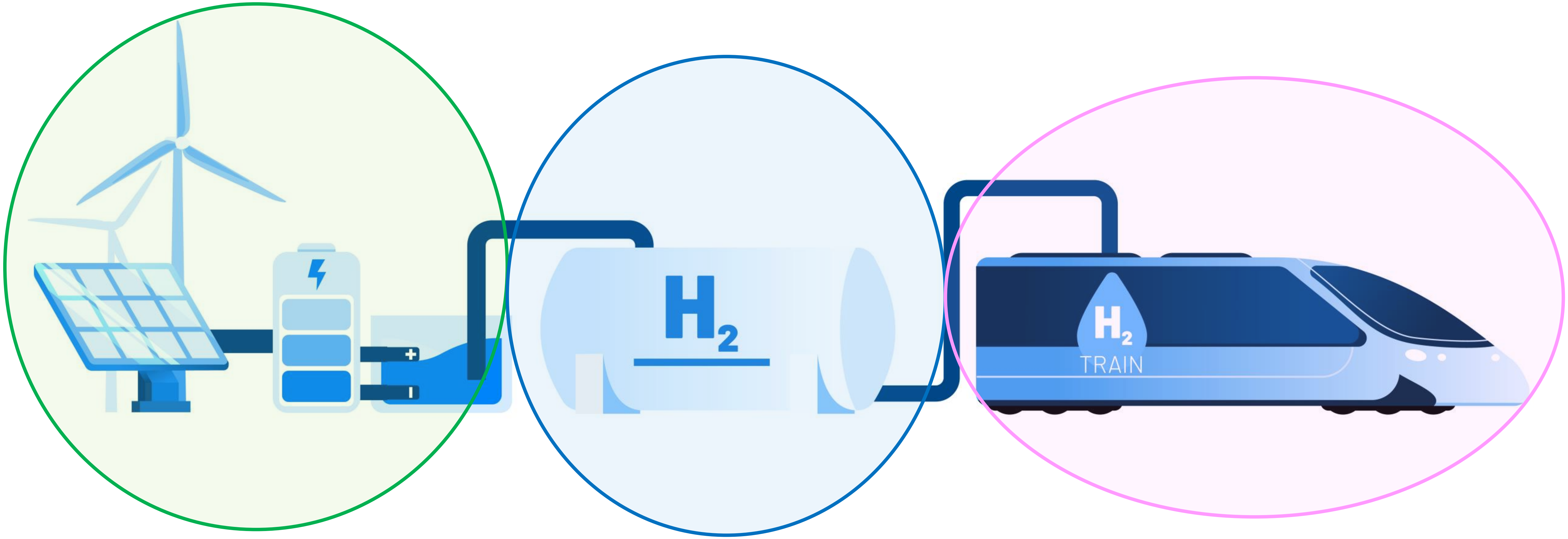
MATLAB EXPO

MATLAB/Simulink 환경에서 그린 수소 공급망에 대한 솔루션

강효석 부장/Ph.D., 매스웍스코리아

MathWorks

Enabling Green Hydrogen – Supply Chain

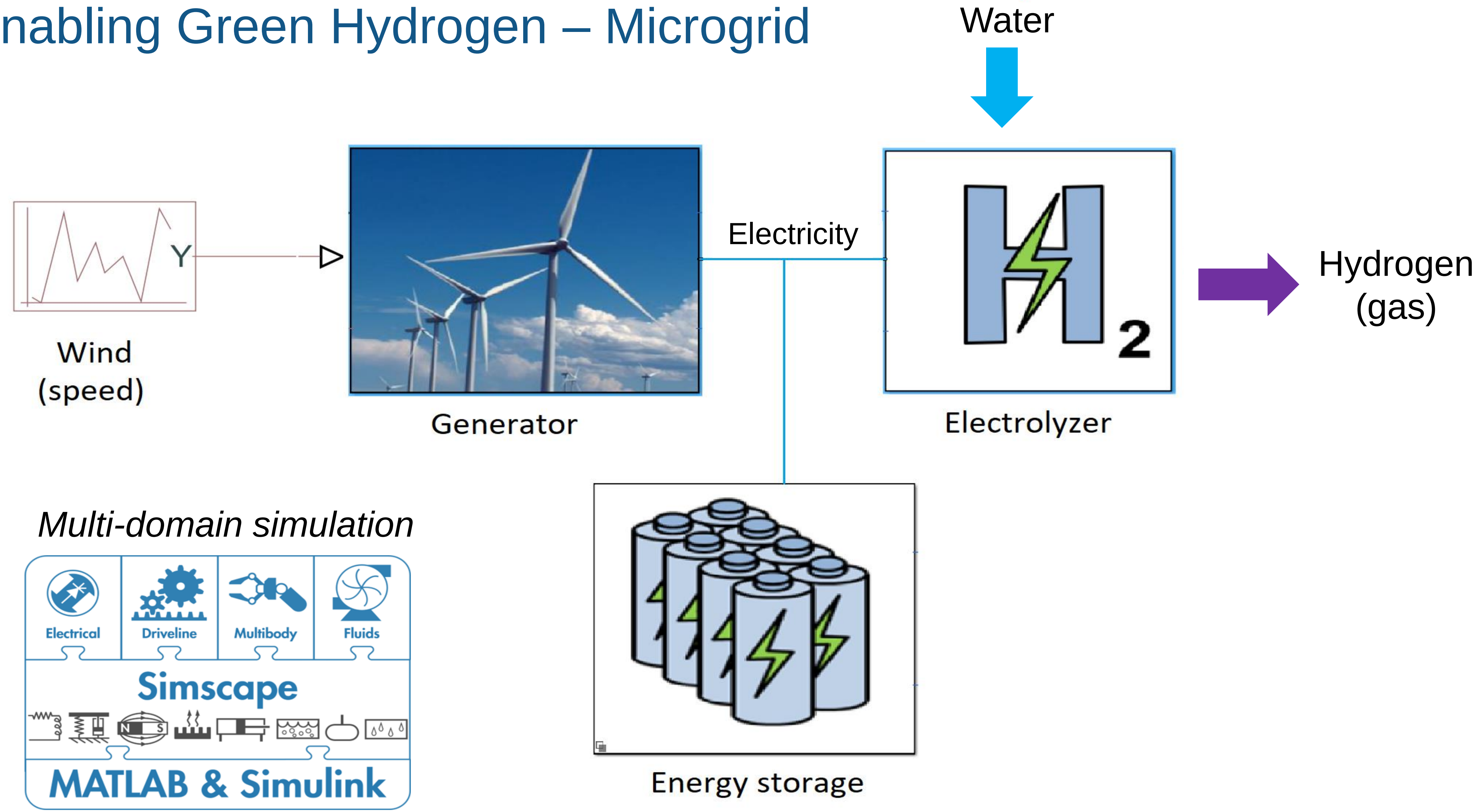


Stage1
Green Hydrogen
Production

Stage2
Hydrogen
Distribution

Stage3
Hydrogen
Consumption

Enabling Green Hydrogen – Microgrid



Enabling Green Hydrogen – Motivation

Advantages

- 100% sustainable
- storable
- versatile
- transportable

Deltas

- high energy consumption
- high cost
- safety (managing H2)

