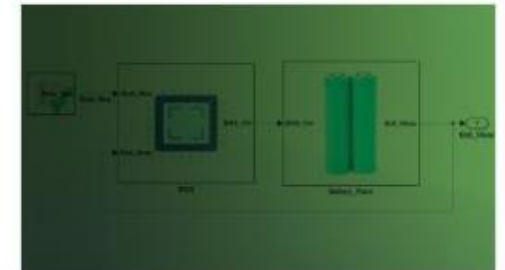
Learn the basics of simulating electrical circuits in Simscape.



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

Come and talk to us at the demo stations!

MATLAB EXPO

Thank you



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