MATLAB EXPO

Going Beyond the Electrical in Modelling Energy Storage Systems

Tom Grimble, MathWorks

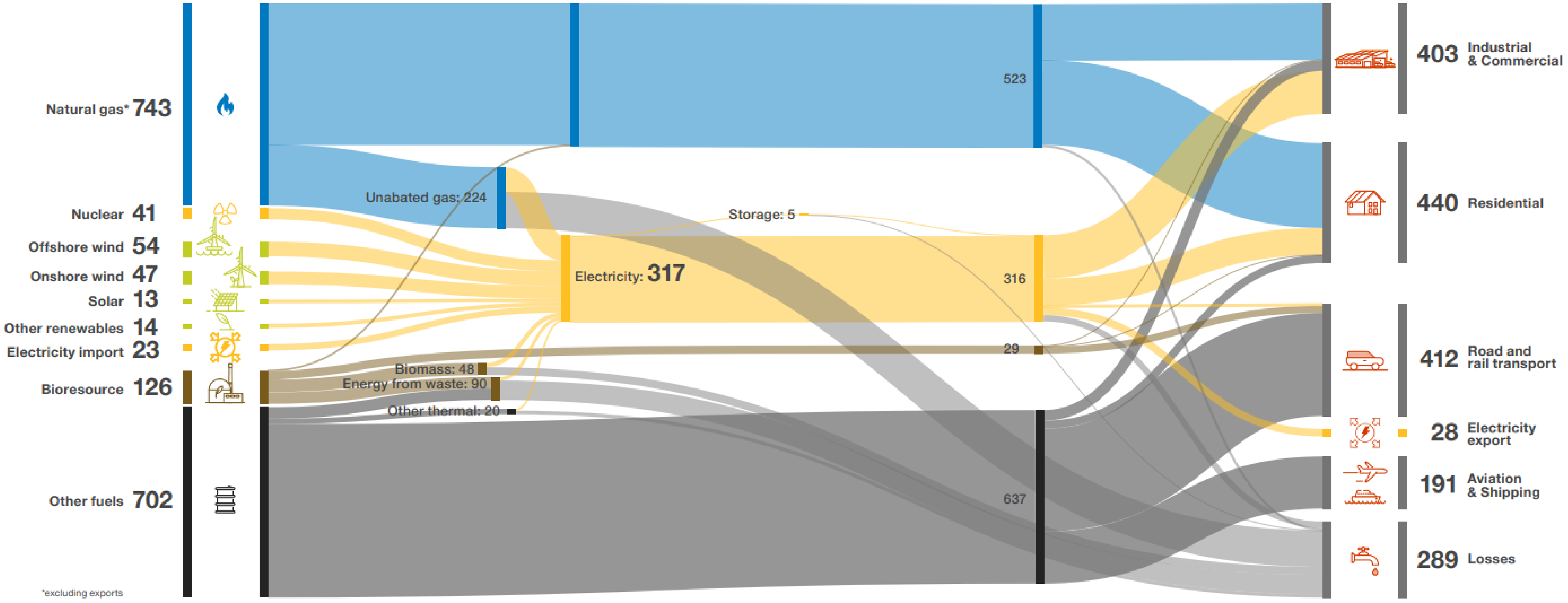
MathWorks®

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

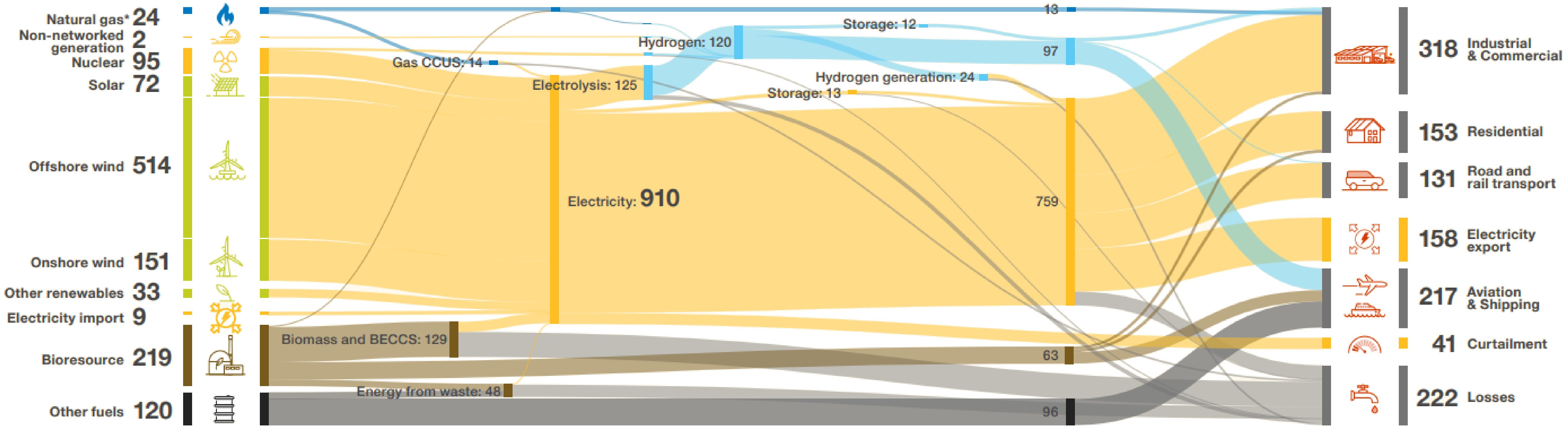
2022 – 1763 TWh



National Grid ESO Future Energy Scenarios 2023 report

What About Tomorrow?

2050 – 1239 TWh



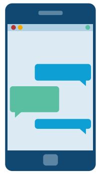
[National Grid ESO Future Energy Scenarios 2023 report]

Growth in Grid Connected Energy Storage

Current UK Capacity

- 2.4 GW

250 million ×

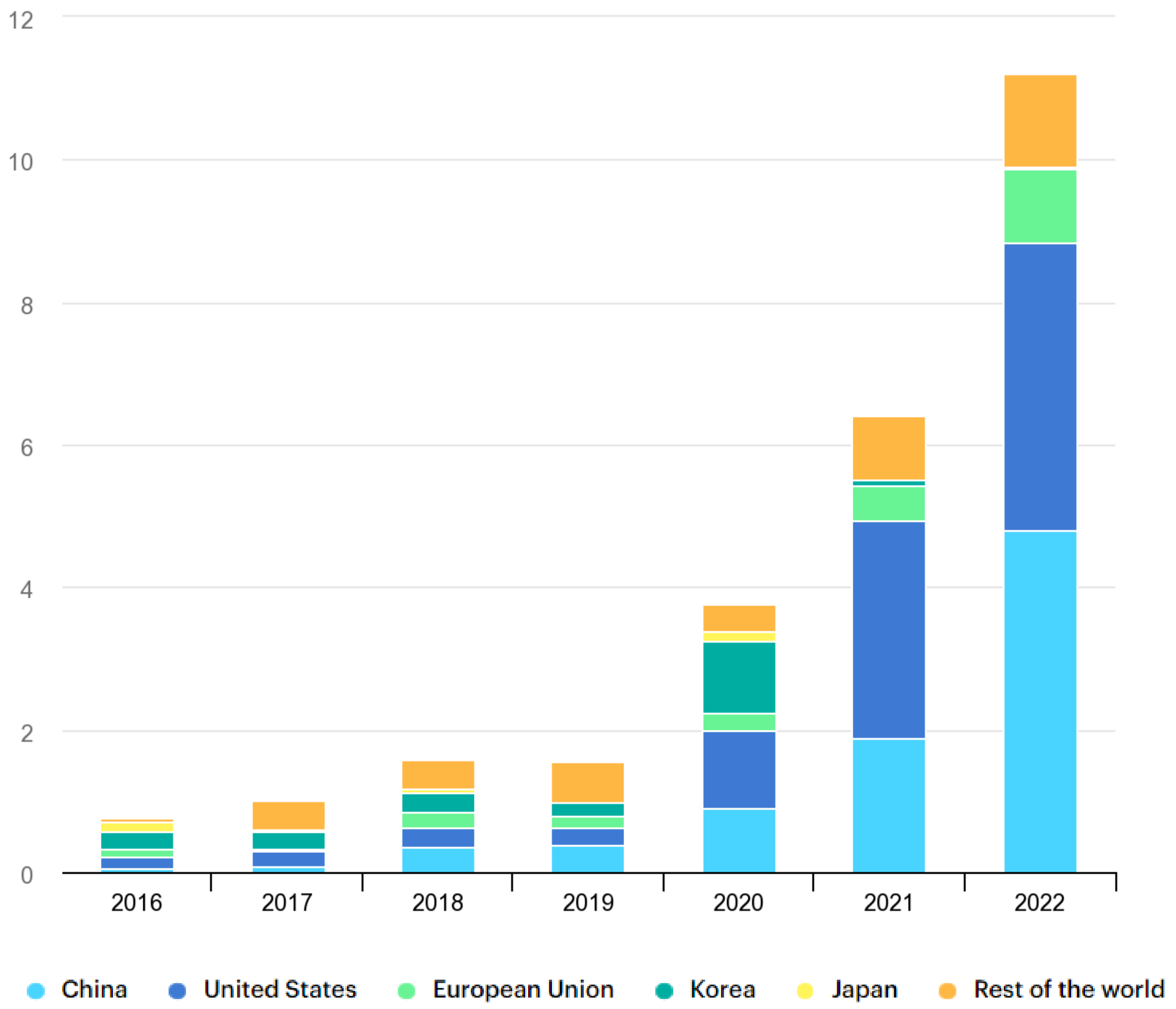


40000 ×

66 GW Additional planned capacity

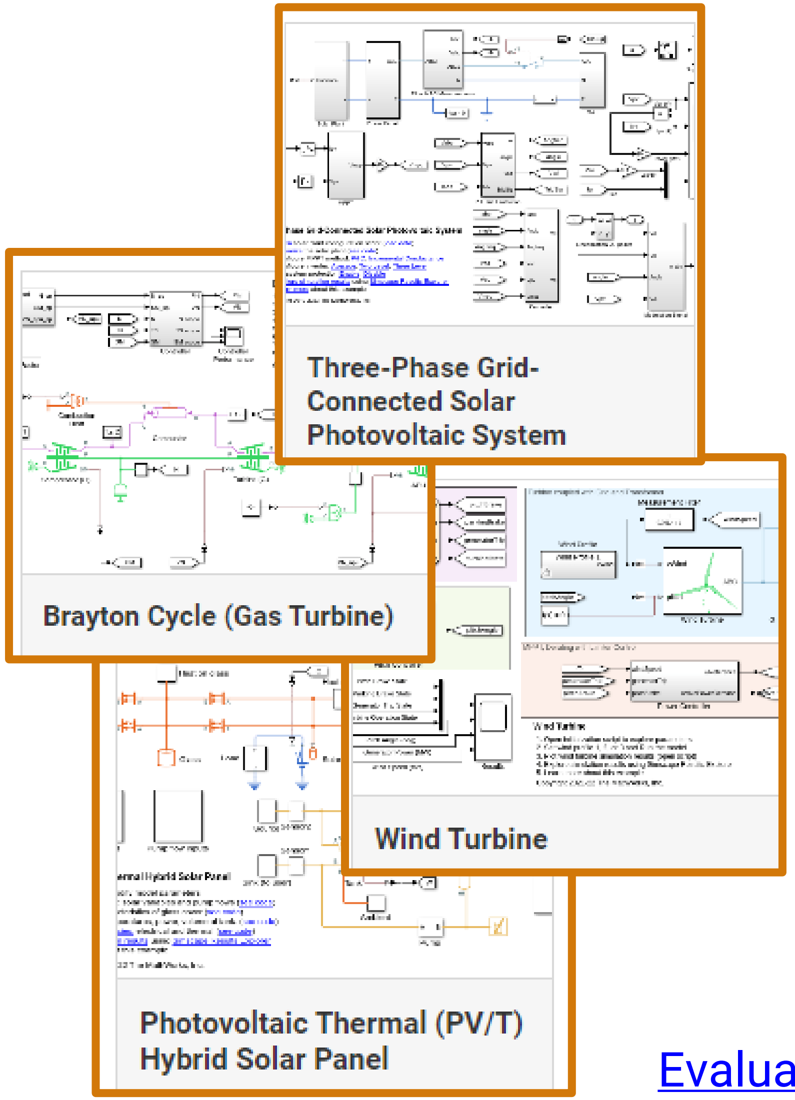
(2022 Grid generation capacity ~80GW)

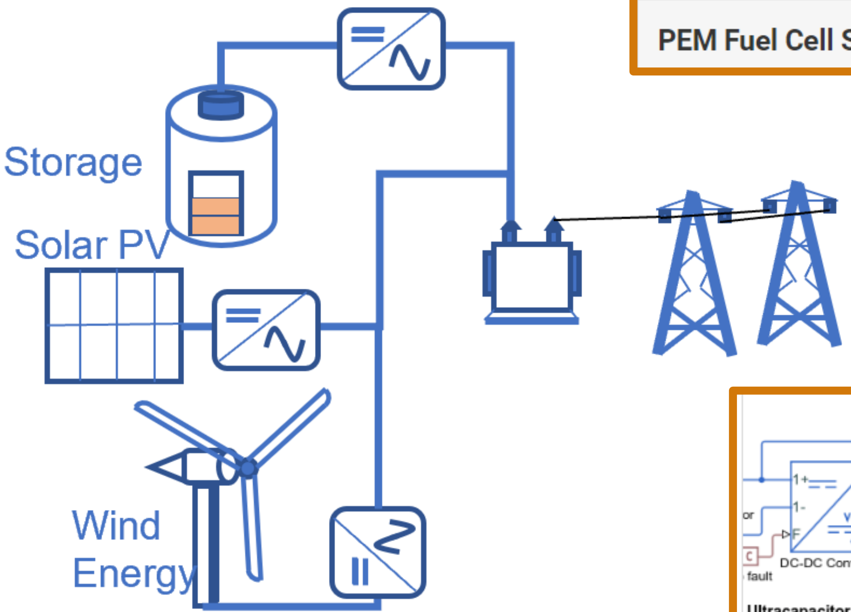
Energy Storage Capacity Increase by Year and Region

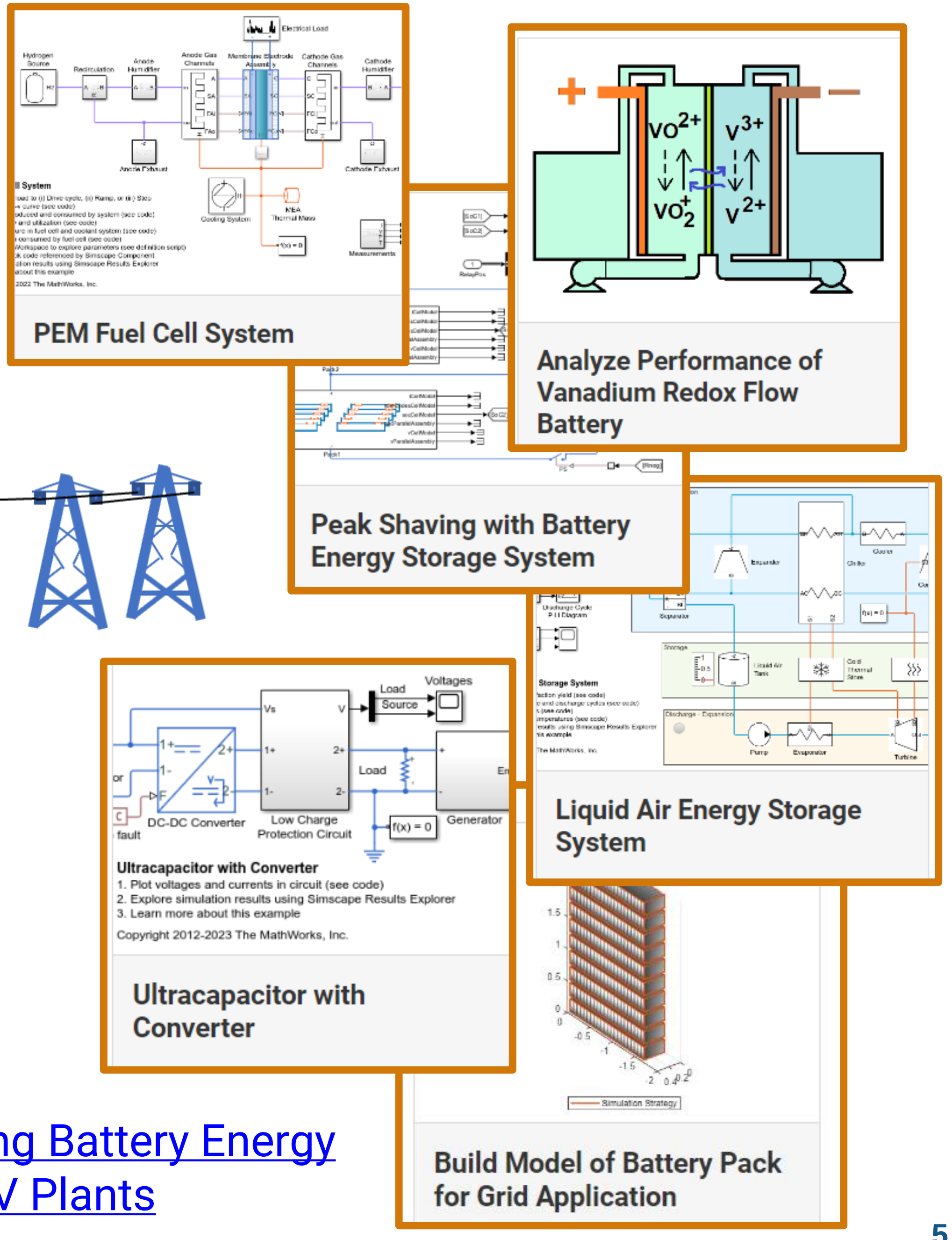


[Energy storage - IEA]

Exploring Technology Options



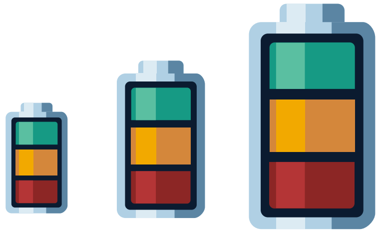




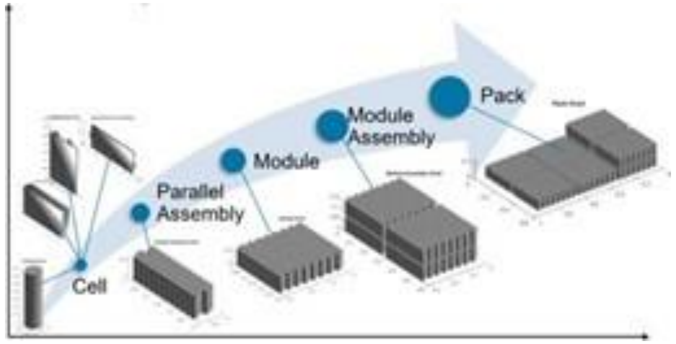
Evaluate Performance of Grid-Forming Battery Energy Storage Systems in Solar PV Plants