⇕

Simulation Based Engineering

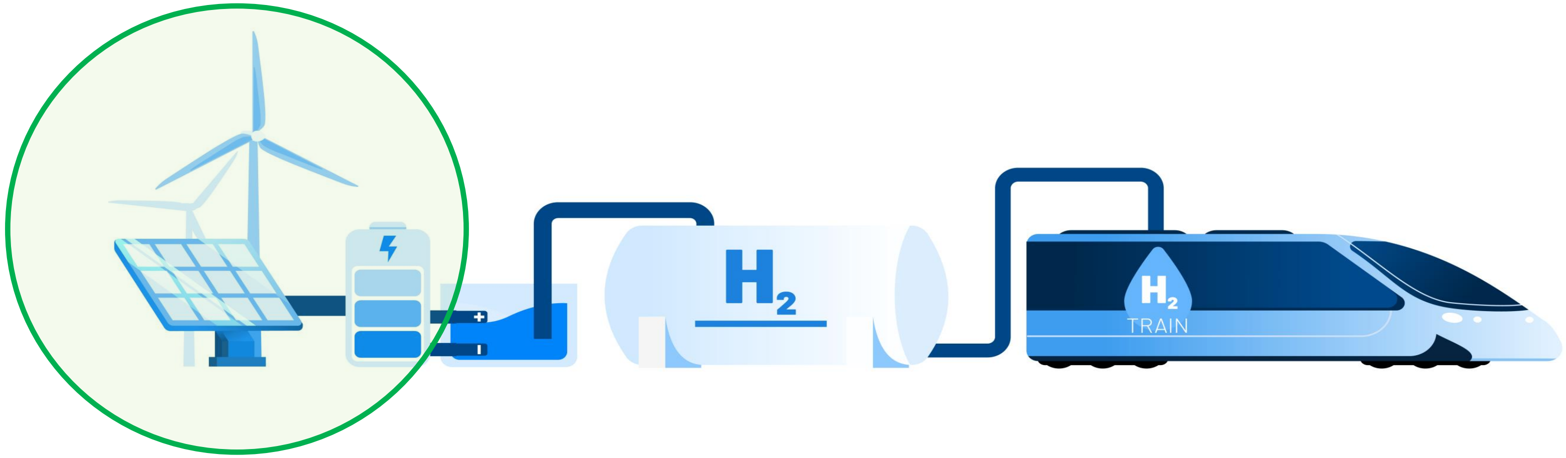
"Green hydrogen: an alternative that reduces emissions and cares for our planet"
Iberdrola > Sustainability > Green Hydrogen

Enabling Green Hydrogen – Key Takeaways

- Assert feasibility
  – Techno-economic analyses
  – Proven concept

- Secure sustainable and robust operation
  – Design Automation
  – Optimization

Stage 1. Green Hydrogen Production (from renewable energy to gas)



Enabling Green Hydrogen - Challenges

Production (Micro-grid)

Unit Level

Component design

- electrolyzer
- energy storage
- power converter unit
- generator

Asset digitalization

- anomaly detection
- lifetime estimation
- prognostics development

System Level

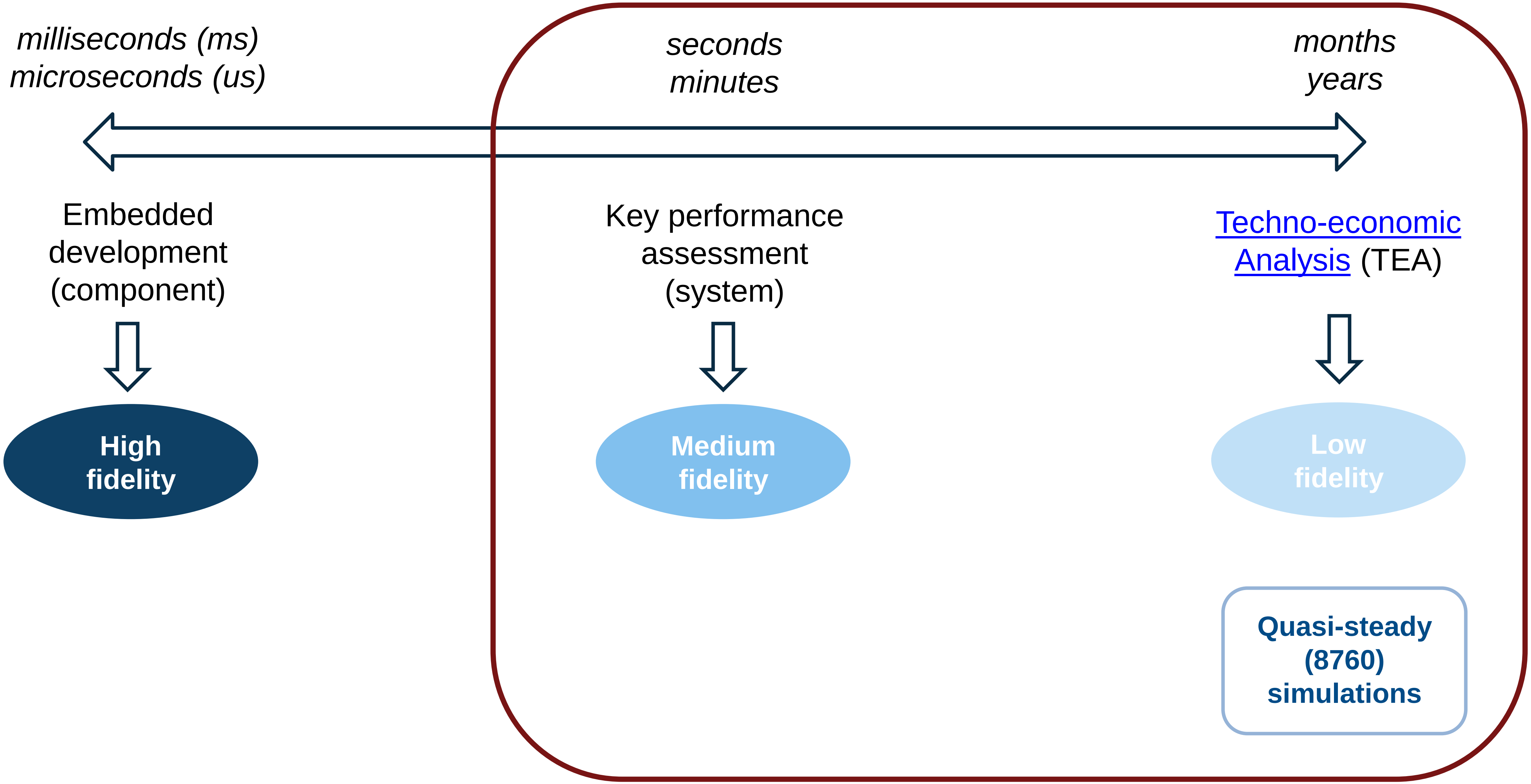
Plant design

- concept evaluation
- physical requirements
- energy balance

High-level algorithmic design

- supervisory logic
- setpoint definition

Enabling Green Hydrogen – Model Fidelity



What Is a Quasi-Steady Simulation and Why Is It Important for Techno-Economic Applications?

Low fidelity

- Techno-economic assessments are typically conducted across **long durations of time at regular time-intervals** ranging from 1 minute to 1 hour (1 hour intervals across 1 year is common – a so called **8760** simulation)
- Techno-economic assessments typically **do not care about system dynamics** but do care about **steady-state operational conditions** at each time-interval.
- **A quasi-steady simulation** assumes that, at each time-step, the dynamics of a system are fast enough that they have reached steady-state. It is primarily an **algebraic, time-based simulation**.
- **A quasi-steady simulation therefore provides a foundation for techno-economic assessments.**

Reduced Order Modeling

Low fidelity

- To incorporate a physical component and its functional control response into a quasi-steady simulation, we need to **remove the dynamics** associated with moving from one operating point to another.
- One way of doing this with an electrical component, is to create a **Thevenin Equivalent model**, with Look-Up Tables (LUTs) that define source voltage and source impedance for a given power level.
- We can also consider the response of a **power converter by creating a LUT that maps duty-cycle to voltage level**.