Different Phases of Design

- System concepts, sizing and costs

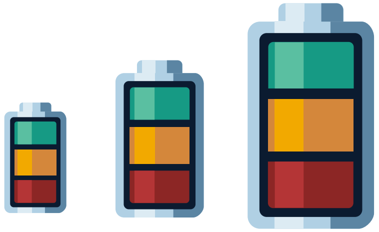


- Detailed component & control design



- Modelling faults to design protection systems

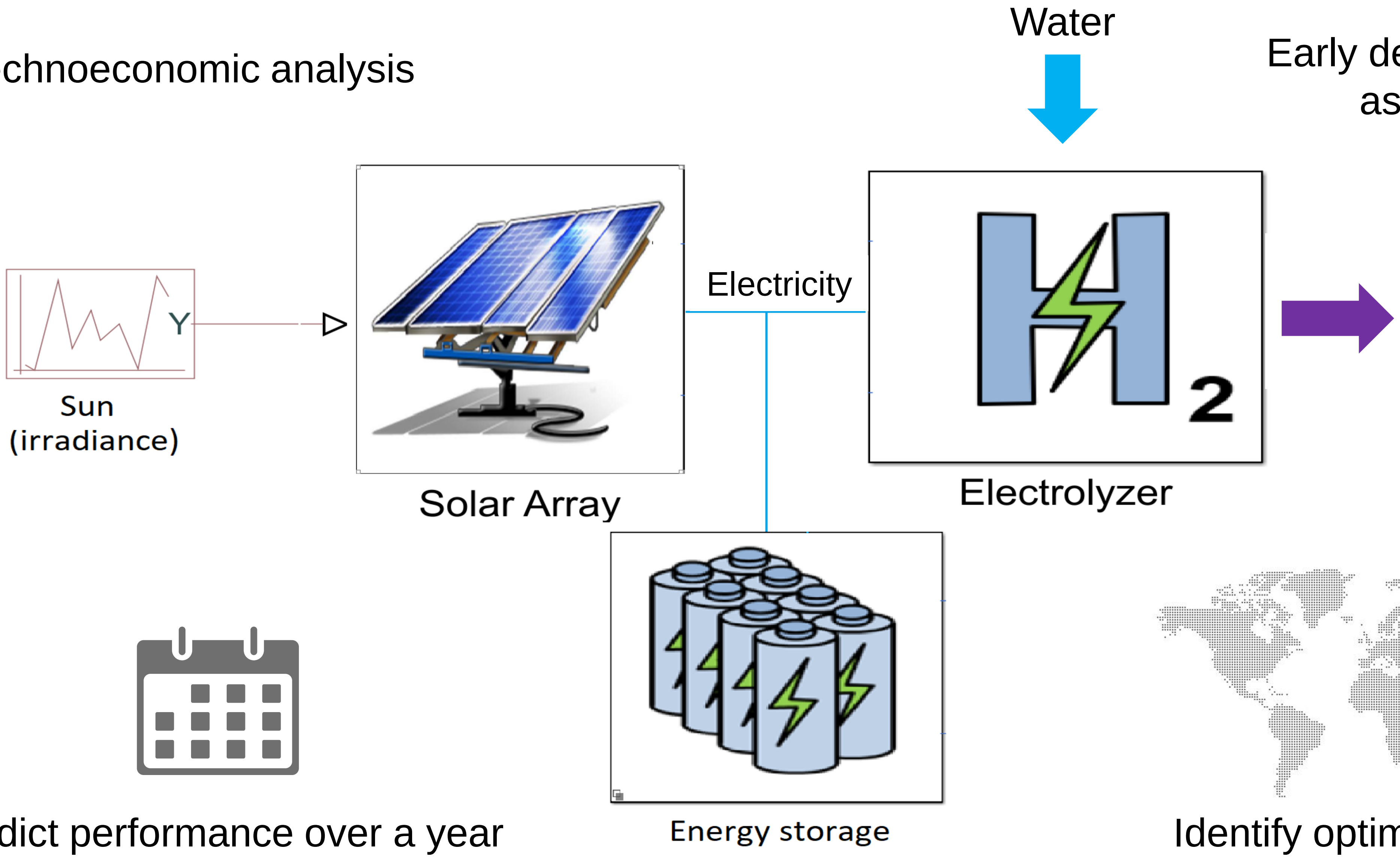
Concept Stage



System Exploration

Technoeconomic analysis

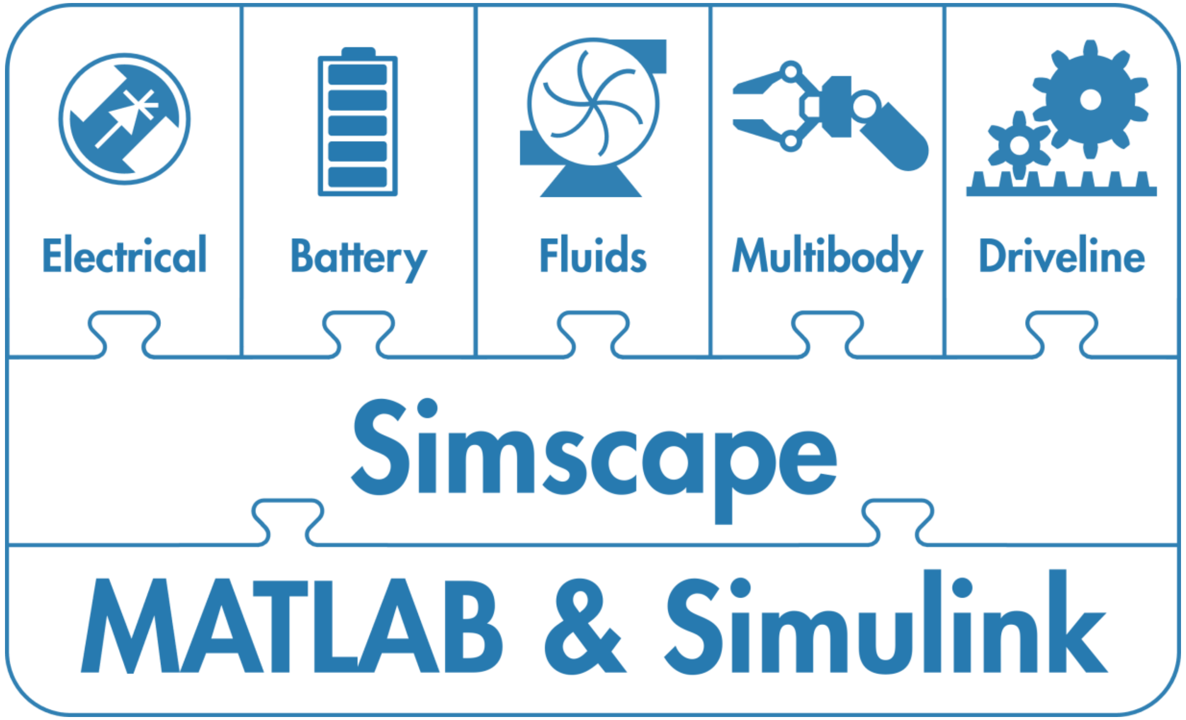
Early design with many assumptions

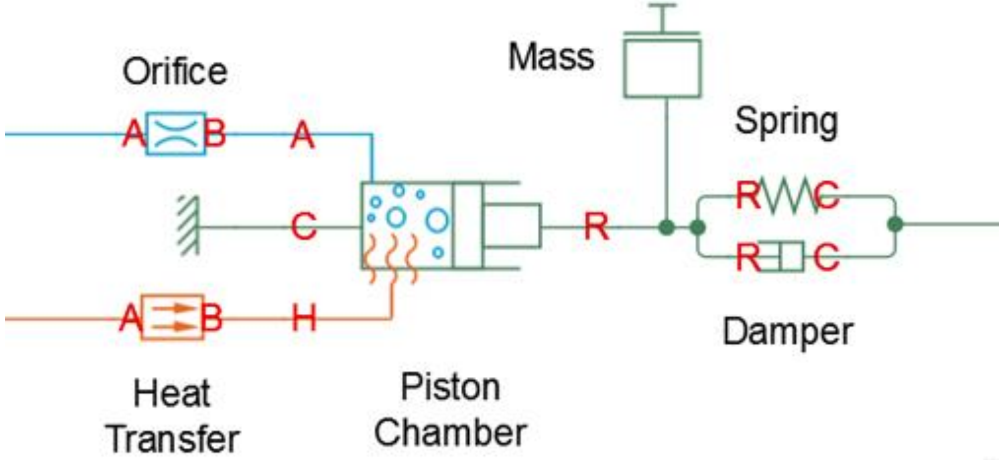


Predict performance over a year

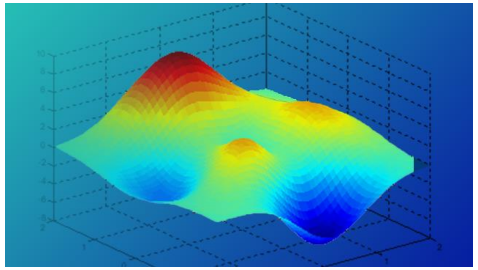
Identify optimal location

Cost Analysis with MATLAB & Simulink

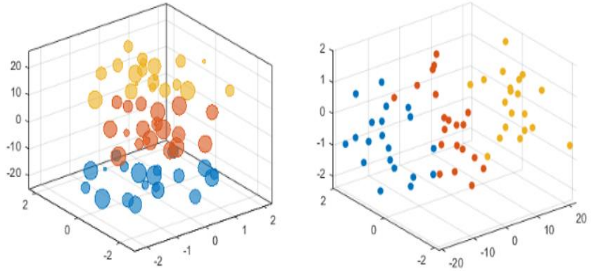




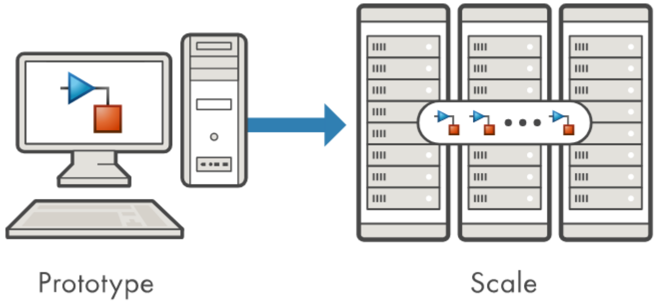
What about £ ?