Enabling Green Hydrogen – TEA (Solar Microgrid)

Low fidelity

Performance assessment

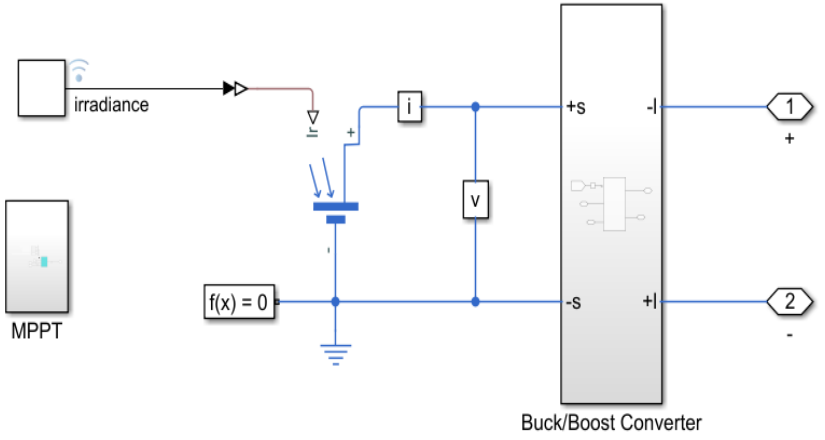
Techno-economic analyses

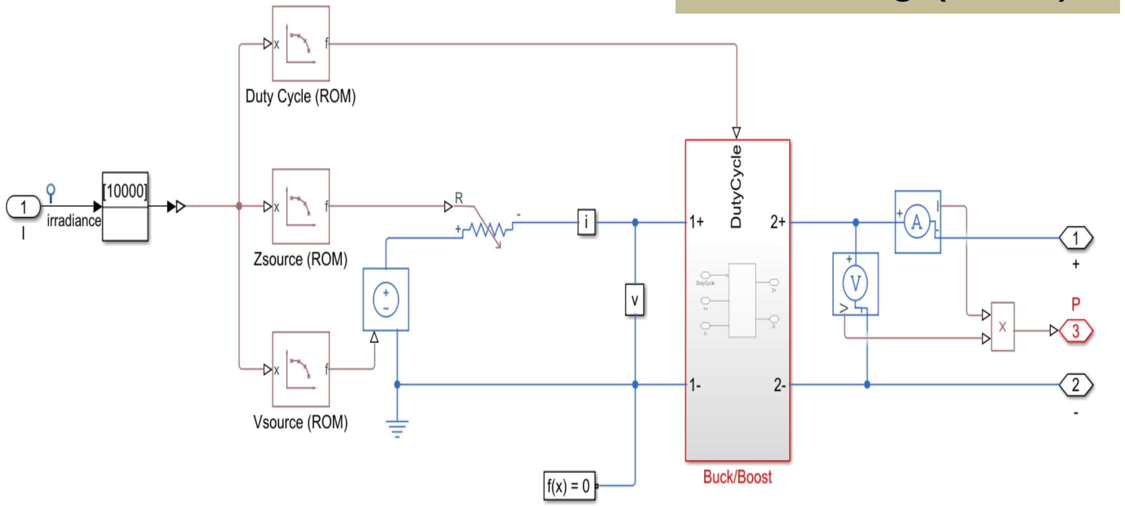
Medium fidelity

Low fidelity

Solar cell & MPPT algorithm

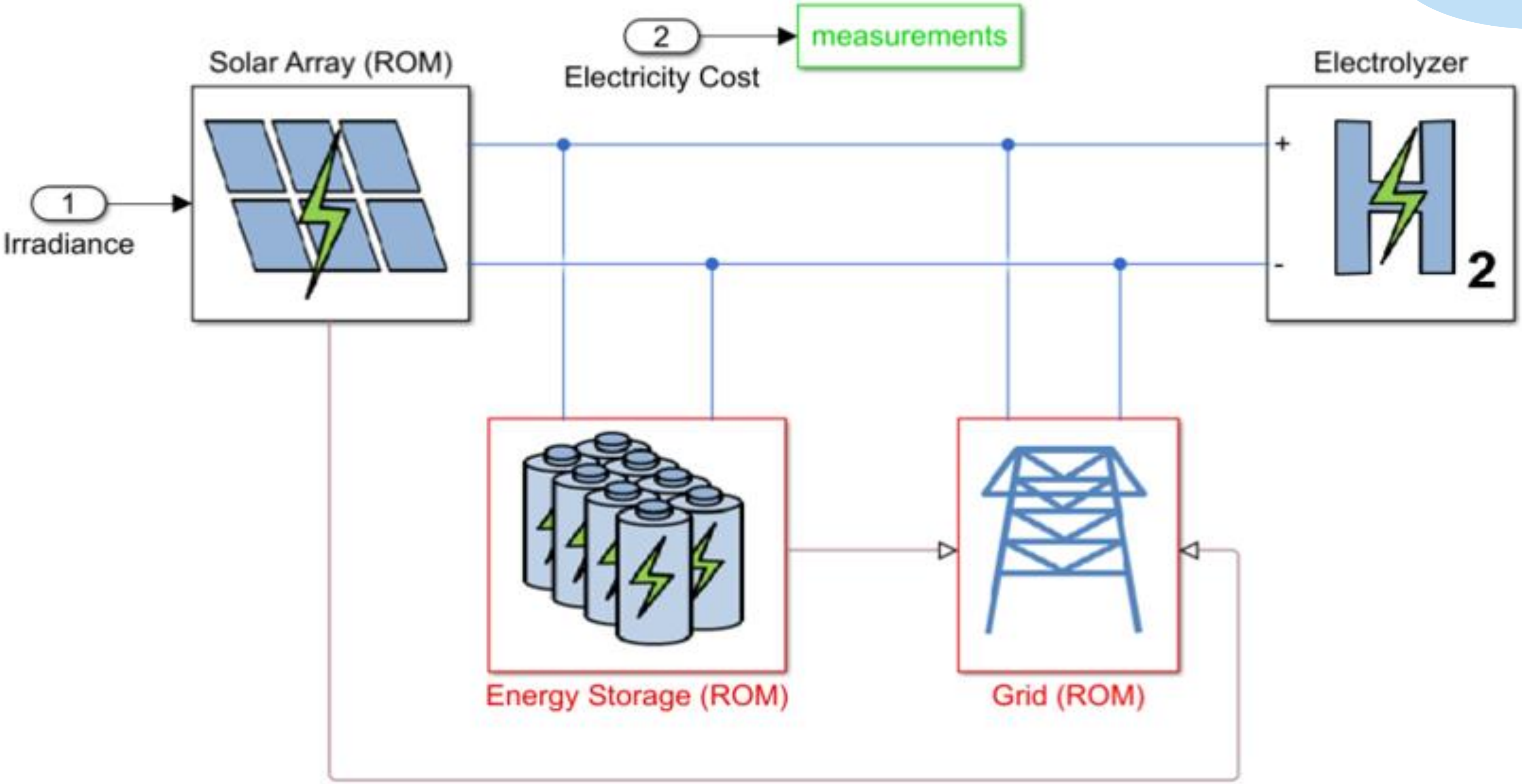
Reduced Order Modeling (ROM)





Green Hydrogen Production – TEA (Solar Microgrid)

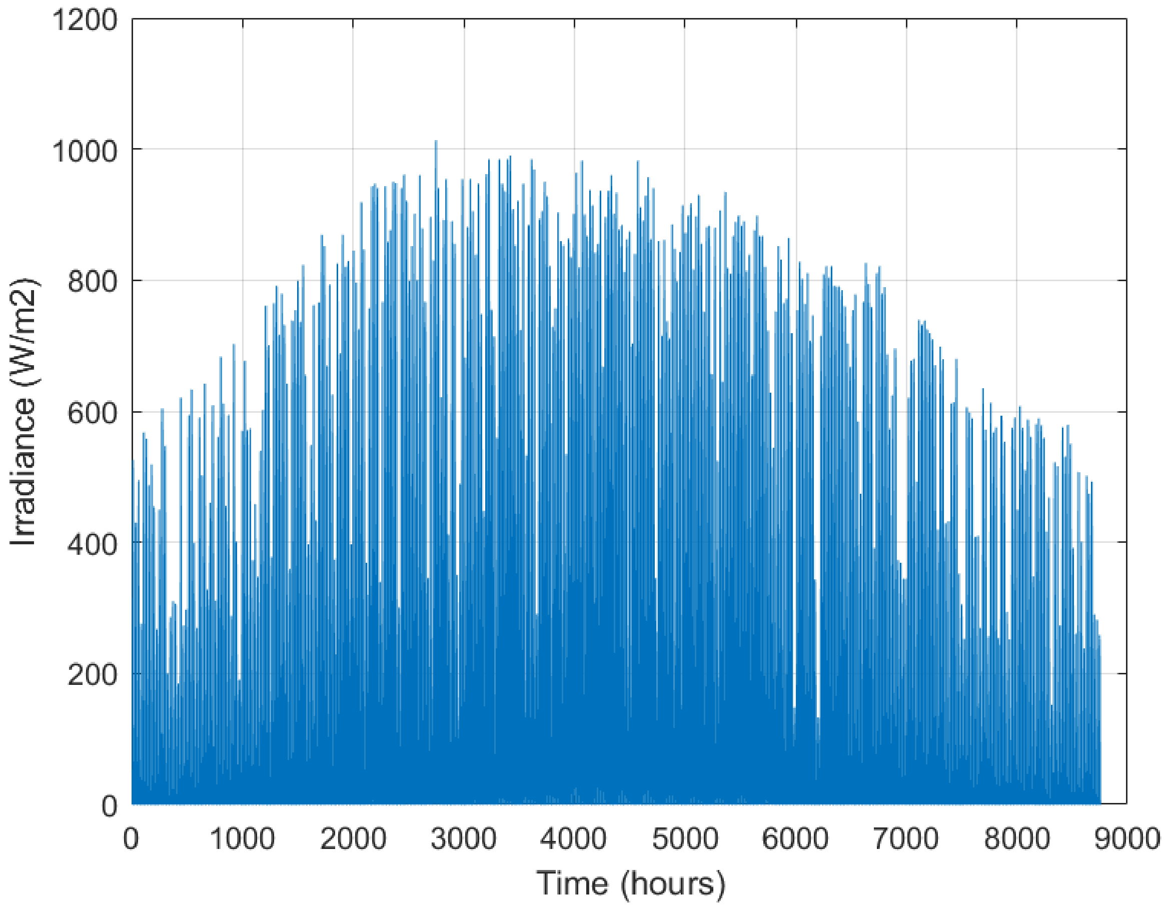
Low fidelity



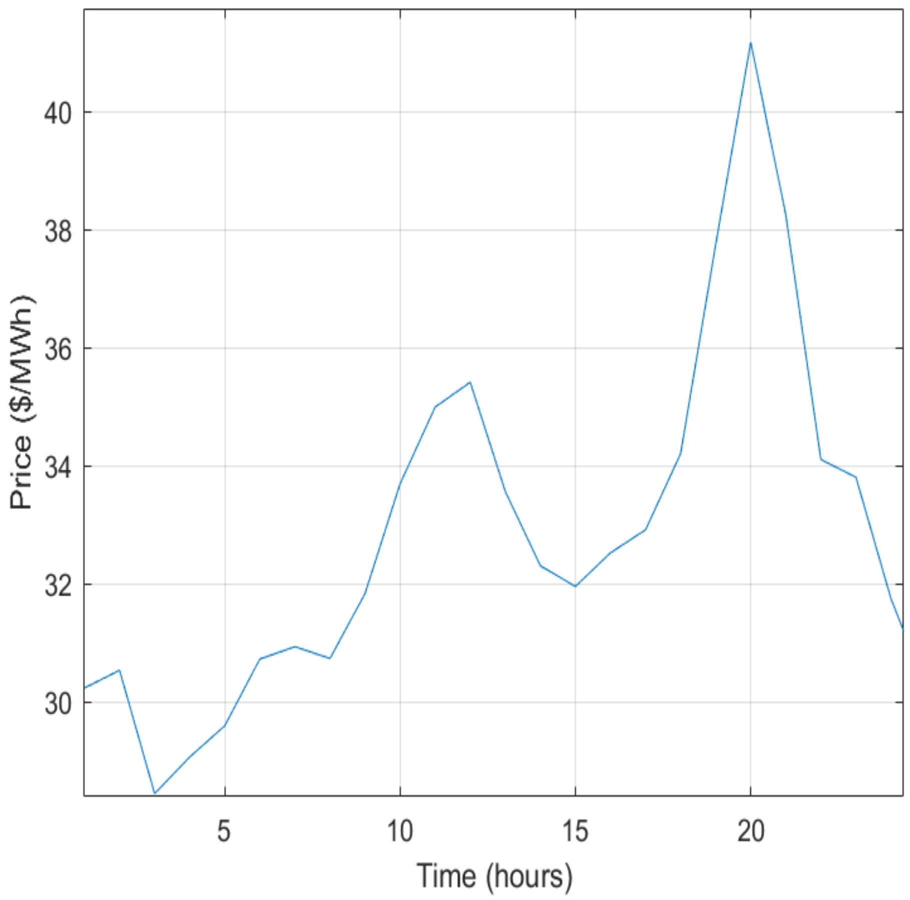
Enabling Green Hydrogen – TEA (Data Re-use)

Low fidelity

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



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



Enabling Green Hydrogen – TEA (Outcome)

Low fidelity

H_2 production: Highest grid cost & Lowest solar resource

```
Elapsed time is 510.209014 seconds.
--------------------------------------

Lowest grid cost is USD 6761.6456 at Phoenix Sky Harbor Intl AP
Highest solar resource is 497.1227MWh at Daggett Barstow-Daggett AP

Highest grid cost is USD 13217.5585 at Quillayute State Airport
lowest solar resource is 291.2997MWh at Quillayute State Airport

--------------------------------------
```