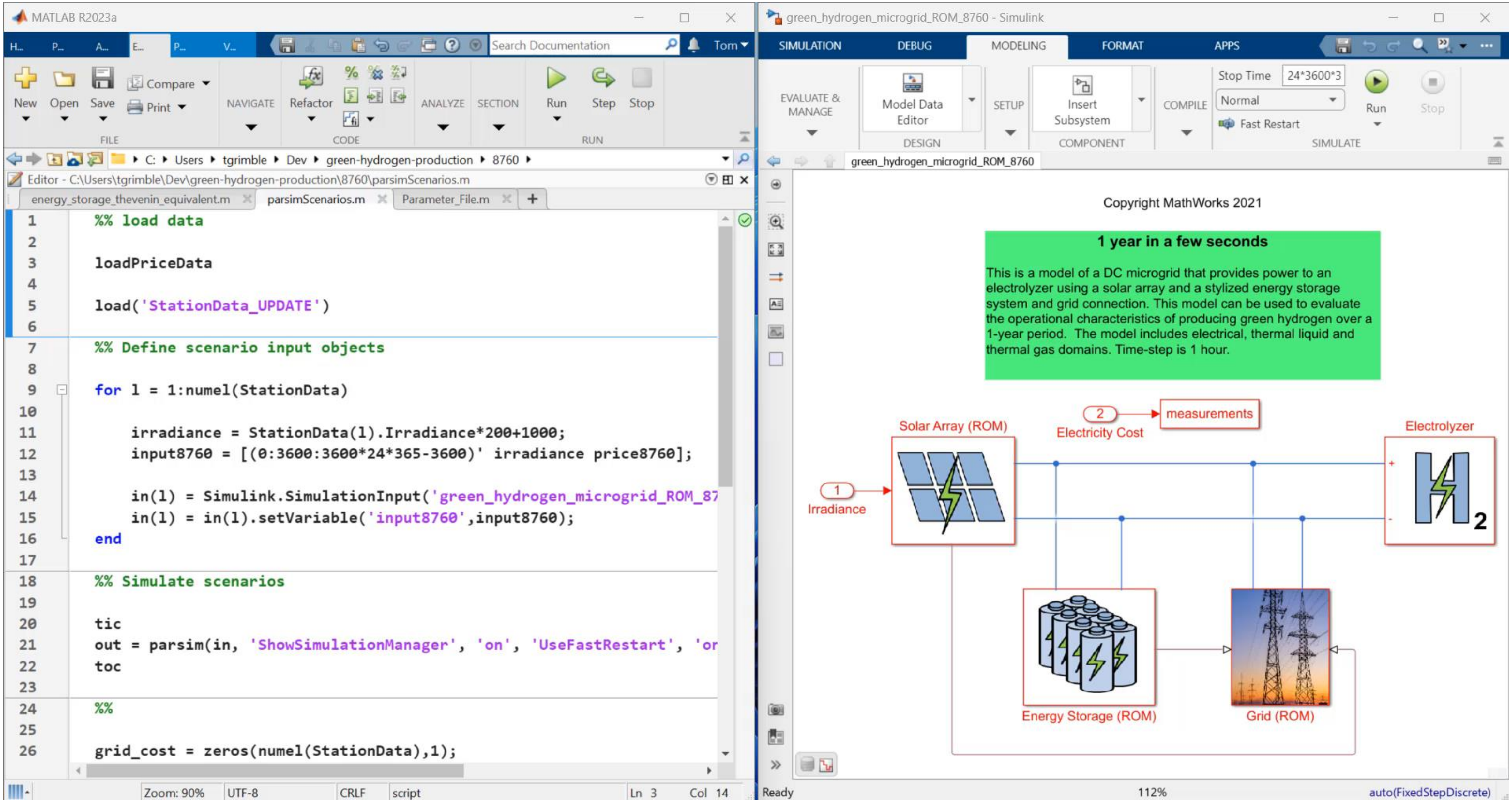
Optimization Algorithms



Visualization

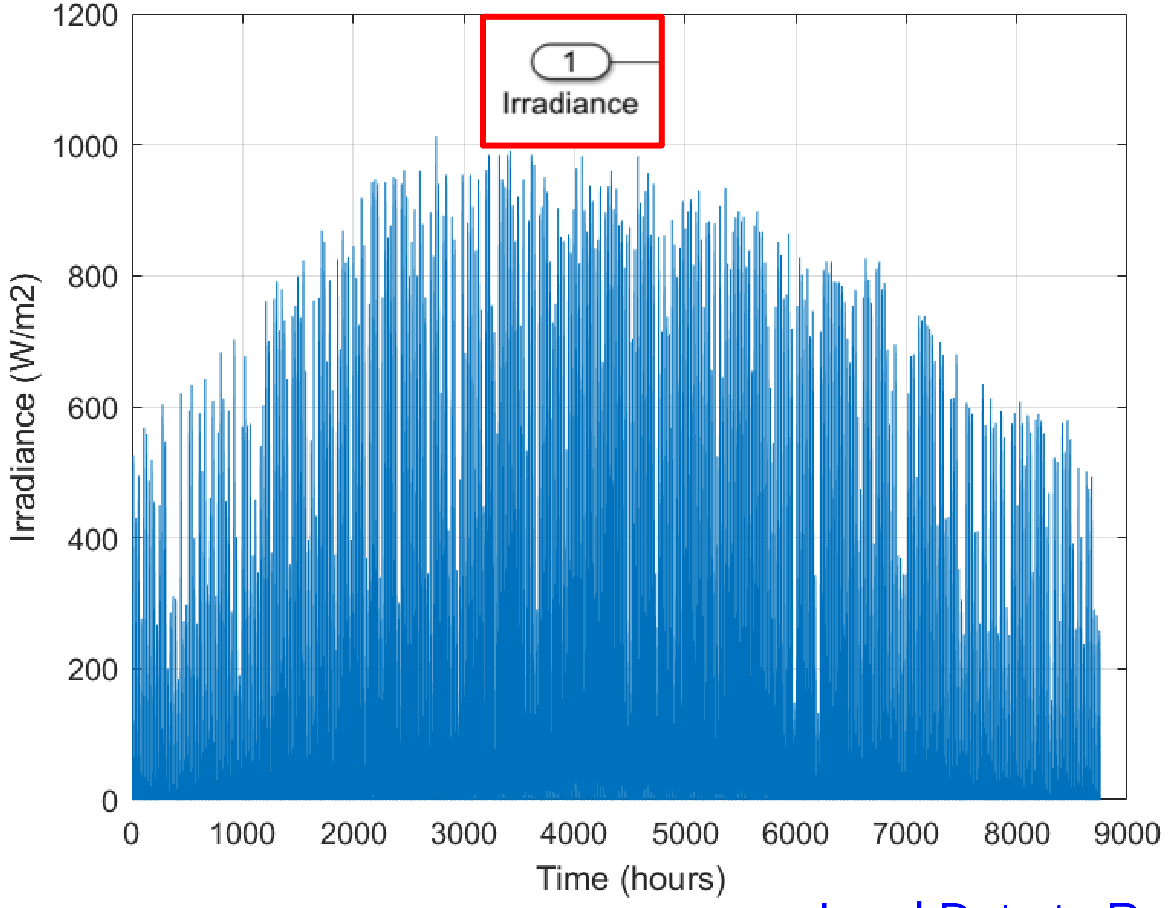


Parallelization & Scaling

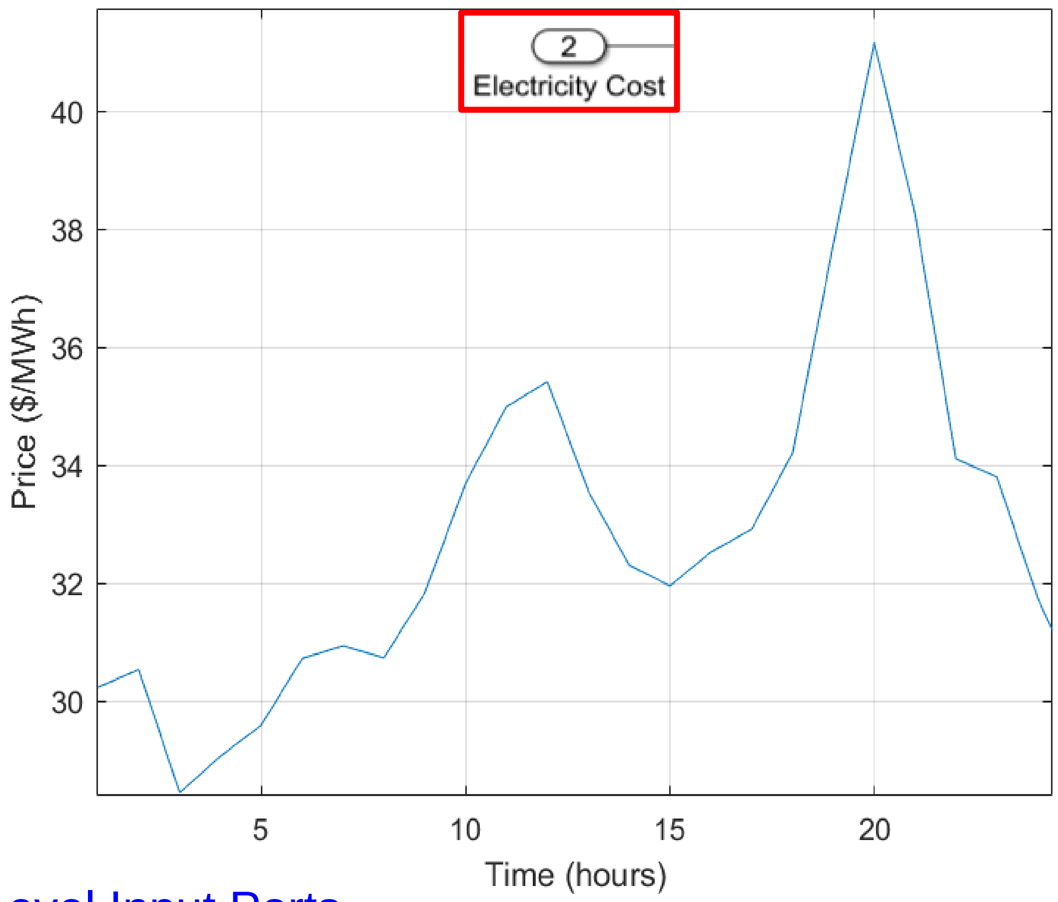

MATLAB R2023a
Search Documentation
New
Open
Save
Compare
Print
FILE
NAVIGATE
Refactor
CODE
ANALYZE
SECTION
Run
Step
Stop
RUN
Editor - C:\Users\tgrimble\Dev\green-hydrogen-production\8760\parsimScenarios.m
energy_storage_thevenin_equivalent.m
parsimScenarios.m
Parameter_File.m
%% load data
loadPriceData
load('StationData_UPDATE')
%% Define scenario input objects
for l = 1:numel(StationData)
irradiance = StationData(l).Irradiance*200+1000;
input8760 = [(0:3600:3600*24*365-3600)' irradiance price8760];
in(l) = Simulink.SimulationInput('green_hydrogen_microgrid_ROM_87
in(l) = in(l).setVariable('input8760',input8760);
end
%% Simulate scenarios
tic
out = parsim(in, 'ShowSimulationManager', 'on', 'UseFastRestart', 'or
toc
%%
grid_cost = zeros(numel(StationData),1);
Zoom: 90%
UTF-8
CRLF
script
Ln 3
Col 14
green_hydrogen_microgrid_ROM_8760 - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
APPS
EVALUATE & MANAGE
Model Data Editor
DESIGN
SETUP
Insert Subsystem
COMPONENT
COMPILE
Stop Time
24*3600*3
Normal
Fast Restart
Run
Stop
SIMULATE
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)
2
Electricity Cost
measurements
Electrolyzer
1
Irradiance
Energy Storage (ROM)
Grid (ROM)
Ready
112%
auto(FixedStepDiscrete)

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

nanoseconds | microseconds | milliseconds | seconds | minutes | hours | days | months | years → Simulation Time

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

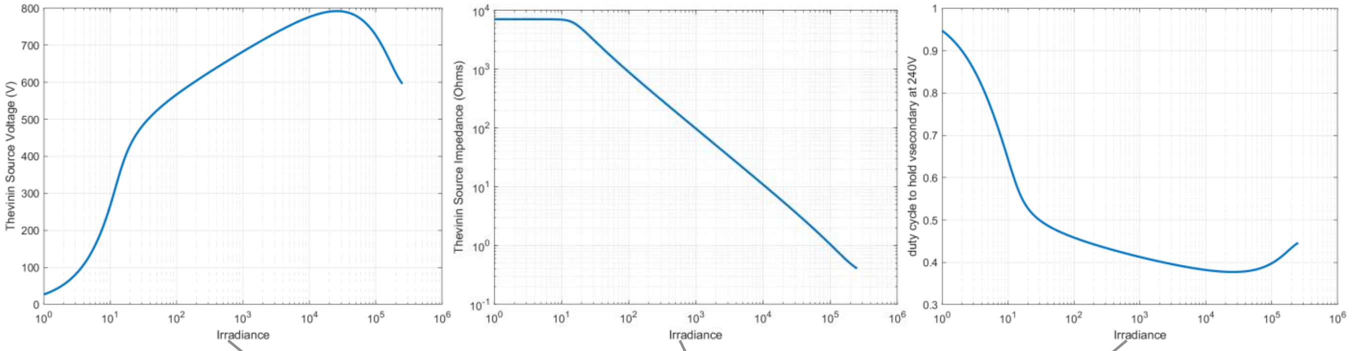
- Regression Trees
- Support Vector Machines
- Neural ODEs
- Ensembles
- Gaussian Process Models
- Recurrent Neural Networks
- Shallow Neural Networks
- Convolutional Neural Networks
- Physically Inspired Neural Networks

ROM Implementation

Performance assessment

Medium fidelity

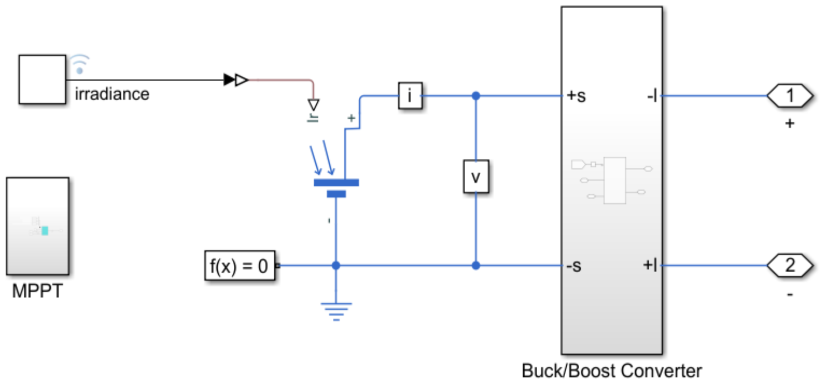
Solar cell & MPPT algorithm

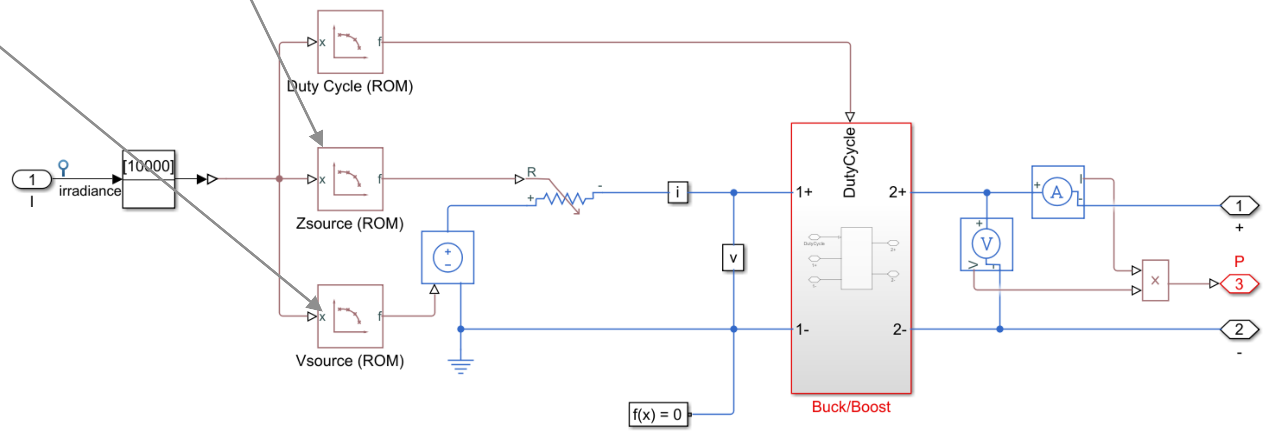


Techno-economic analysis

Low fidelity

Reduced Order Modeling (ROM)

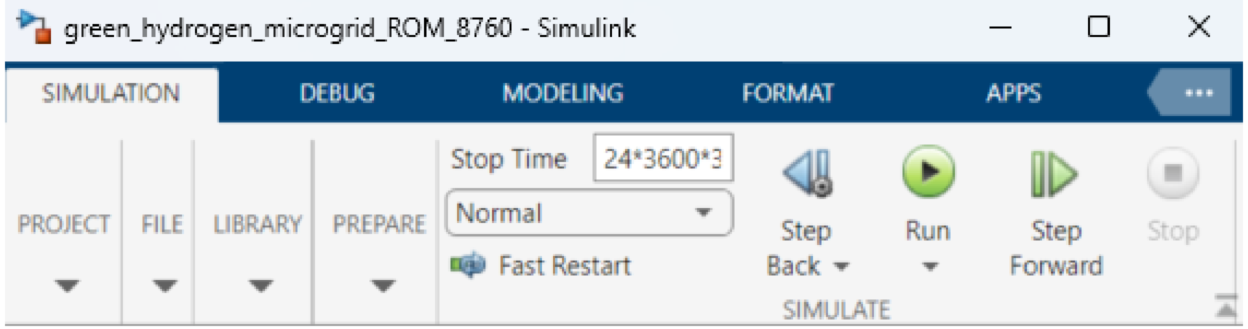




Capture steady state operating point

Quasi-steady lookup table model

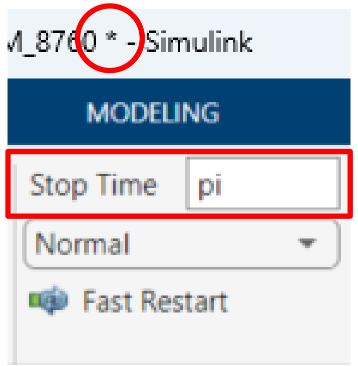
Clean Instancing for Model Setup



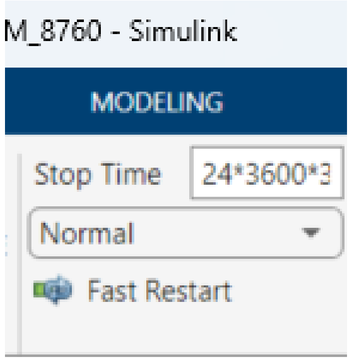

```
StopTime = "24*3600*365"
```

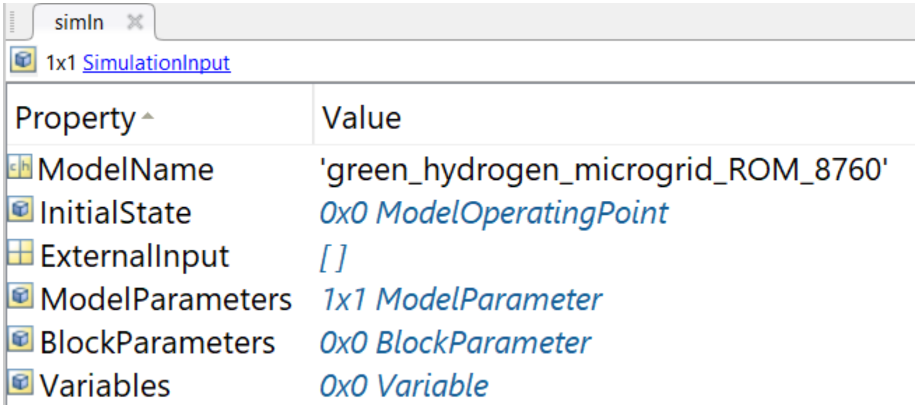
To change this via script:

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




```
simIn = Simulink.SimulationInput(gcs);
simIn = simIn.setModelParameter(StopTime = "pi");
```

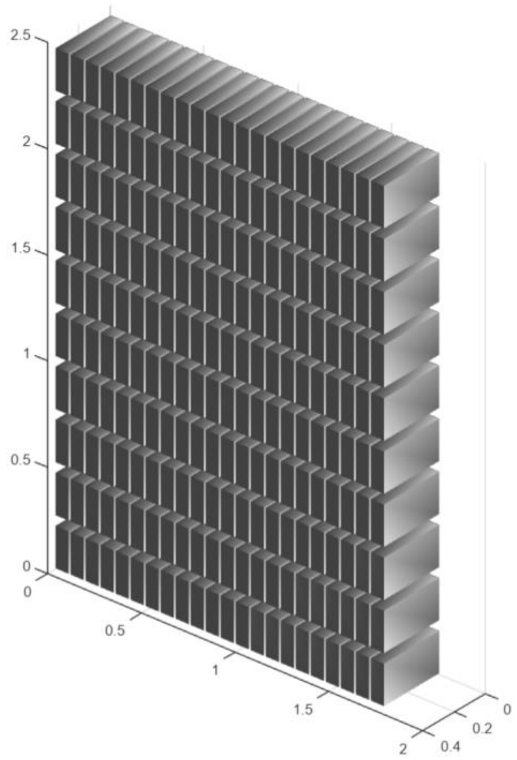




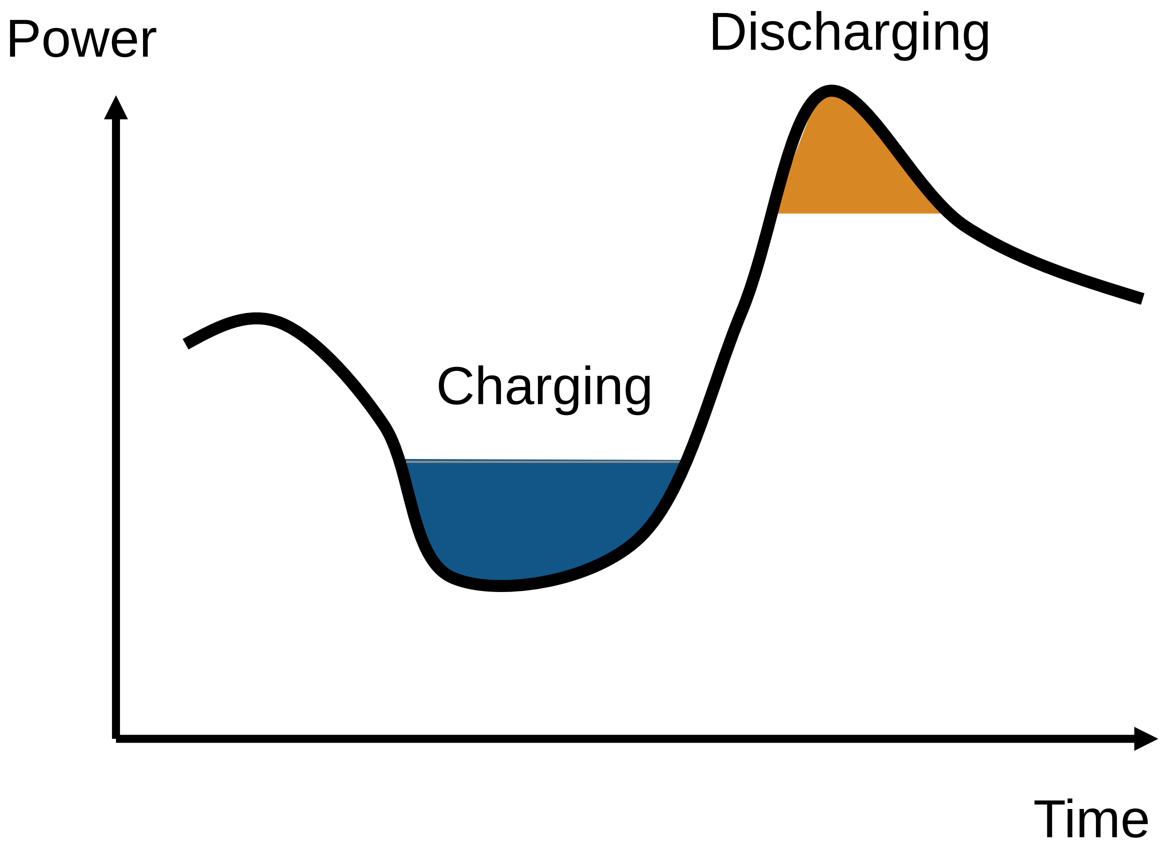
[Create Simulink.SimulationInput objects to make changes to model for multiple or individual simulations]