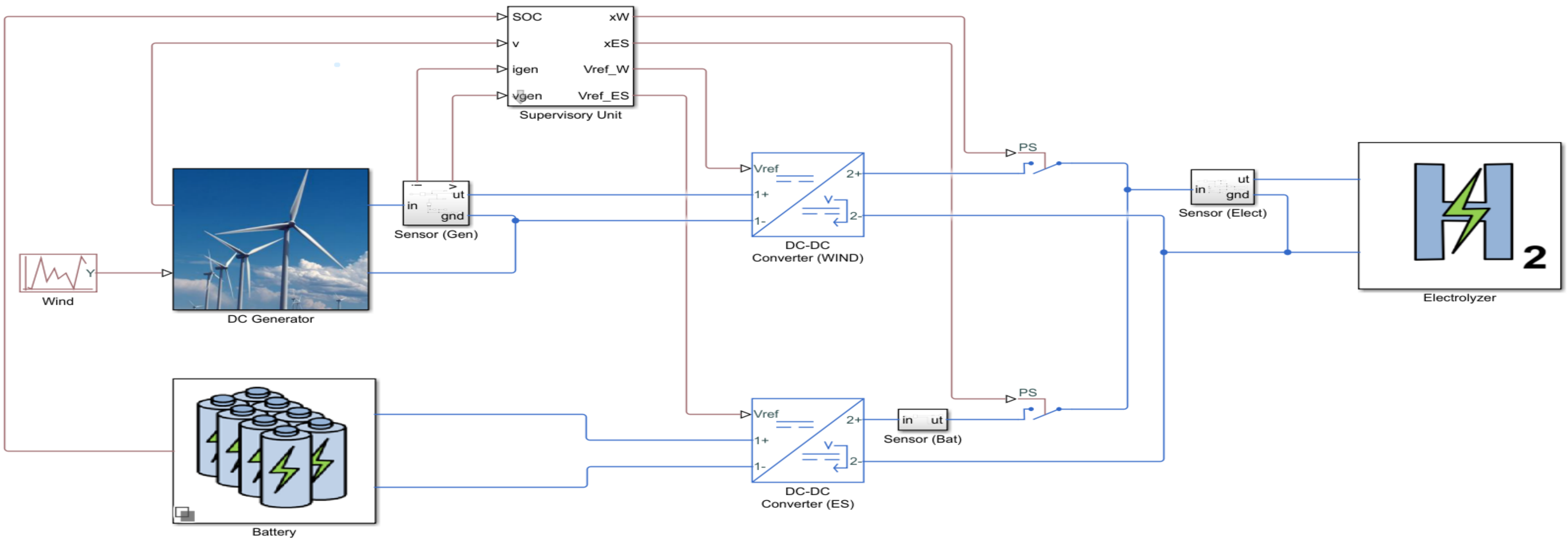
242 years in 500 seconds
i.e.
1 year every 2 seconds

Reduced Order Models + **Parallel Computing** = **Agile Insights (decision-making)**

Enabling Green Hydrogen – System Performance

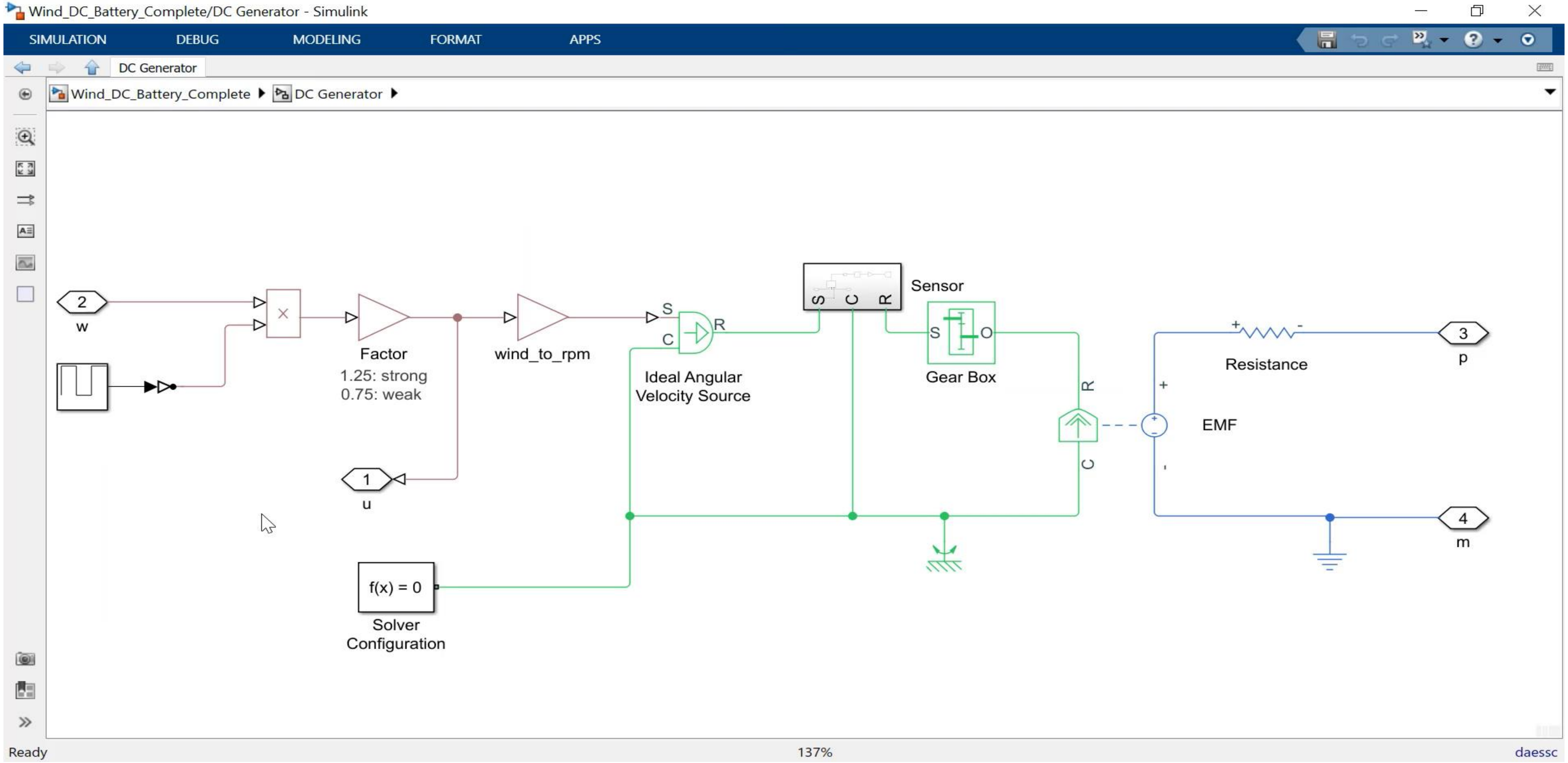
Medium fidelity

- expected H_2 production & water consumption
- suitable control strategy (conditions, use of physical assets)
- energy storage (dimensioning, expected duty regime)
- planning of operations (collect – replace - maintain)



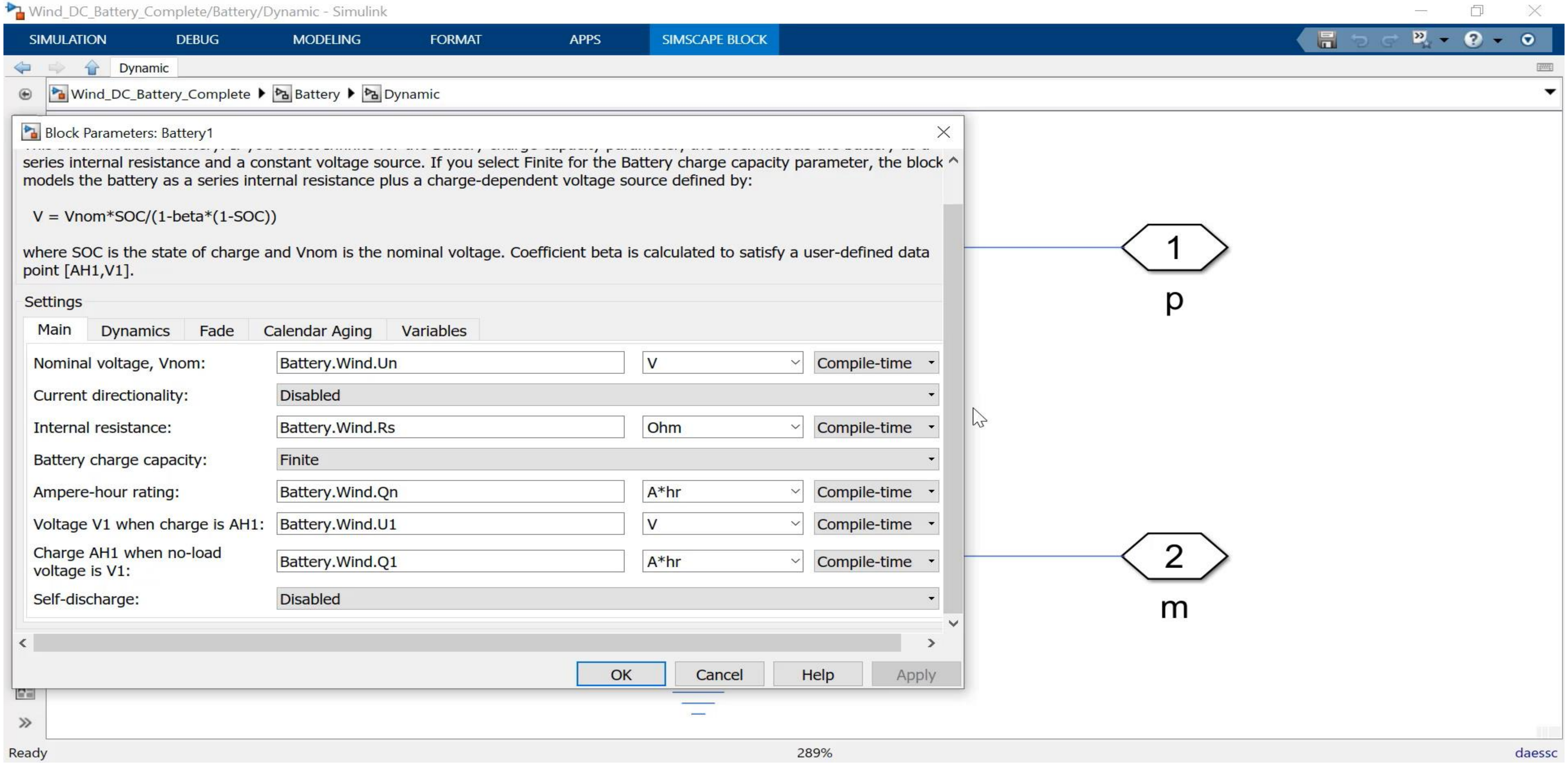
Enabling Green Hydrogen – System Performance

Medium fidelity



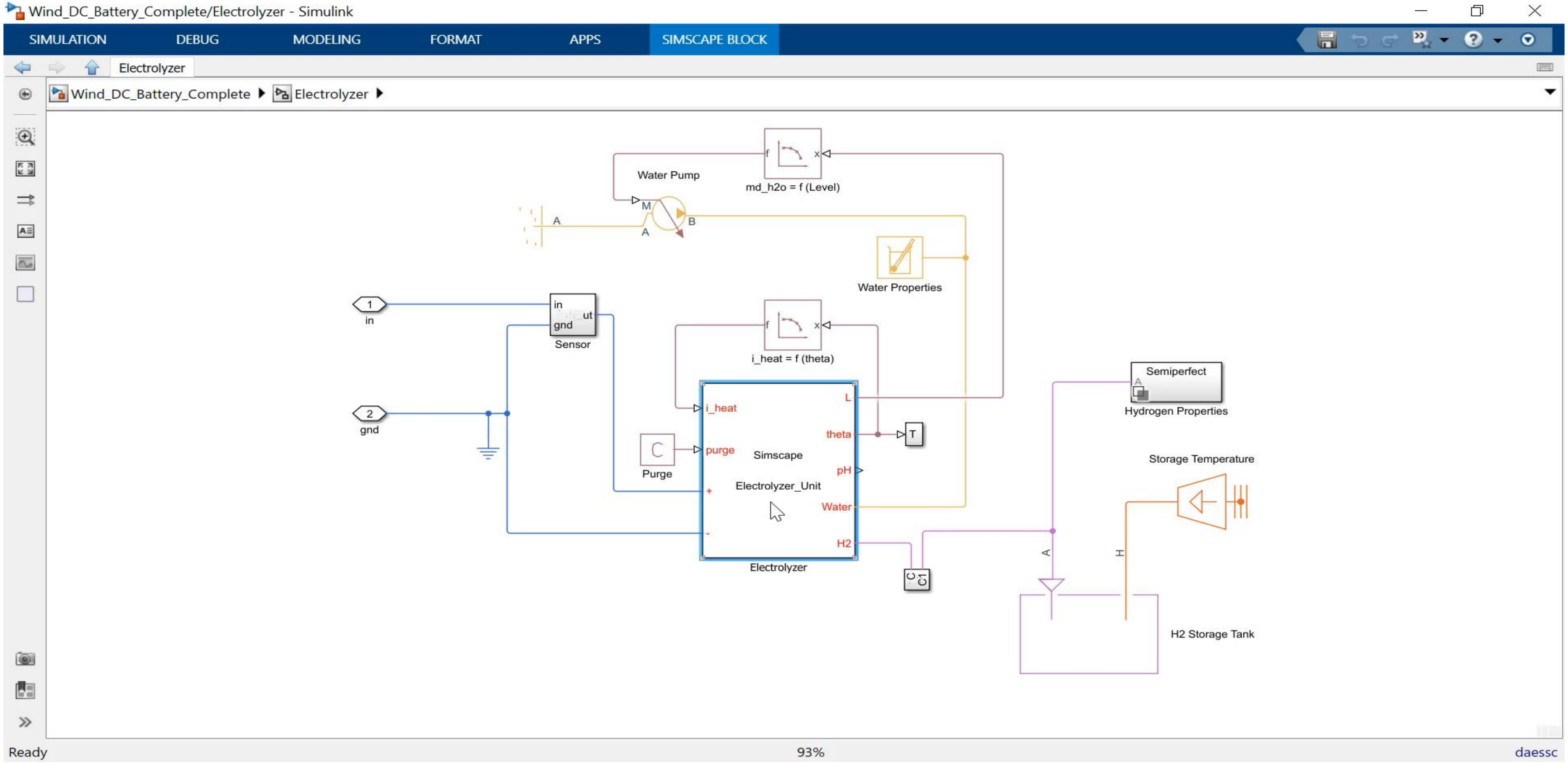
Enabling Green Hydrogen – System Performance