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

Detailed Design

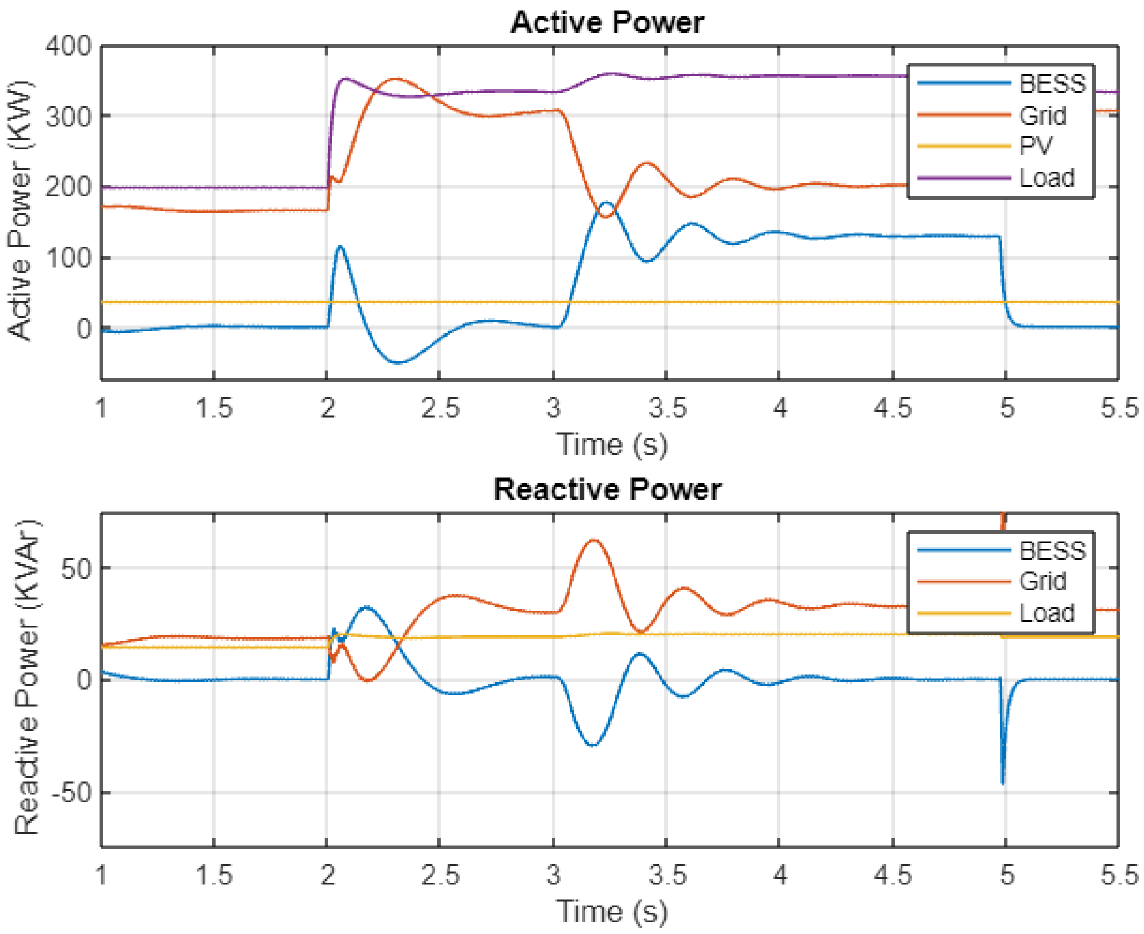


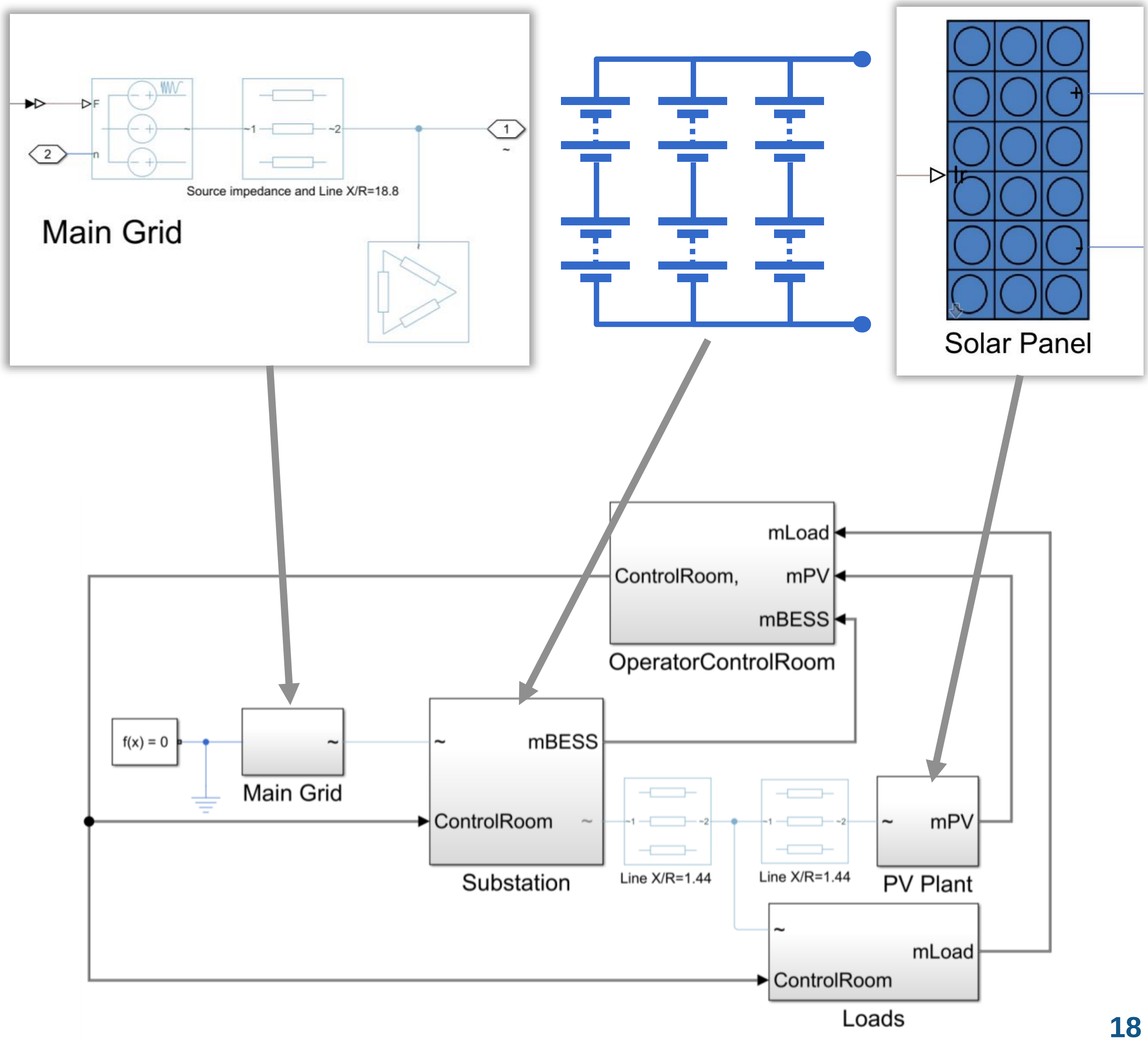
Peak Shaving



Peak Shaving

How do we model this complex battery architecture?

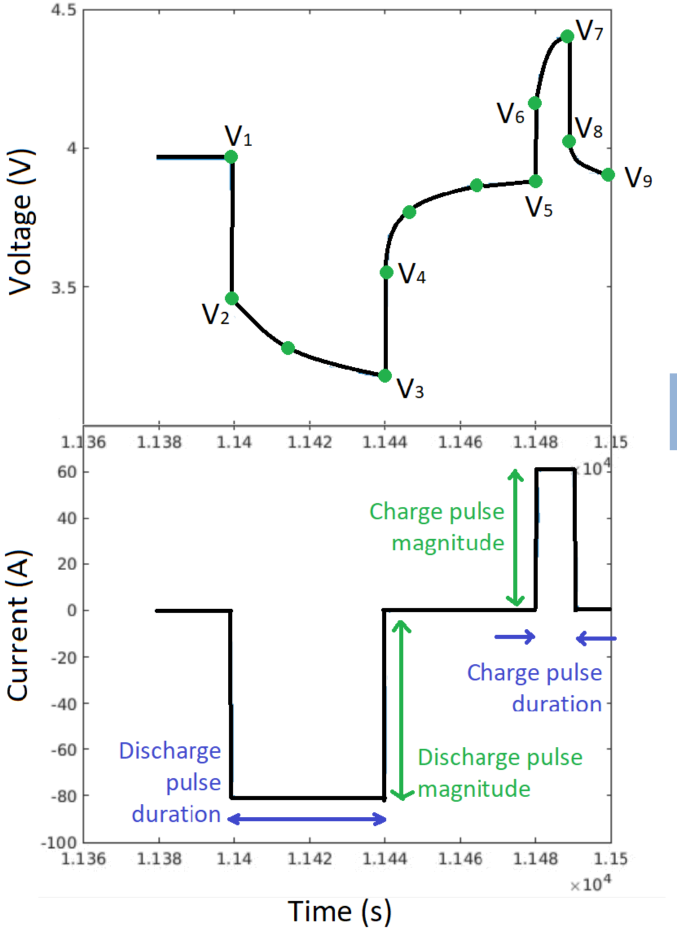


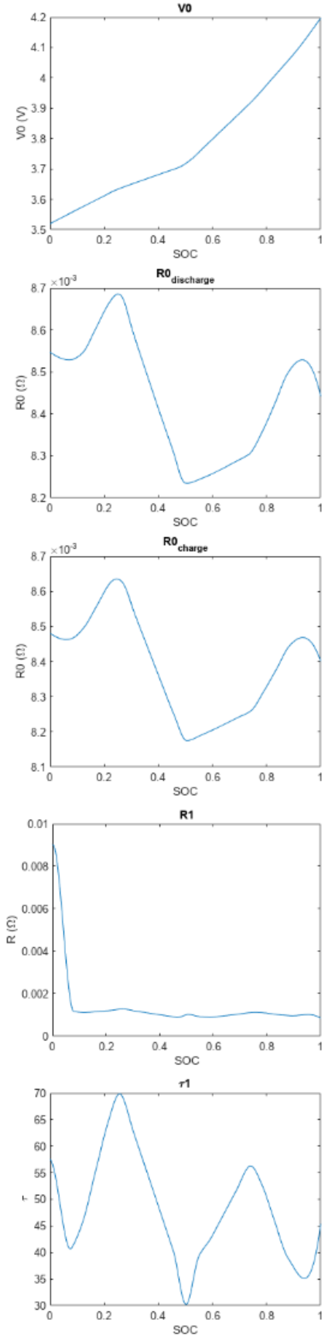


[Peak Shaving with Battery Energy Storage System - MATLAB & Simulink - MathWorks United Kingdom]

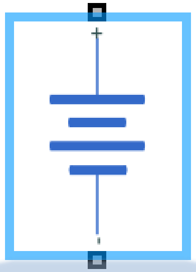
Battery Parameters

Fit from Data

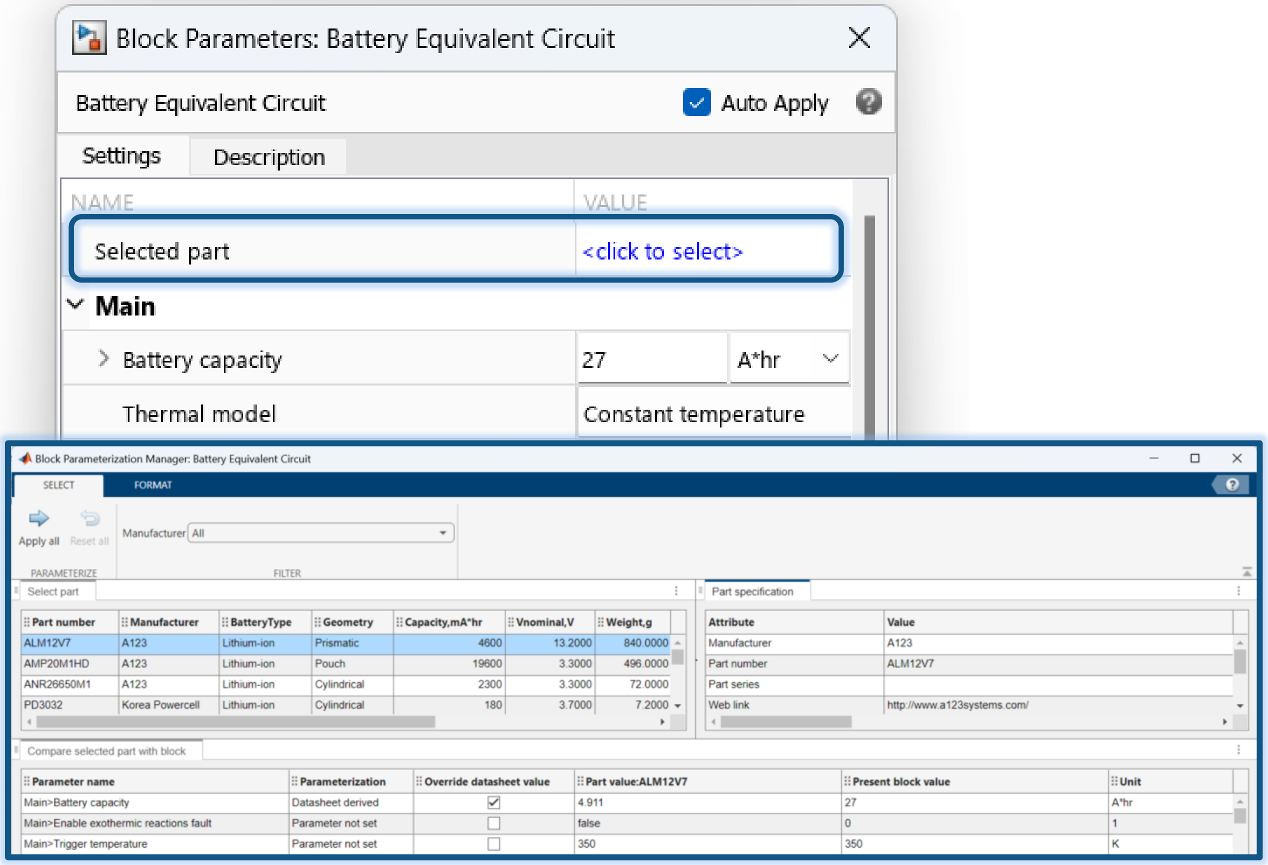




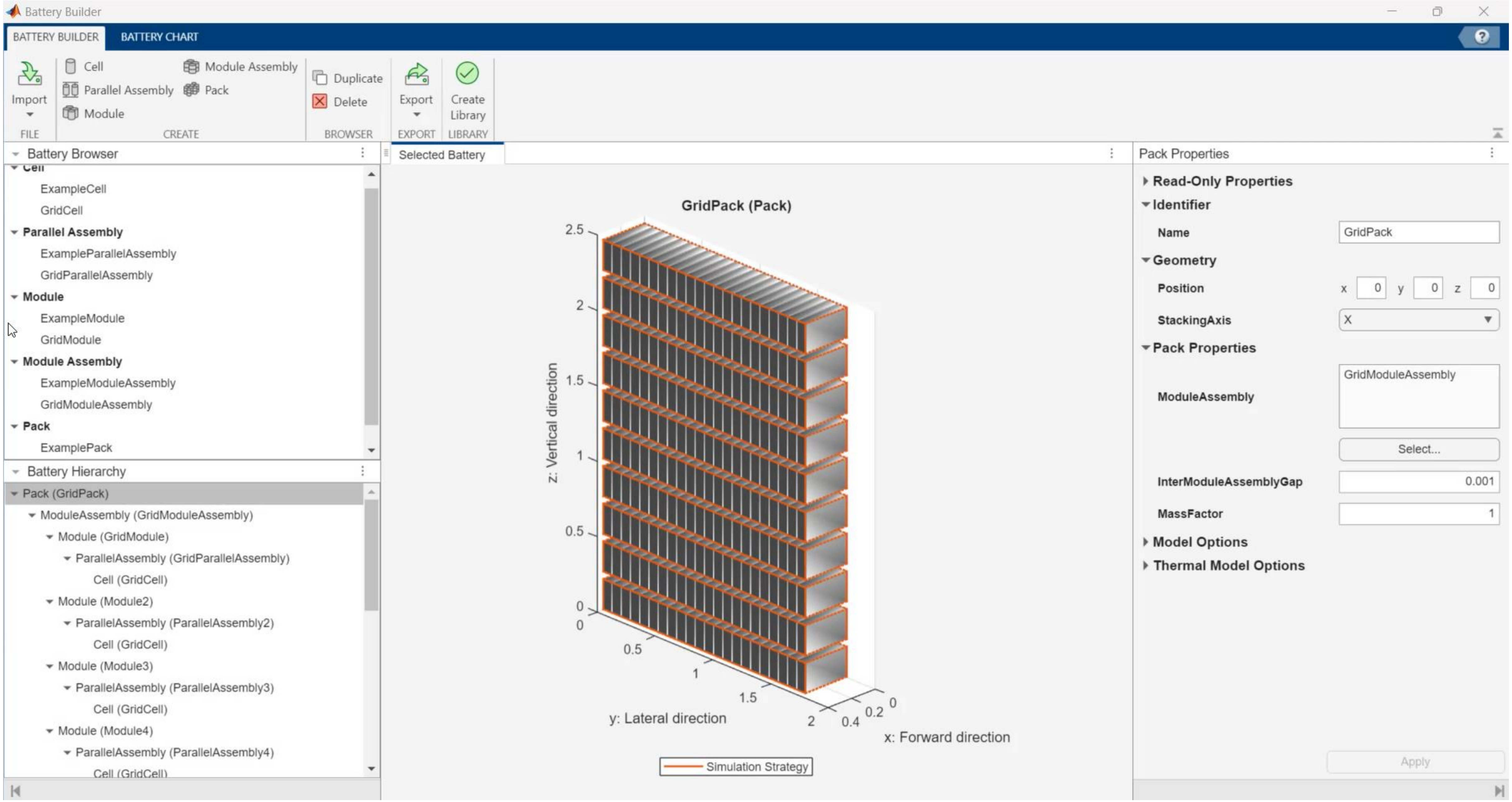
Pre-parametrized parts



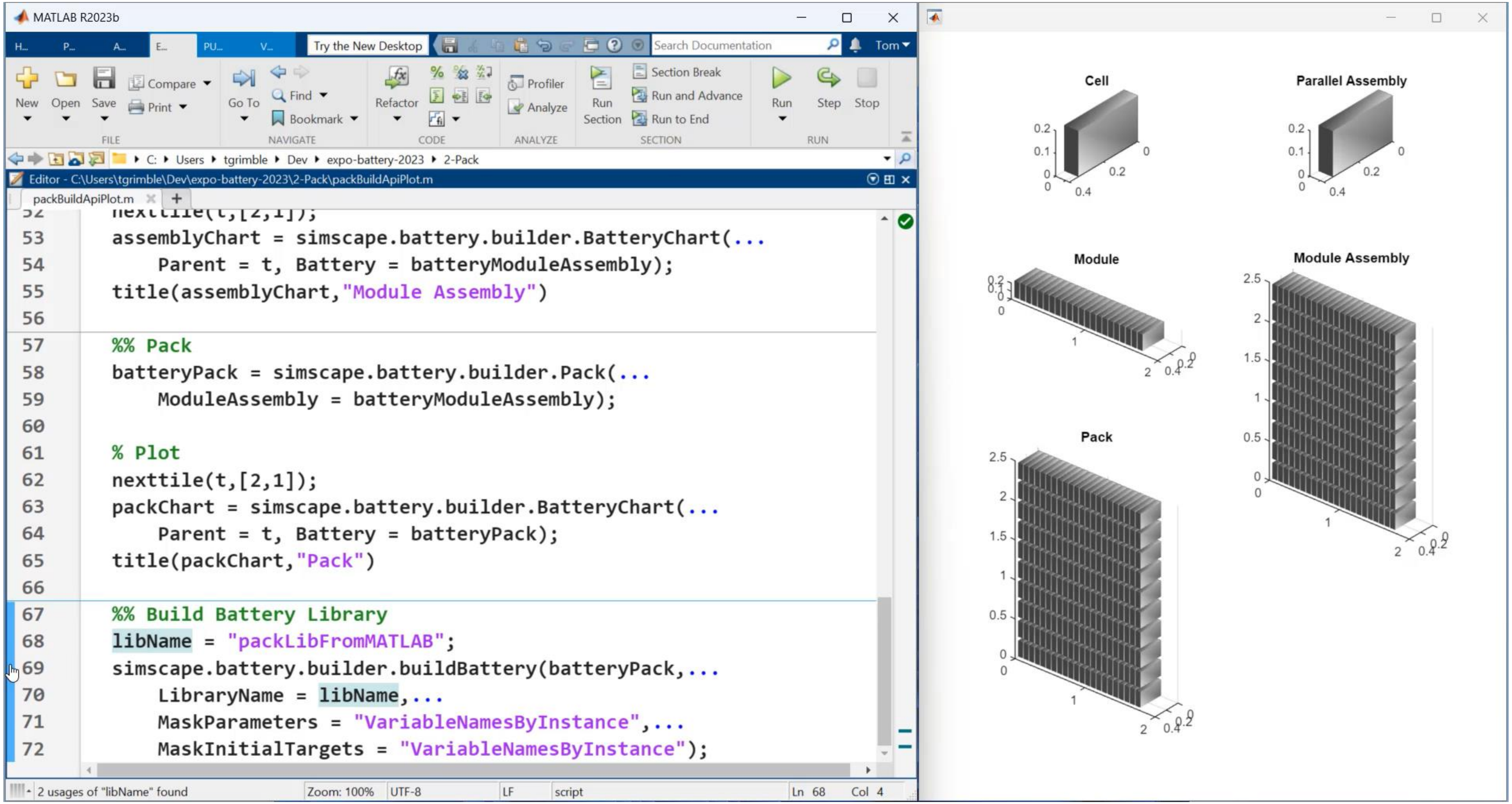
Battery Equivalent Circuit



[Characterize Battery Cell for Electric Vehicles](#)

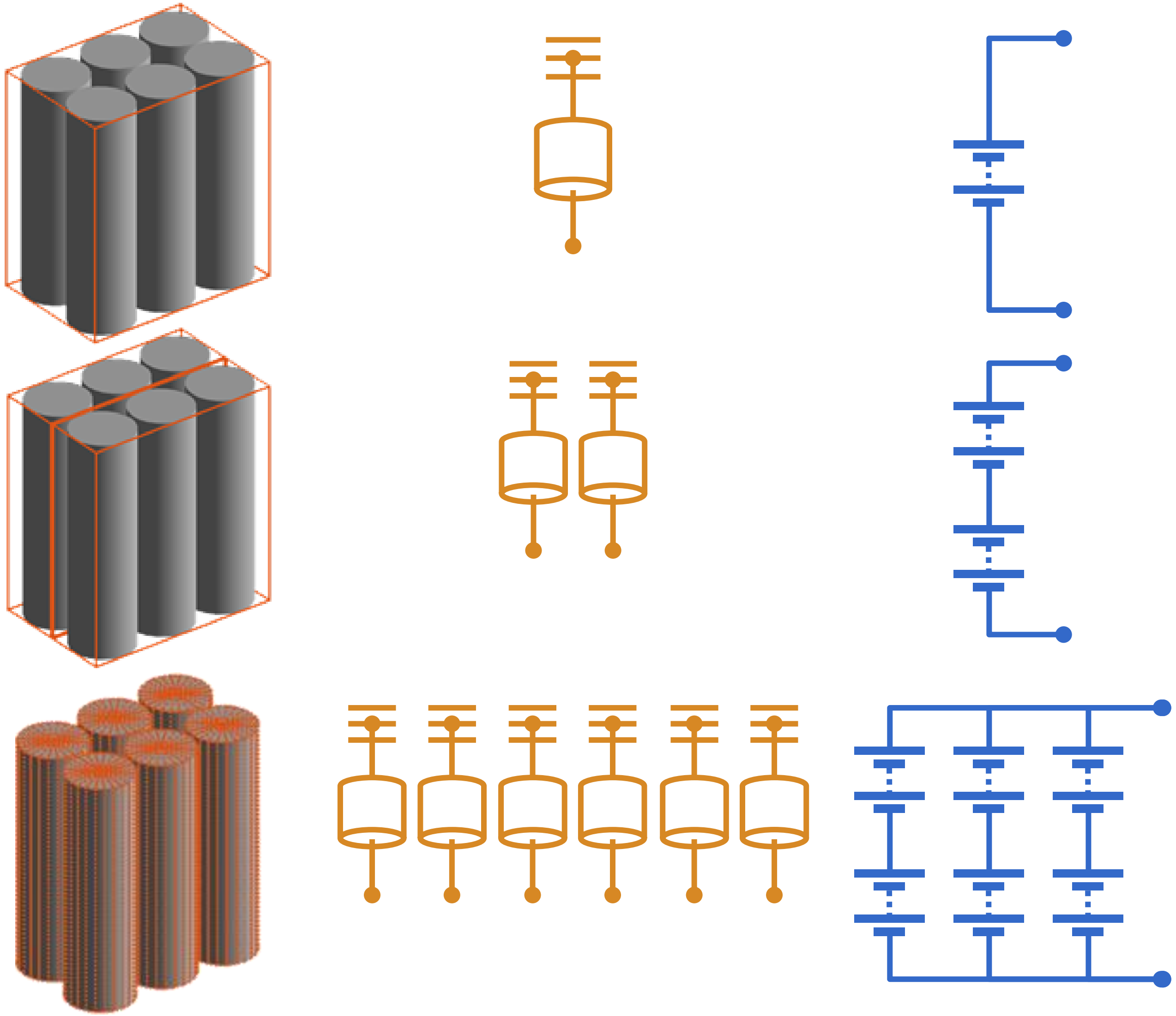

Battery Builder
BATTERY BUILDER
BATTERY CHART
Import
FILE
Cell
Parallel Assembly
Module
Module Assembly
Pack
CREATE
Duplicate
Delete
BROWSER
Export
EXPORT
Create Library
LIBRARY
Battery Browser
Cell
ExampleCell
GridCell
Parallel Assembly
ExampleParallelAssembly
GridParallelAssembly
Module
ExampleModule
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
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



Battery Pack Model Fidelity

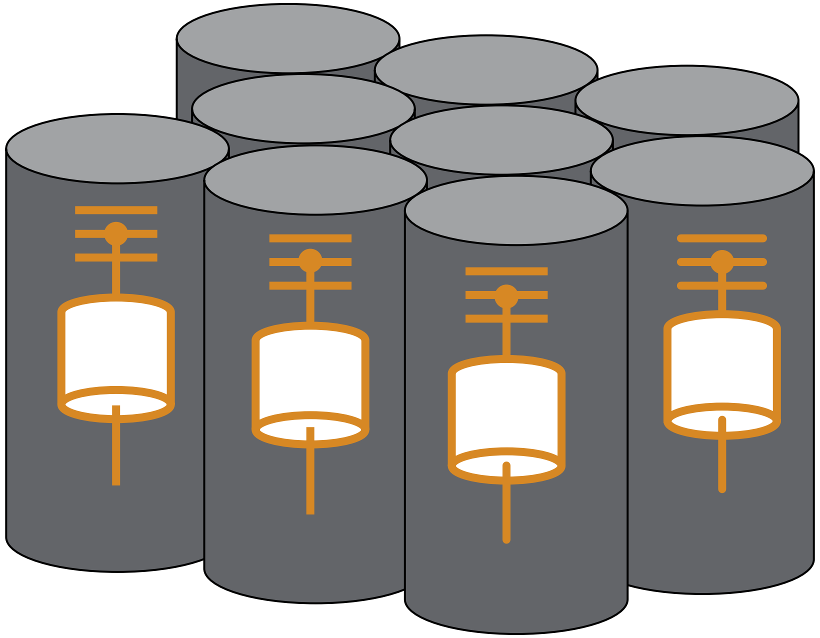
Pack Visualization	Equivalent Thermal Model	Equivalent Electrical Model



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

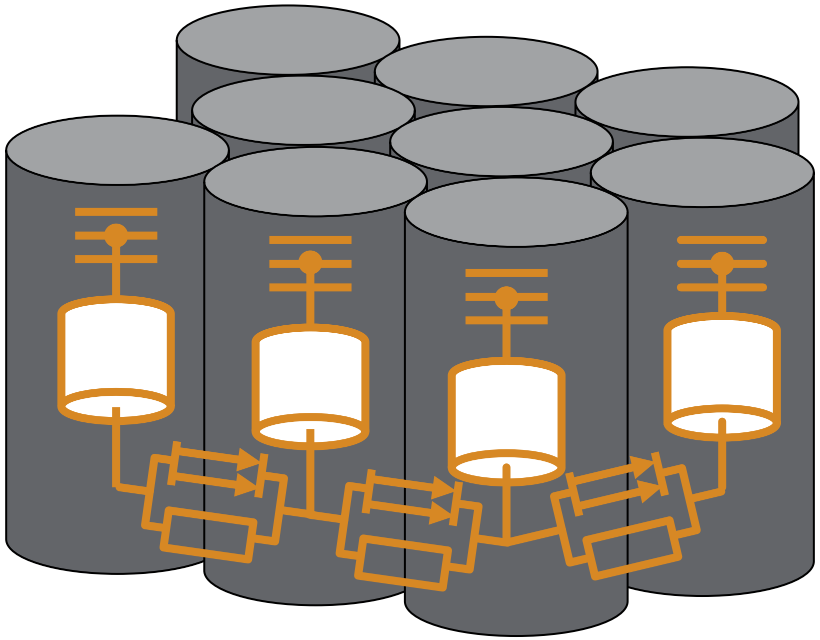
More to Model Resolution

Thermal Connections



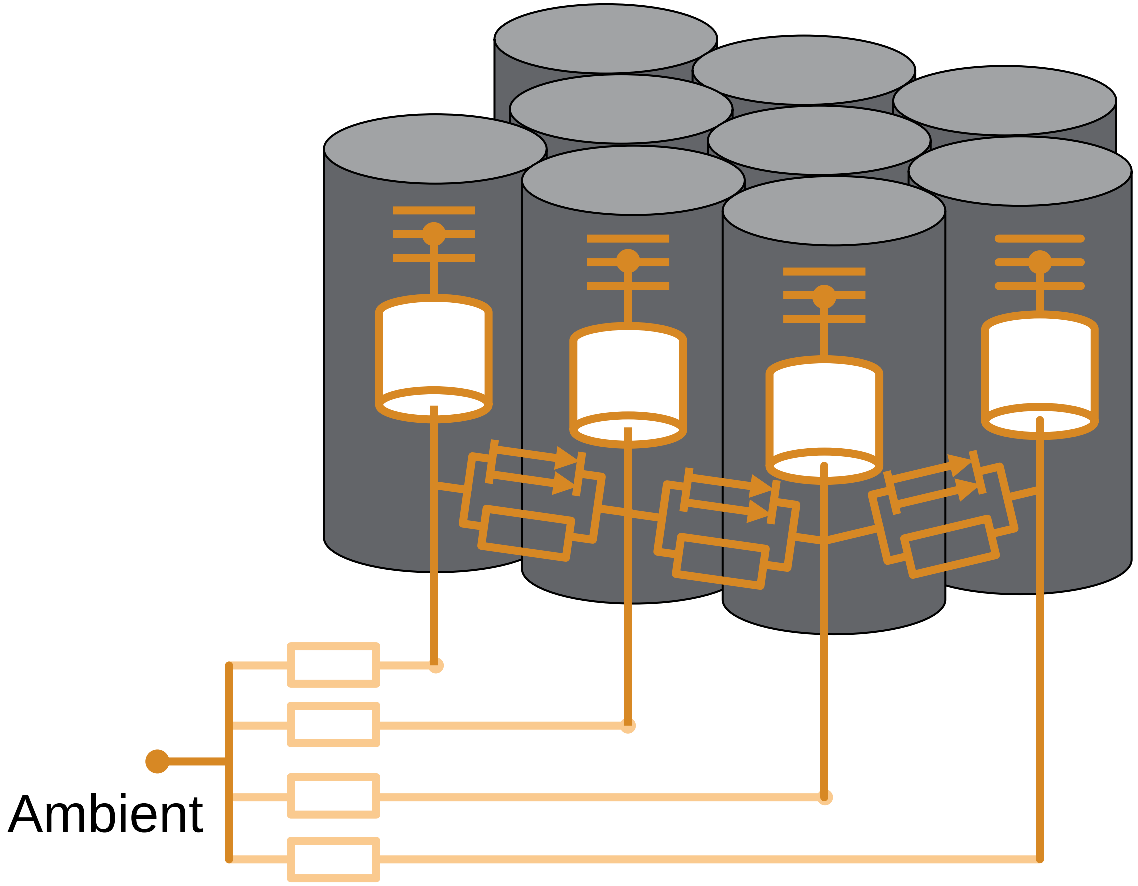
```
batteryModule = simscape.battery.builder.Module(...
    ParallelAssembly = pAssembly,...
    NumSeriesAssemblies = 3,...
    ModelResolution = "Detailed");
```

Thermal Connections



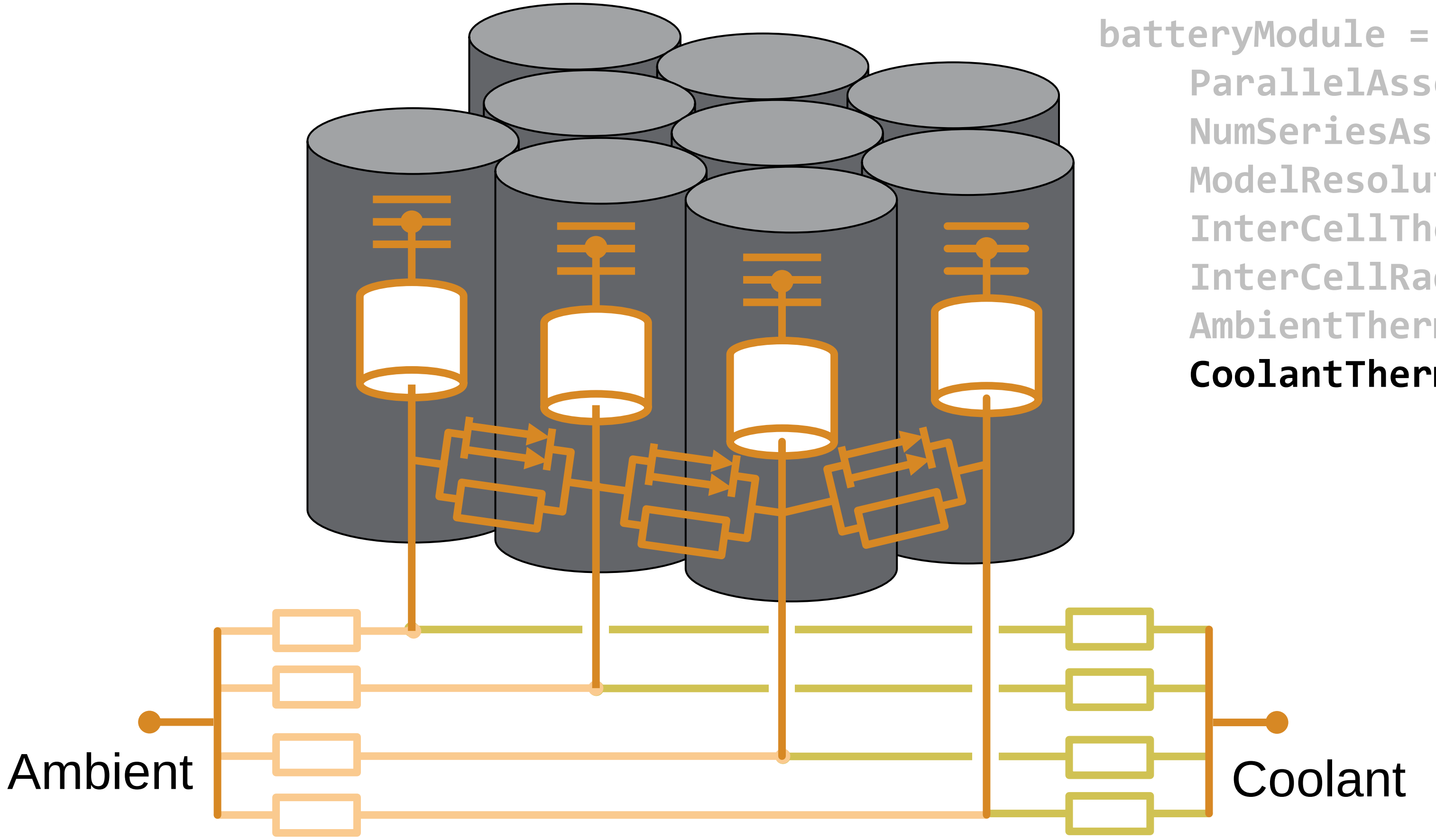
```
batteryModule = simscape.battery.builder.Module(...
    ParallelAssembly = pAssembly,...
    NumSeriesAssemblies = 3,...
    ModelResolution = "Detailed",...
    InterCellThermalPath = "on",...
    InterCellRadiativeThermalPath = "on");
```

Thermal Connections



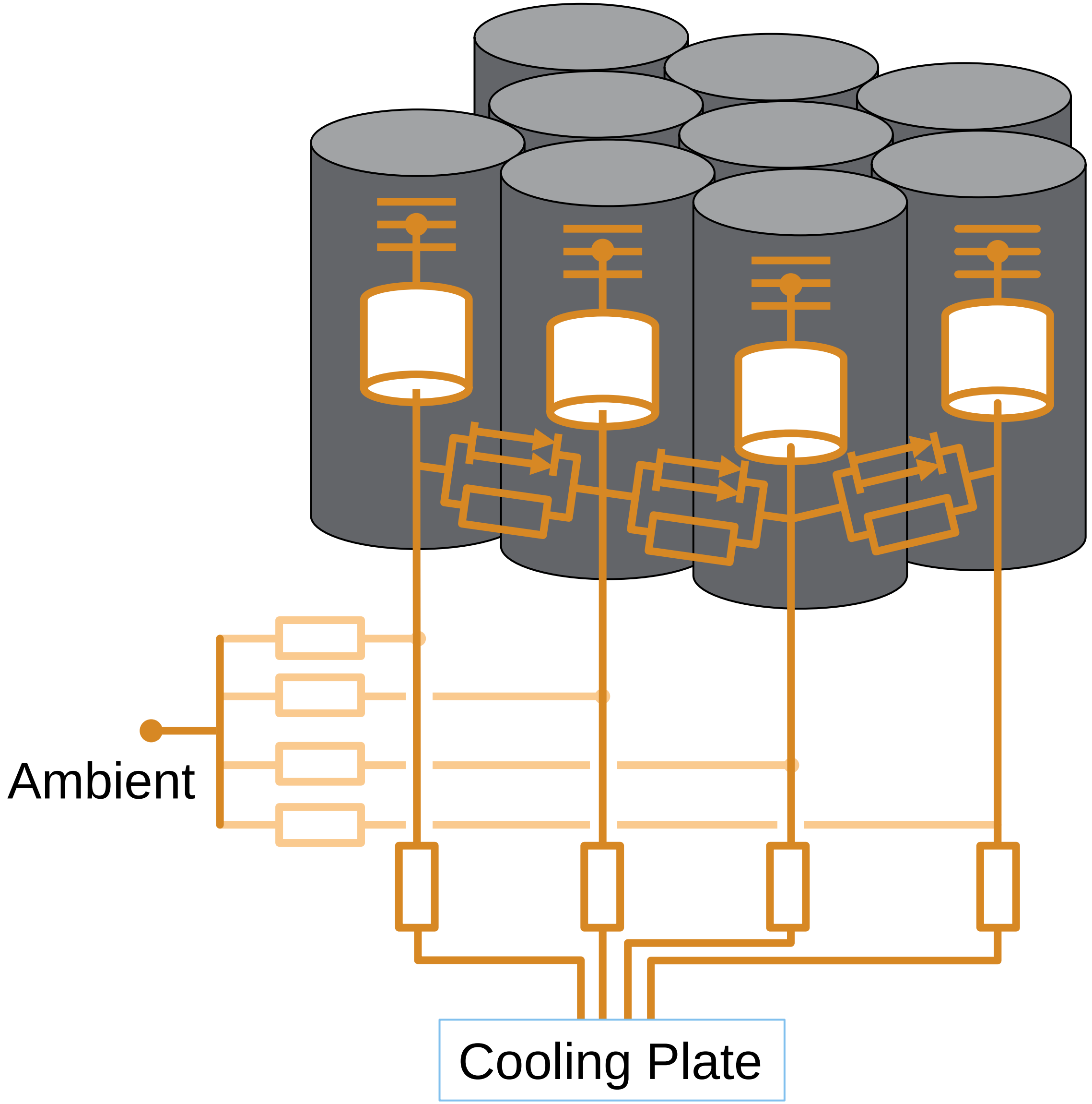

```
batteryModule = simscape.battery.builder.Module(...
    ParallelAssembly = pAssembly,...
    NumSeriesAssemblies = 3,...
    ModelResolution = "Detailed",...
    InterCellThermalPath = "on",...
    InterCellRadiativeThermalPath = "on",...
    AmbientThermalPath = "CellBasedThermalResistance");
```