Medium fidelity



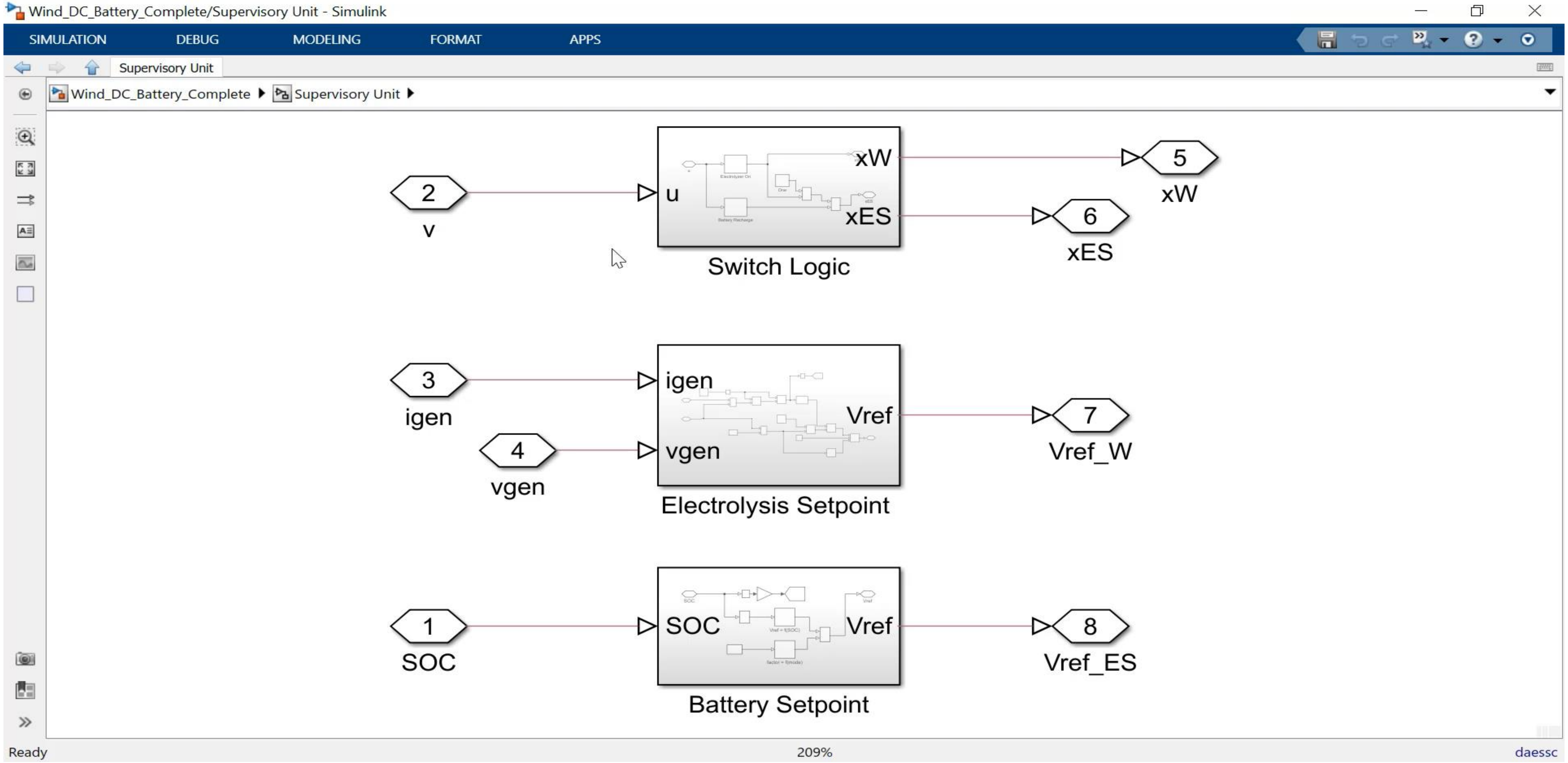
Enabling Green Hydrogen – System Performance

Medium fidelity



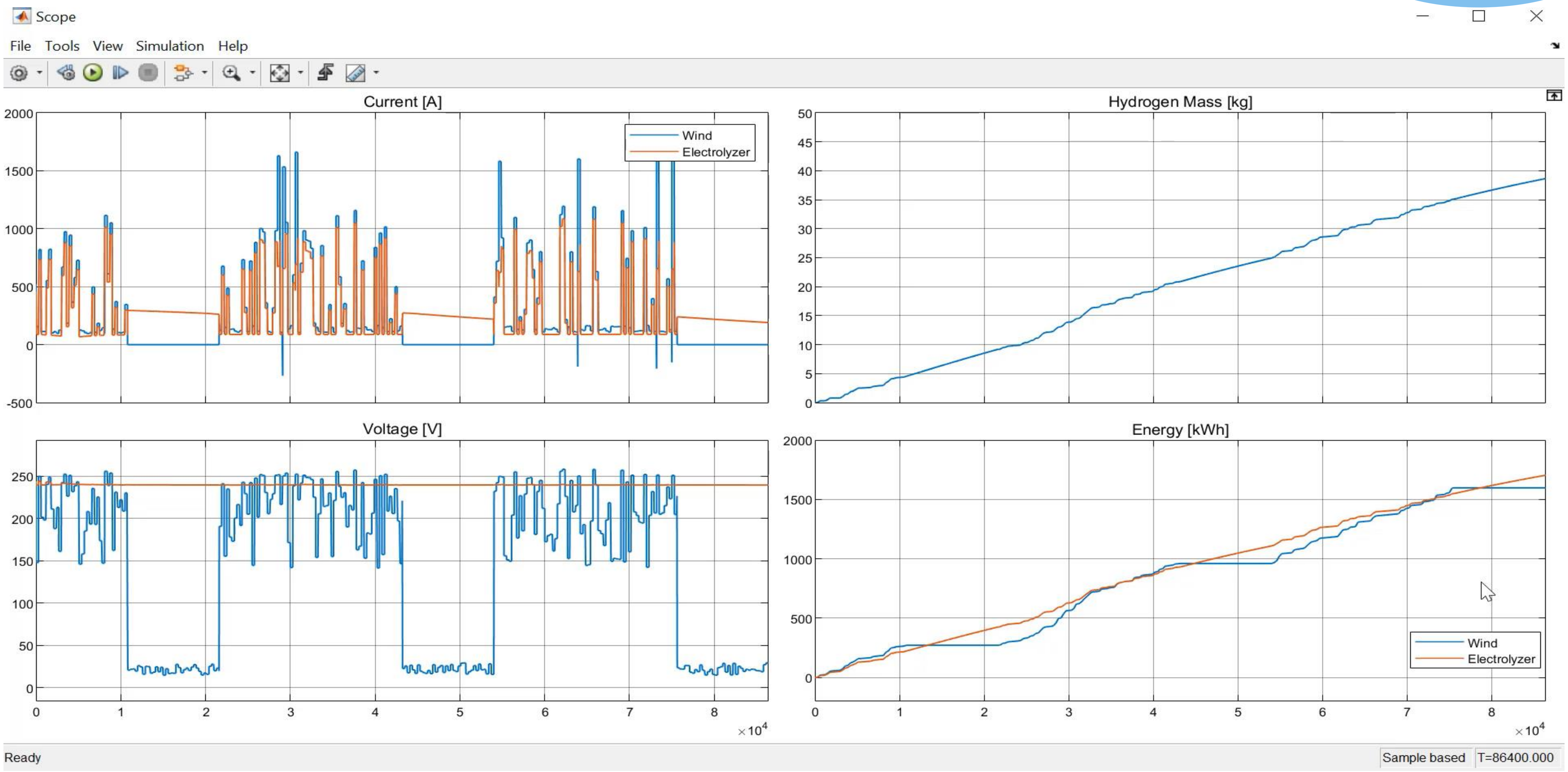
Enabling Green Hydrogen – System Performance