Thermal Connections

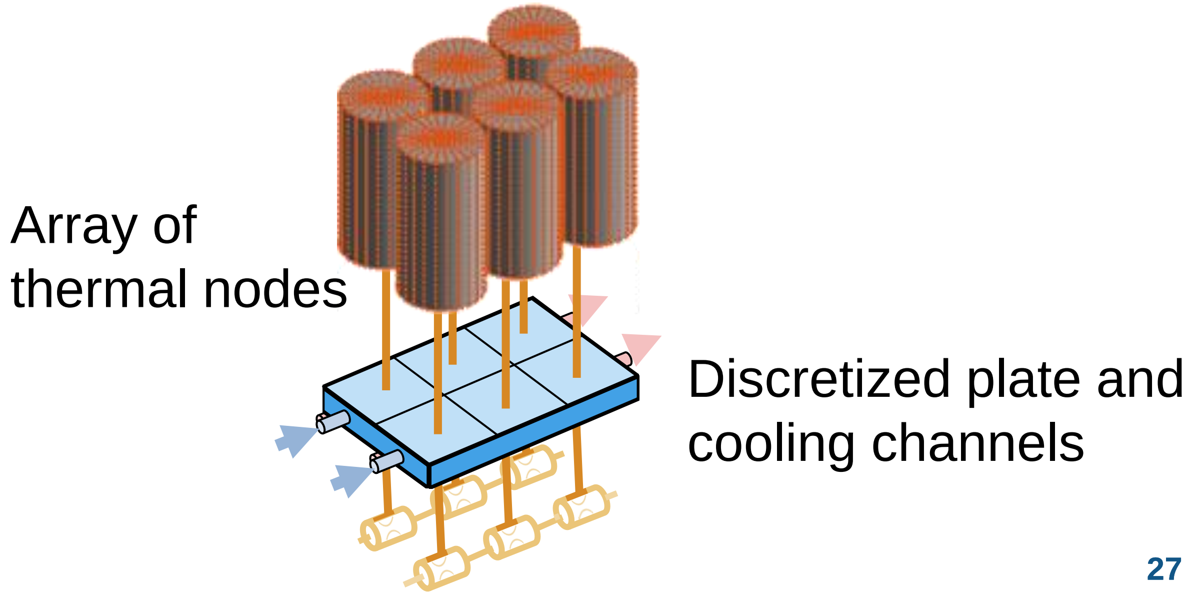



```
batteryModule = simscape.battery.builder.Module(...
    ParallelAssembly = pAssembly,...
    NumSeriesAssemblies = 3,...
    ModelResolution = "Detailed",...
    InterCellThermalPath = "on",...
    InterCellRadiativeThermalPath = "on",...
    AmbientThermalPath = "CellBasedThermalResistance",...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

Thermal Connections

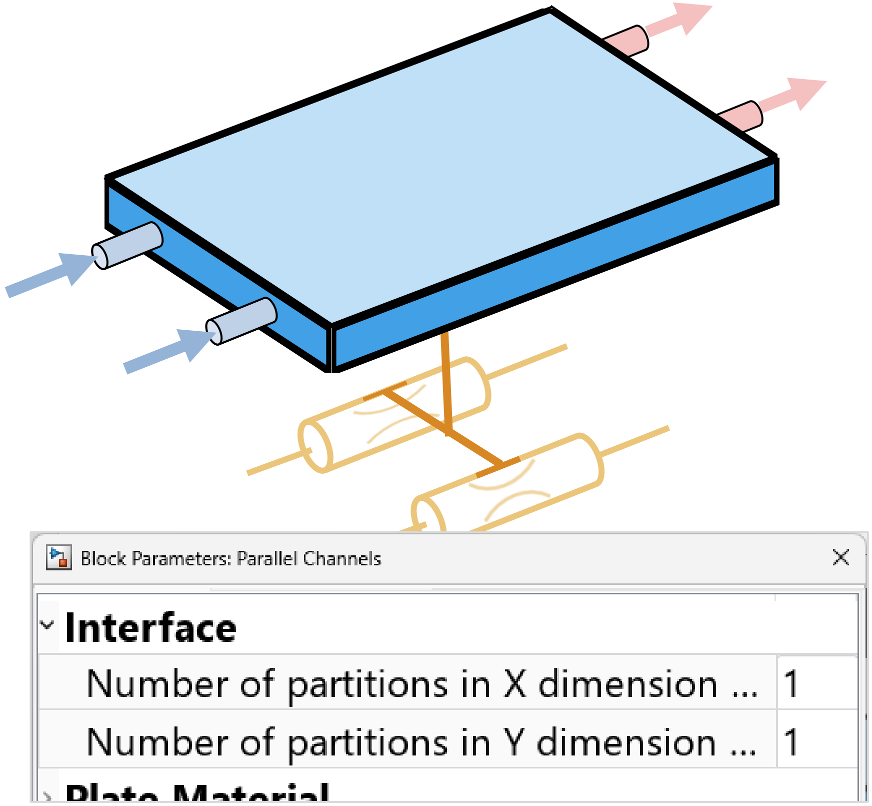


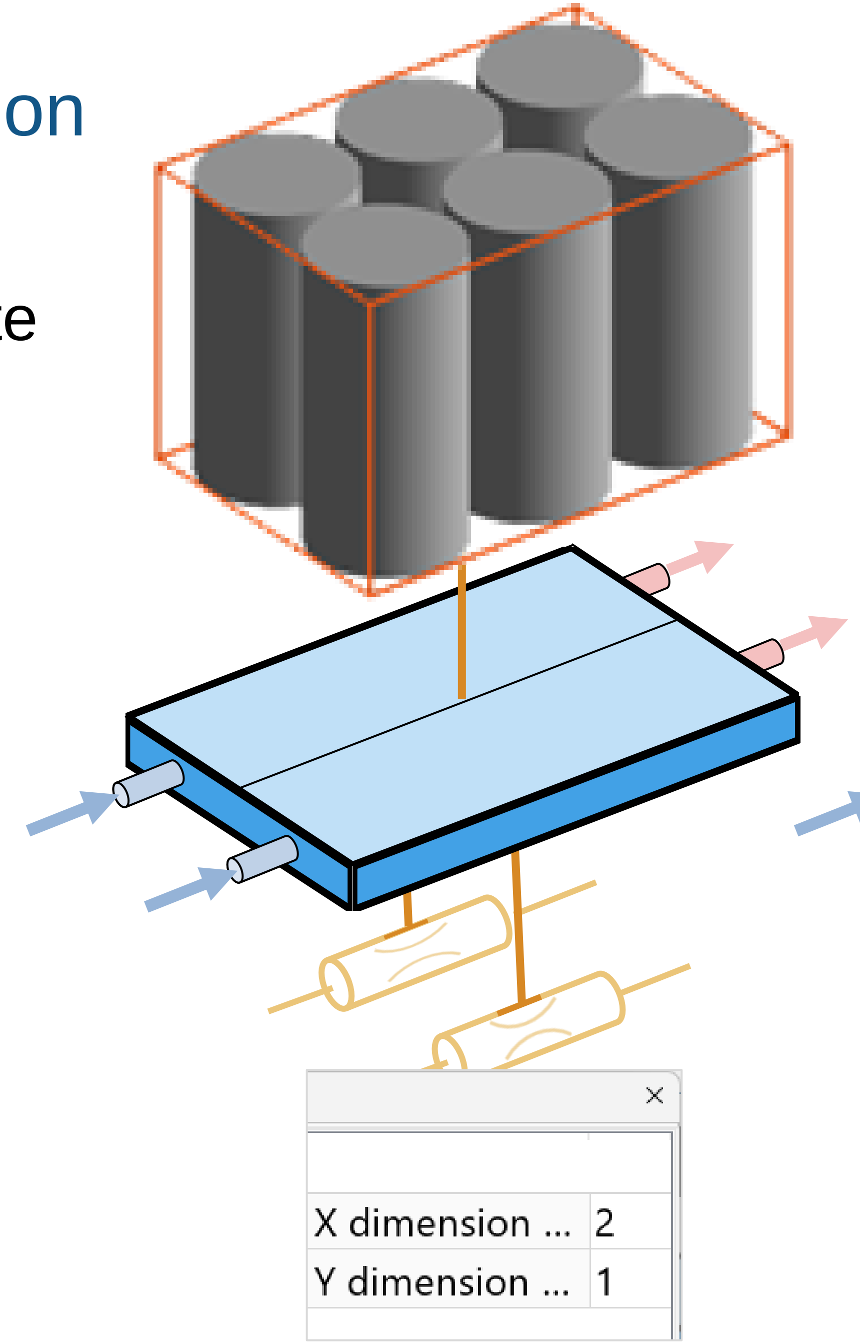

```
batteryModule = simscape.battery.builder.Module(...
    ParallelAssembly = pAssembly,...
    NumSeriesAssemblies = 3,...
    ModelResolution = "Detailed",...
    InterCellThermalPath = "on",...
    InterCellRadiativeThermalPath = "on",...
    AmbientThermalPath = "CellBasedThermalResistance",...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

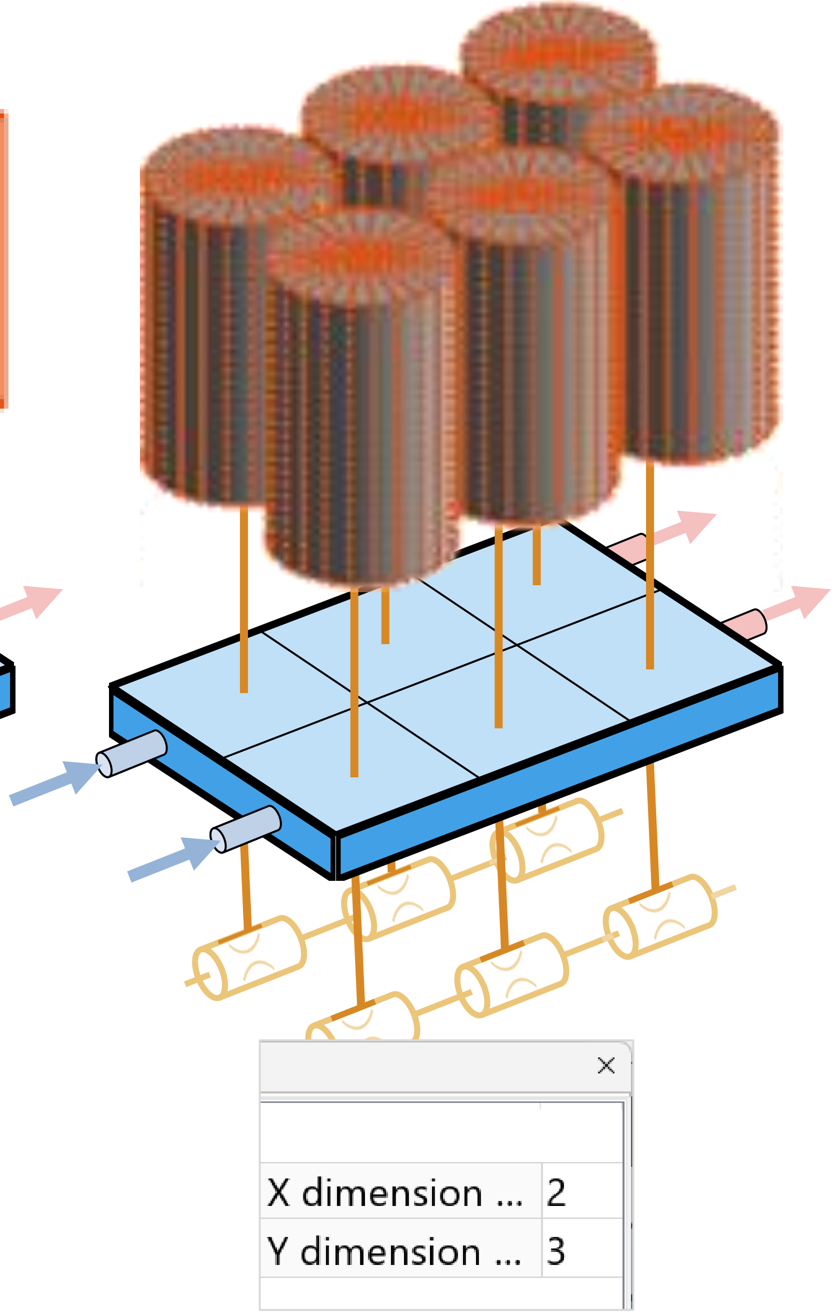


Cooling Plate Connection

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

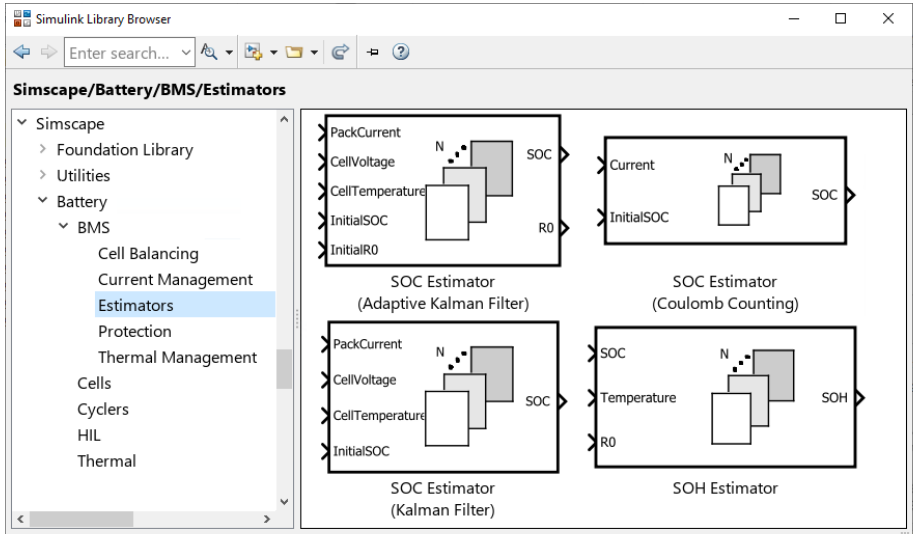


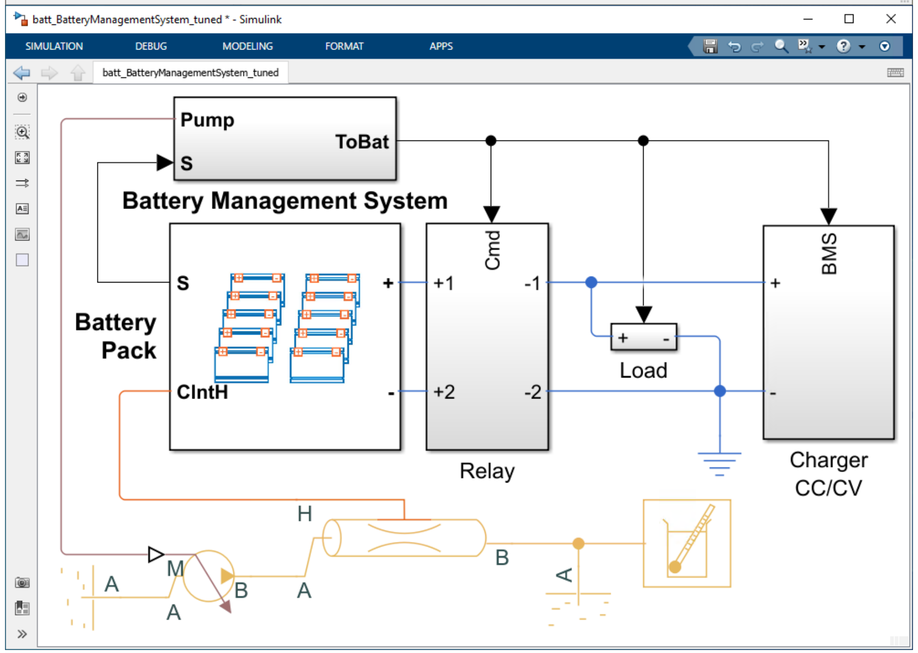




[Connect Cooling Plate to Battery Blocks]

Control Algorithms & Deployment

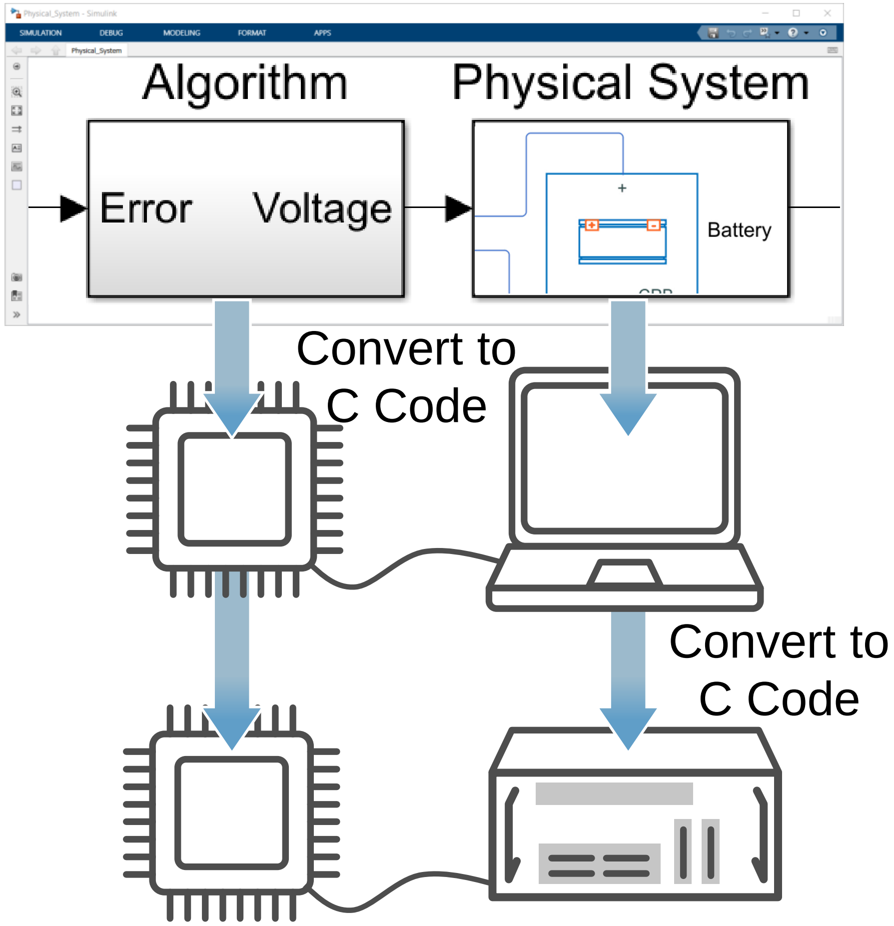




Battery Management Systems In Simscape Battery

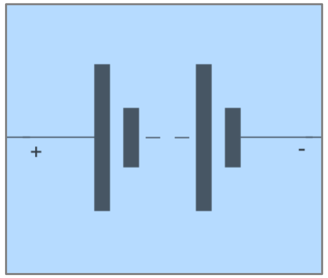
Processor-in-the-Loop (PIL)

Hardware-in-the-Loop (HIL)

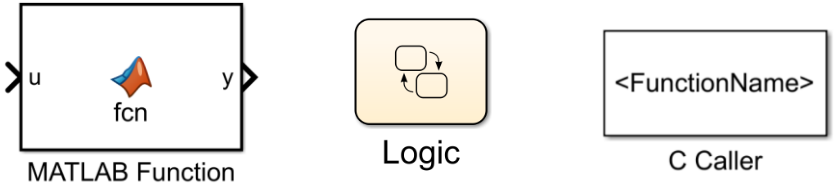


Customization

Customization and flexibility are at the core of MATLAB & Simulink



Custom cell



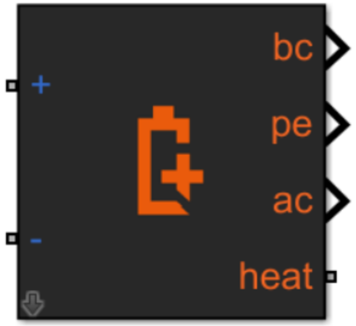
$$i = (C_0 + C_v v)\frac{dv}{dt} + \frac{v}{r_d}$$


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

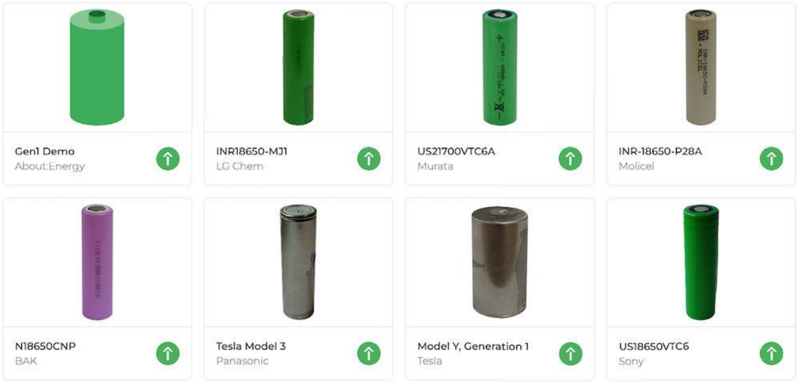
Customize physical models with Simscape language

[Simscape Customization]

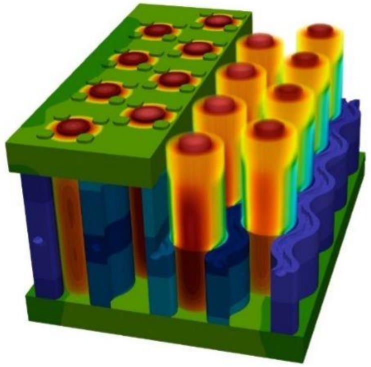
Extensions and Partners



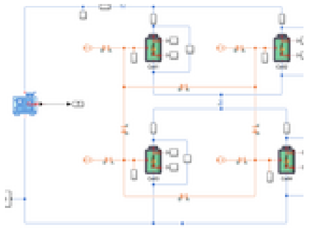
BATEMO
UNDERSTANDING BATTERIES



ABOUT:ENERGY



QUICKERSIM



A Simscape-Battery-Library

Version 2.0.0.0 (4.15 MB) by W. Dhammika Widanage

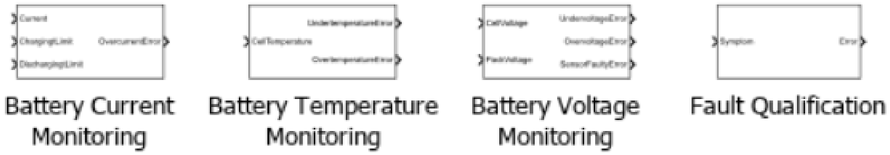
A Li-ion battery library written in Matlab Simscape language. Battery models include electrochemical models with ageing and ECMs.

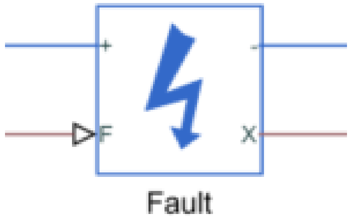
https://github.com/WDWidanage/Simscape-Battery-Library

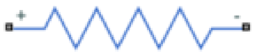
Fault Robustness

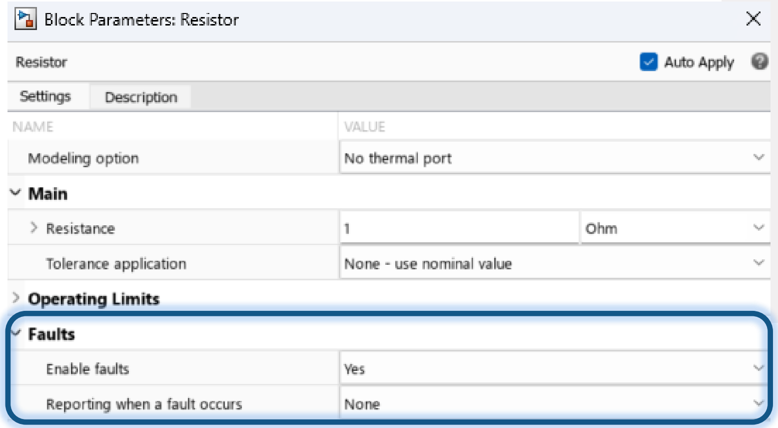
Faults & System Protection

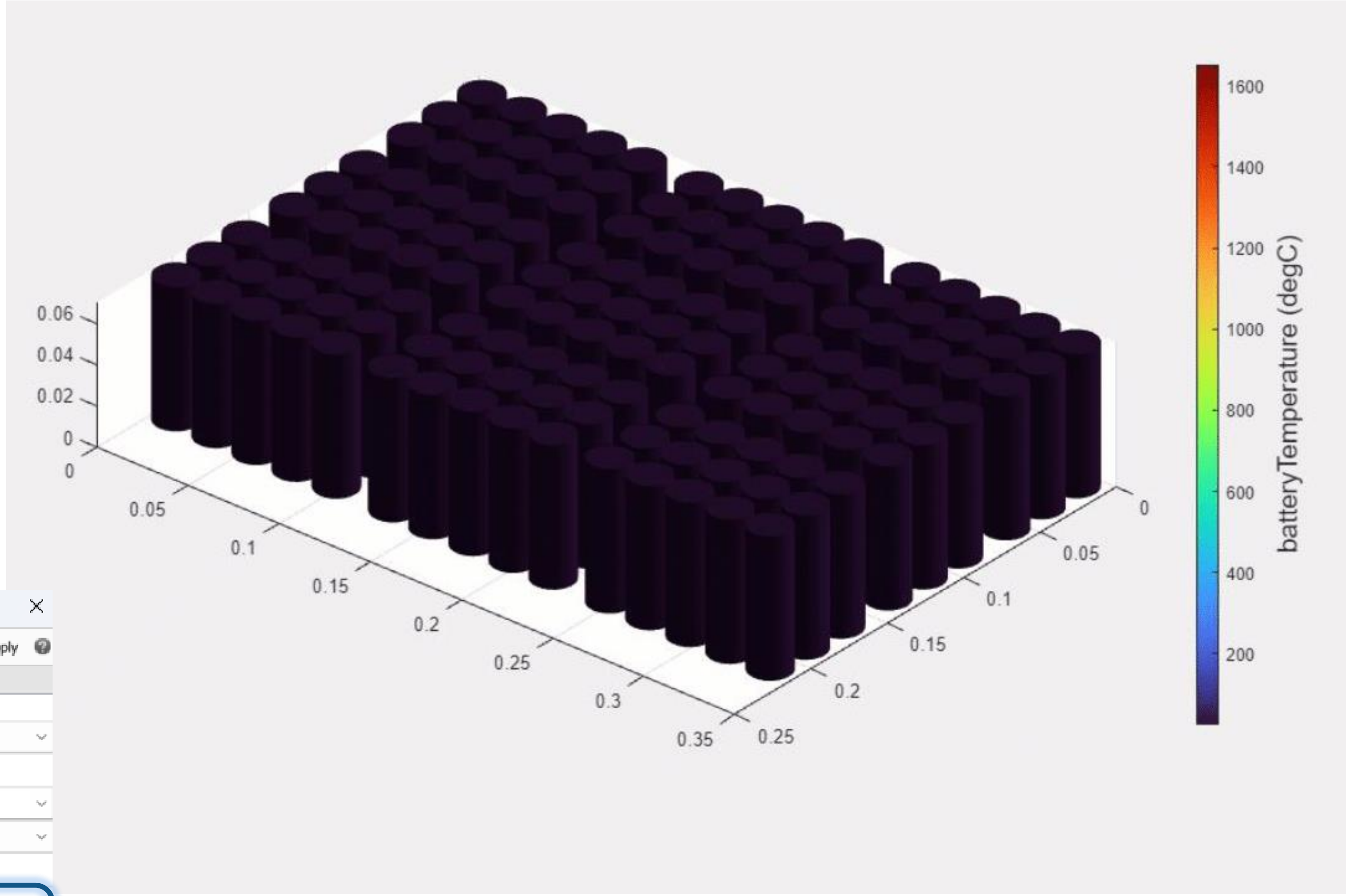
- Simscape
  - Foundation Library
  - Utilities
  - Battery
    - BMS
      - Cell Balancing
      - Current Management
      - Estimators
      - Protection
      - Thermal Management

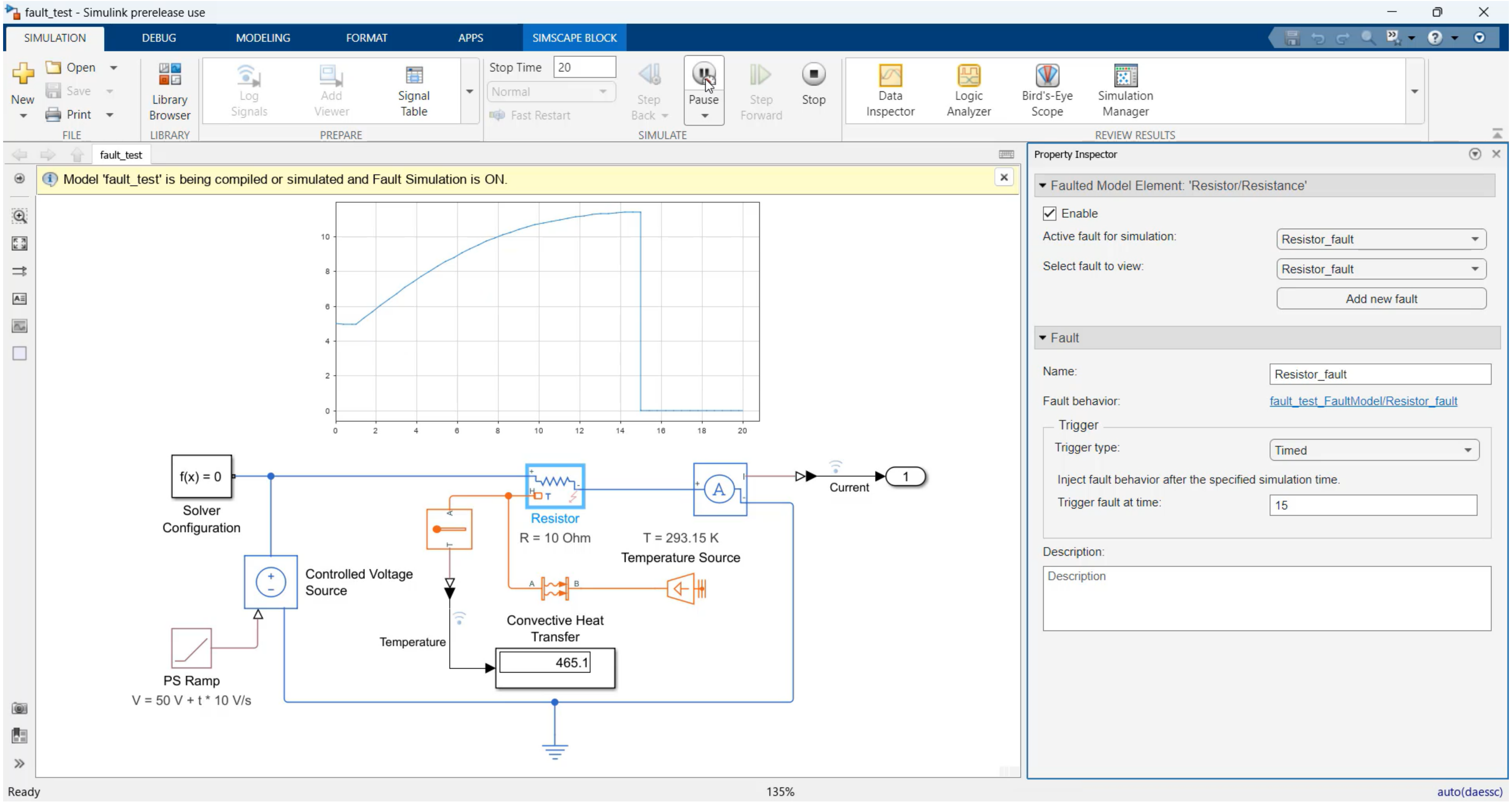




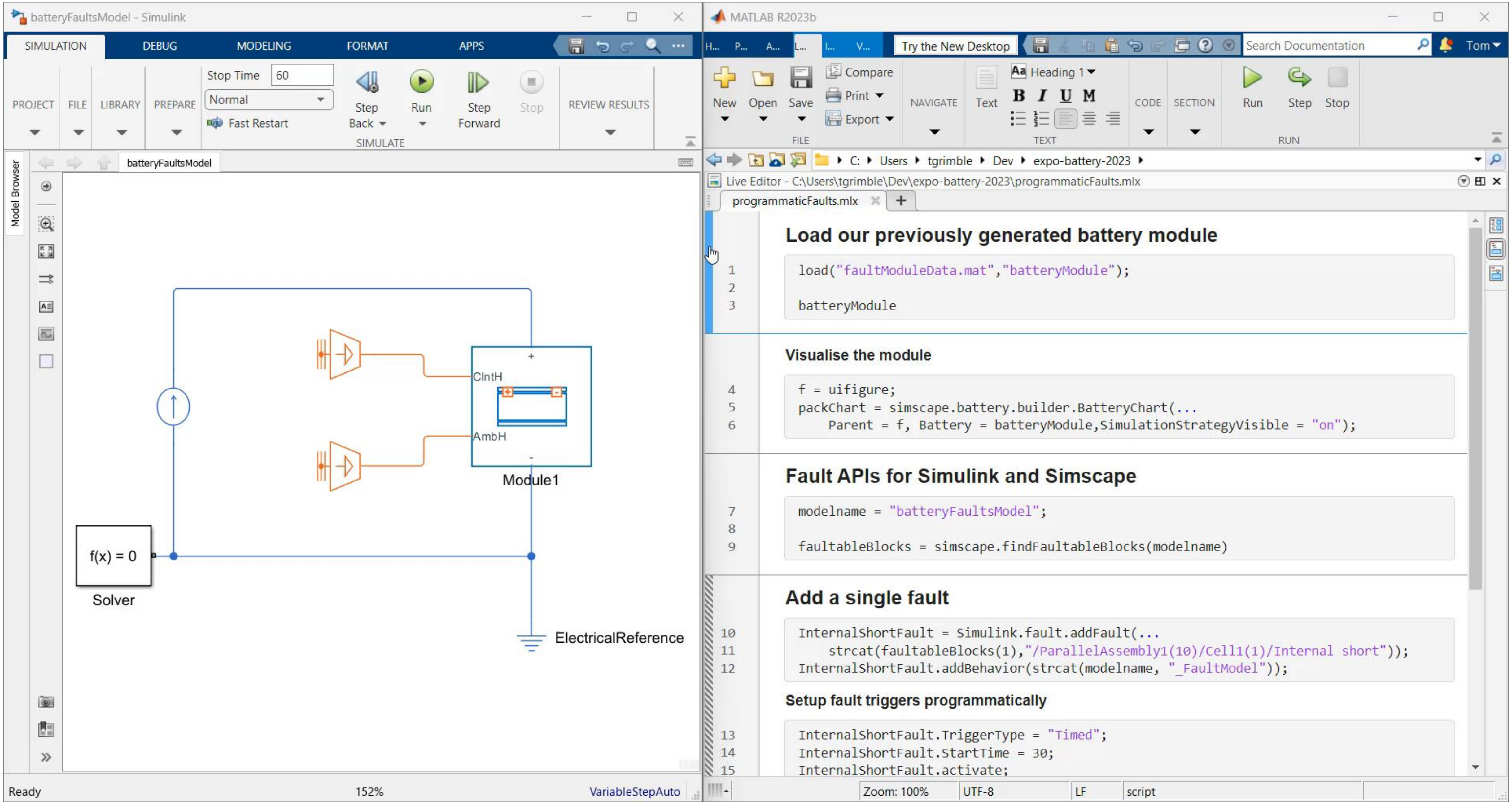




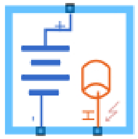



fault_test - Simulink prerelease use
SIMULATION
DEBUG
MODELING
FORMAT
APPS
SIMSCAPE BLOCK
New
Open
Save
Print
FILE
Library Browser
LIBRARY
Log Signals
Add Viewer
Signal Table
PREPARE
Stop Time
20
Normal
Fast Restart
Step Back
Pause
Step Forward
Stop
SIMULATE
Data Inspector
Logic Analyzer
Bird's-Eye Scope
Simulation Manager
REVIEW RESULTS
fault_test
Model 'fault_test' is being compiled or simulated and Fault Simulation is ON.
f(x) = 0
Solver Configuration
Resistor
R = 10 Ohm
T = 293.15 K
Temperature Source
Current
1
Controlled Voltage Source
Convective Heat Transfer
Temperature
465.1
PS Ramp
V = 50 V + t * 10 V/s
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)

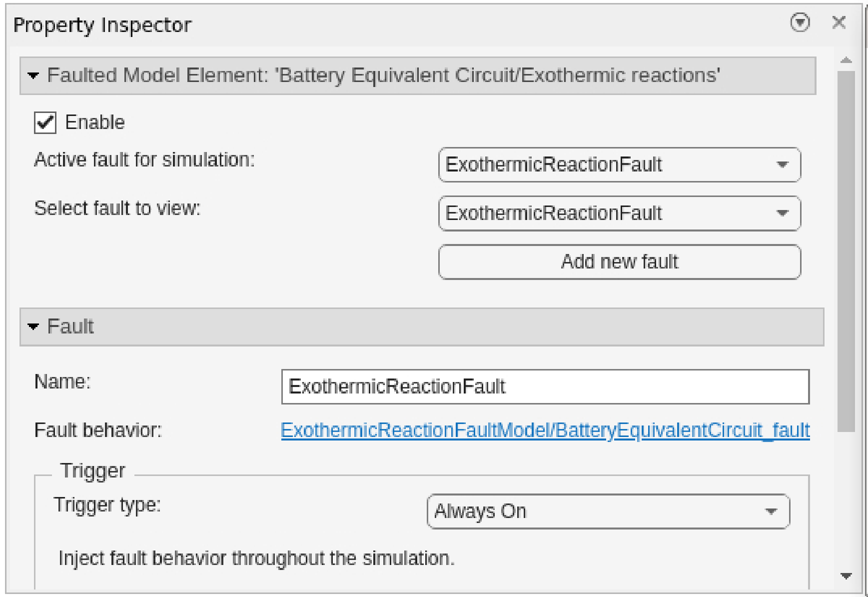
MATLAB EXPO

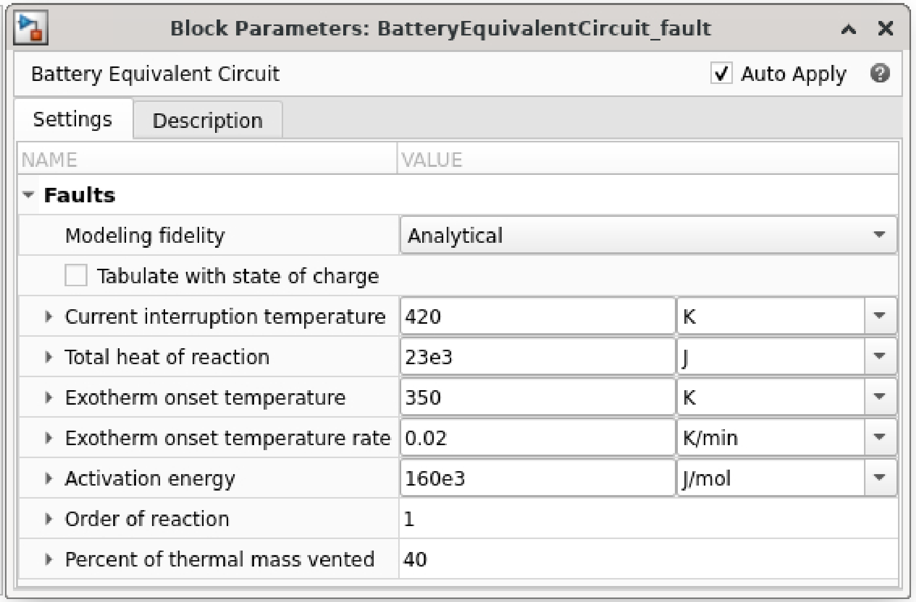

batteryFaultsModel - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
APPS
PROJECT
FILE
LIBRARY
PREPARE
Stop Time
60
Normal
Fast Restart
Step Back
Run
Step Forward
Stop
SIMULATE
REVIEW RESULTS
Model Browser
batteryFaultsModel
ClntH
AmbH
Module1
f(x) = 0
Solver
ElectricalReference
Ready
152%
VariableStepAuto
MATLAB R2023b
Try the New Desktop
Search Documentation
Tom
New
Open
Save
Compare
Print
Export
FILE
NAVIGATE
Text
Heading 1
TEXT
CODE
SECTION
Run
Step
Stop
RUN
C: Users tgrimble Dev expo-battery-2023
Live Editor - C:\Users\tgrimble\Dev\expo-battery-2023\programmaticFaults.mlx
programmaticFaults.mlx
Load our previously generated battery module
load("faultModuleData.mat","batteryModule");
batteryModule
Visualise the module
f = uifigure;
packChart = simscape.battery.builder.BatteryChart(...
Parent = f, Battery = batteryModule,SimulationStrategyVisible = "on");
Fault APIs for Simulink and Simscape
modelname = "batteryFaultsModel";
faultableBlocks = simscape.findFaultableBlocks(modelname)
Add a single fault
InternalShortFault = Simulink.fault.addFault(...
strcat(faultableBlocks(1),"/ParallelAssembly1(10)/Cell1(1)/Internal short"));
InternalShortFault.addBehavior(strcat(modelname, "_FaultModel"));
Setup fault triggers programmatically
InternalShortFault.TriggerType = "Timed";
InternalShortFault.StartTime = 30;
InternalShortFault.activate;
Zoom: 100%
UTF-8
LF
script

Battery Cell Fault Modeling

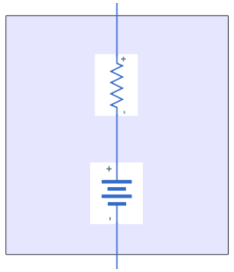


Battery Equivalent Circuit

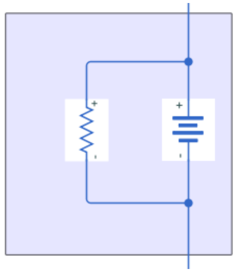




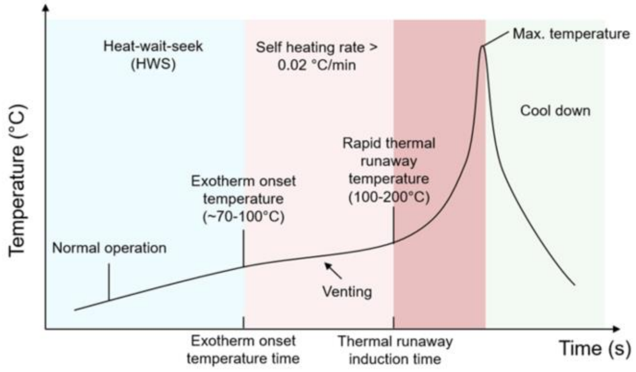
Additional Resistance Fault



Internal Short Fault



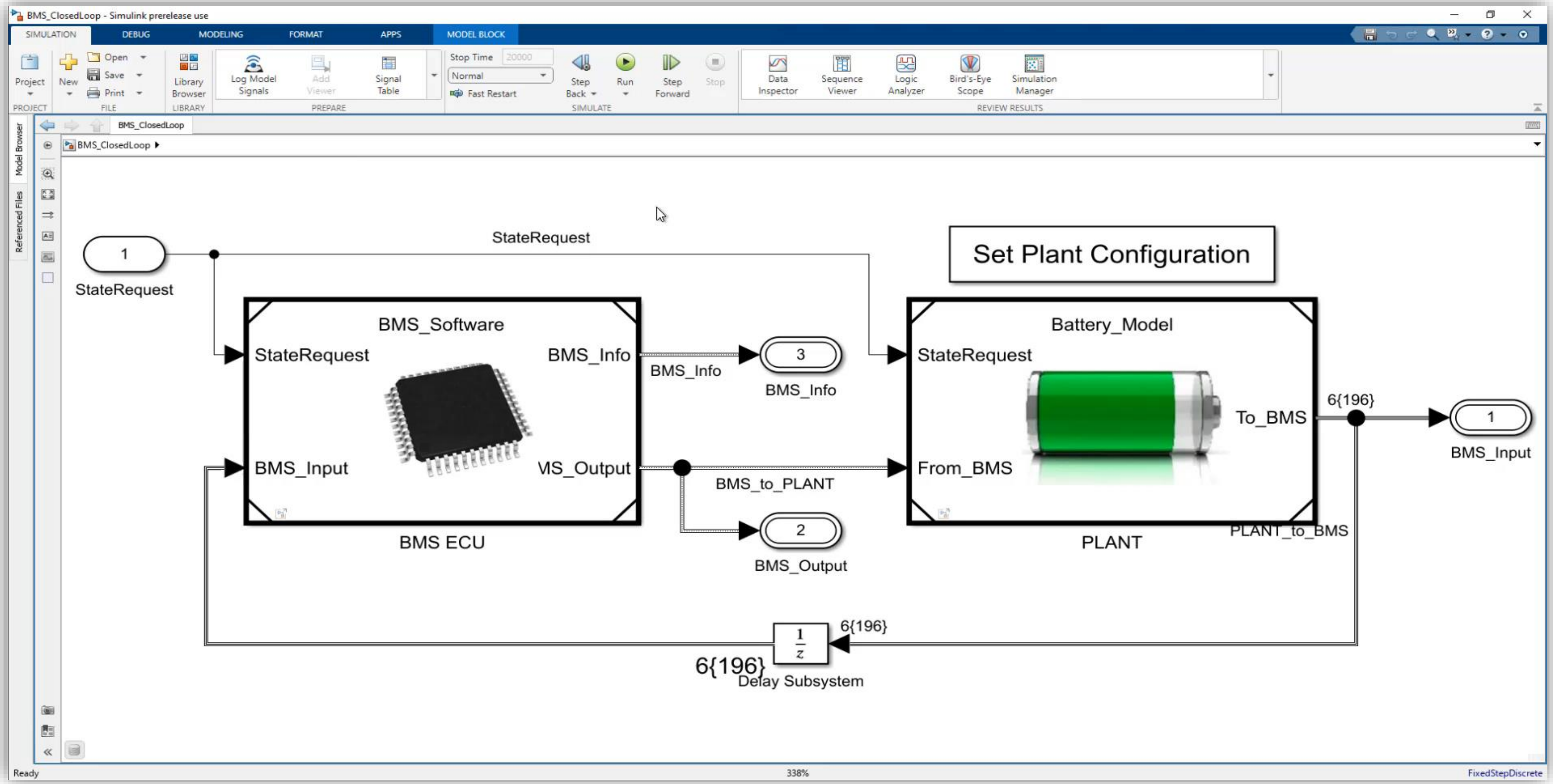
Exothermic Reaction Fault

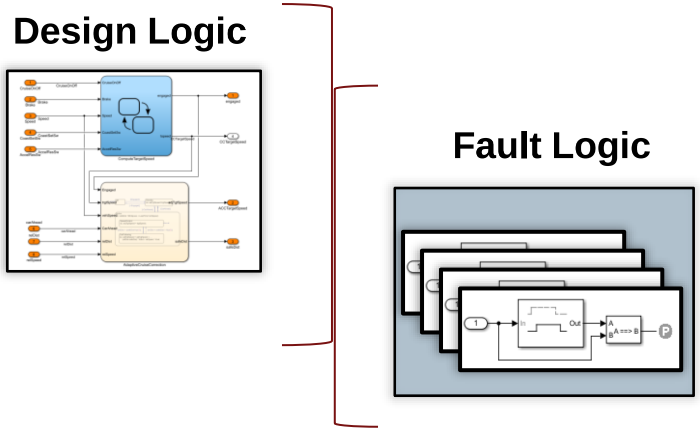


- Definition of time or condition dependent faults.
- Support modeling of thermal runaway events.

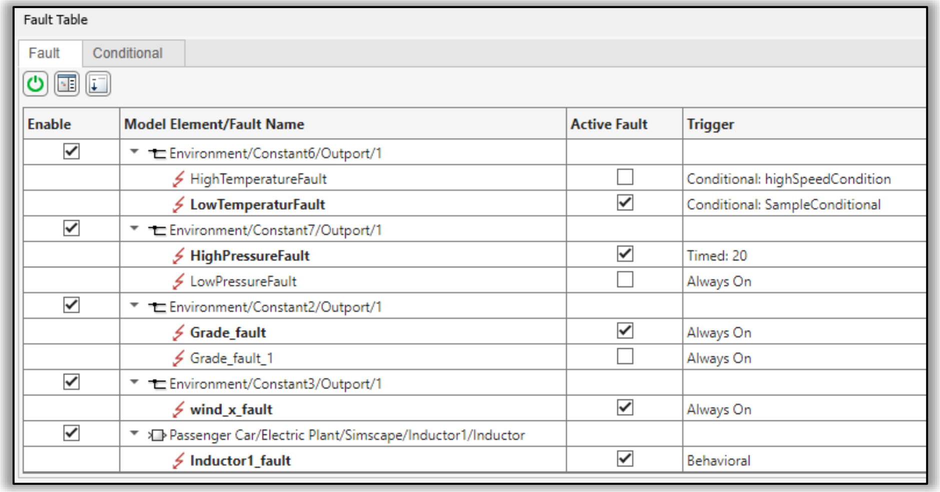
[Inject Faults in Battery Models]

Unified Fault Framework



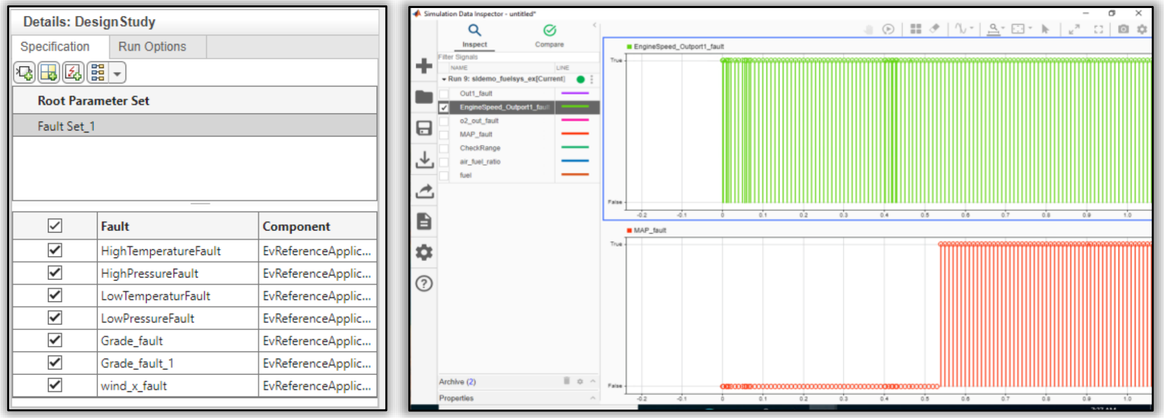


Model faults without modifying the design

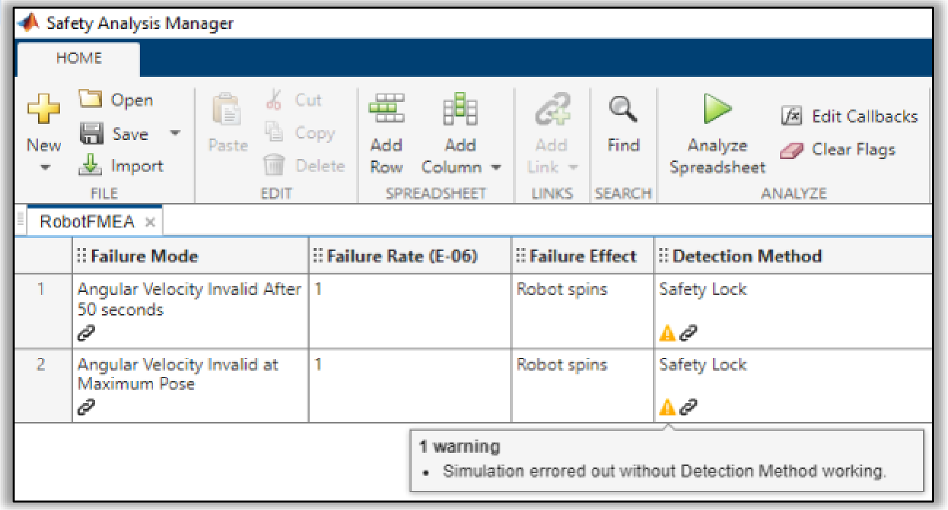


Manage faults across multiple domains

[Simulink Fault Analyzer™]



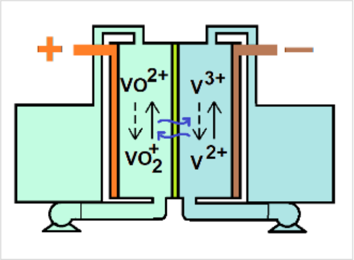
Simulate, explore and analyze fault effects

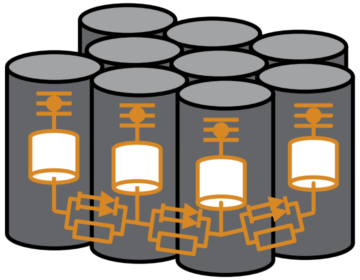


Perform systematic safety analysis using simulation

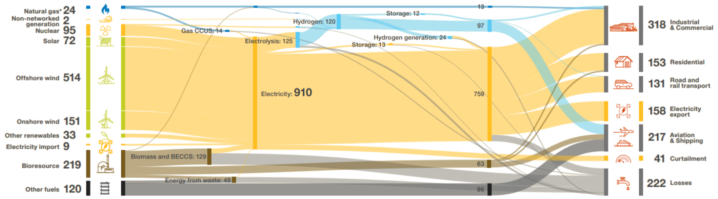
Conclusions

- Energy Storage is far more than just electrical systems





- Critical to simulate real world power storage challenges



- 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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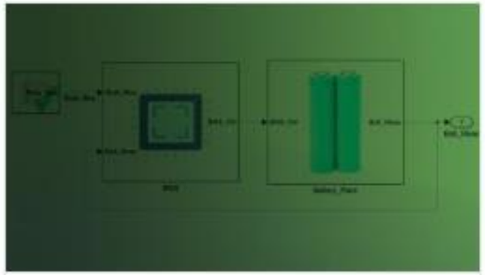
INTERMEDIATE



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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