Medium fidelity



Enabling Green Hydrogen – System Performance

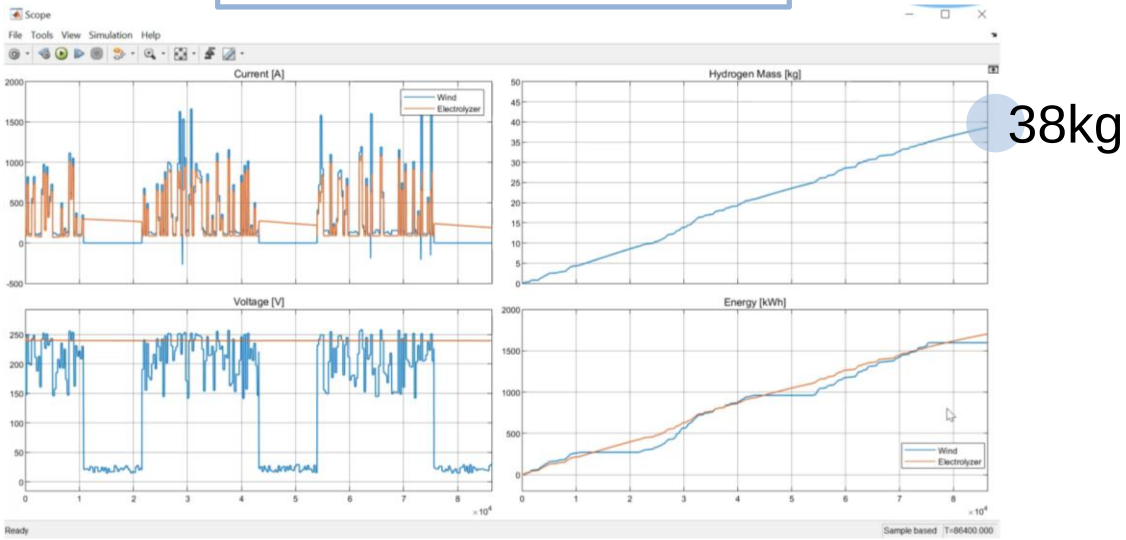
Medium fidelity

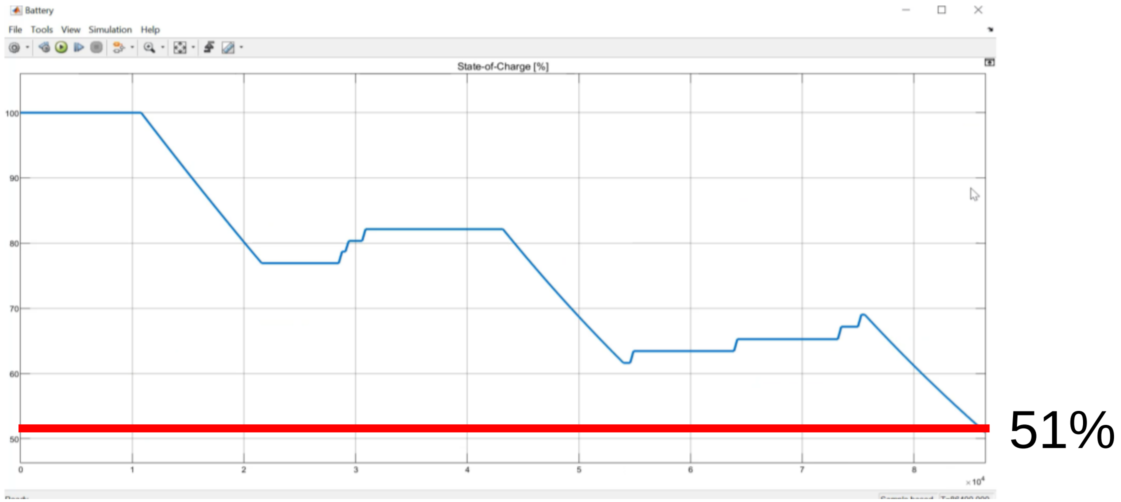


Enabling Green Hydrogen – System Performance

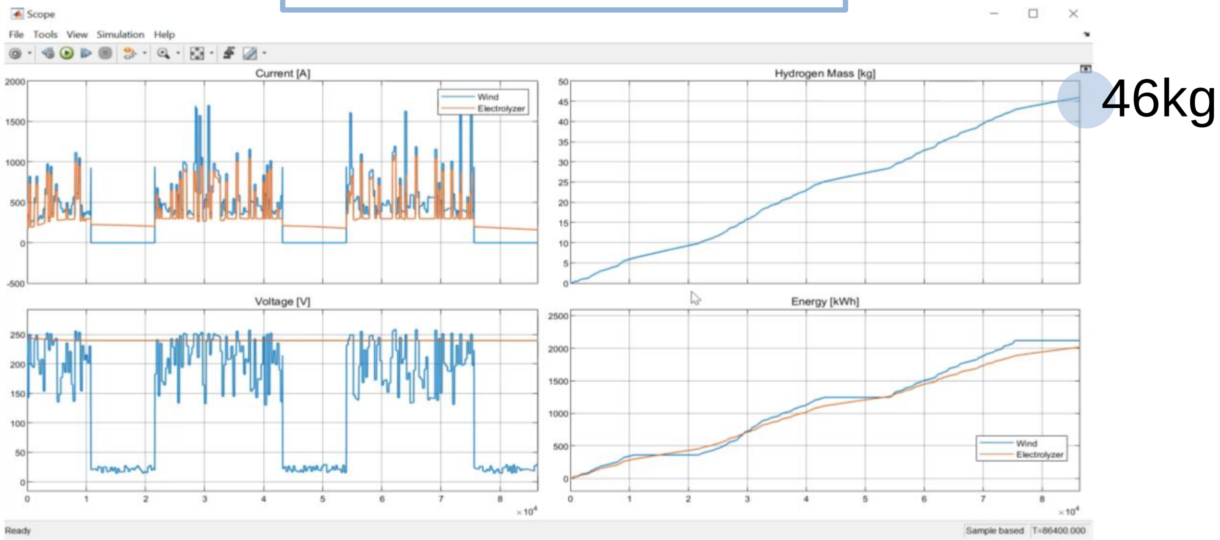
Medium fidelity

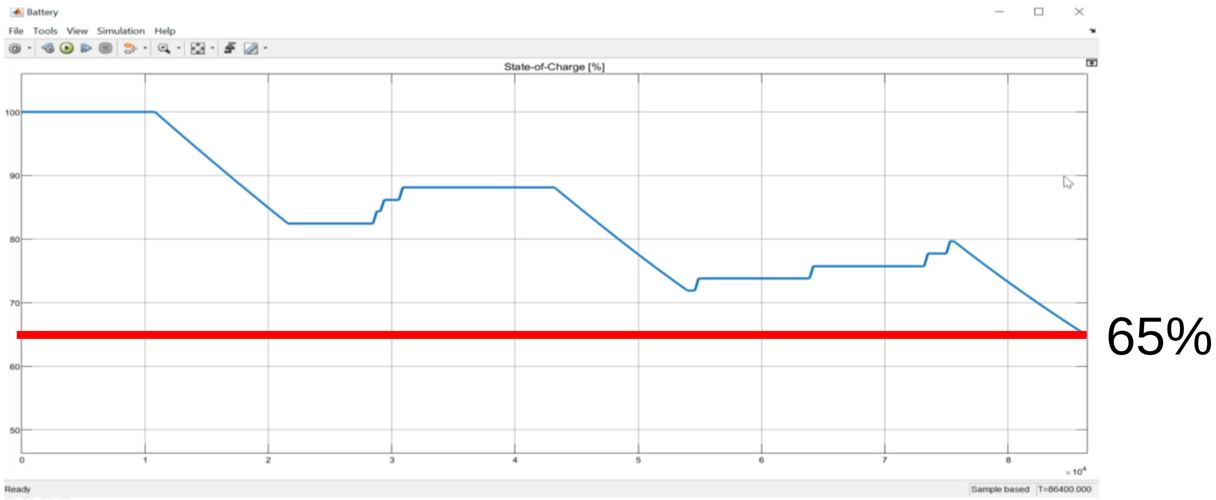
Voltage-based Control





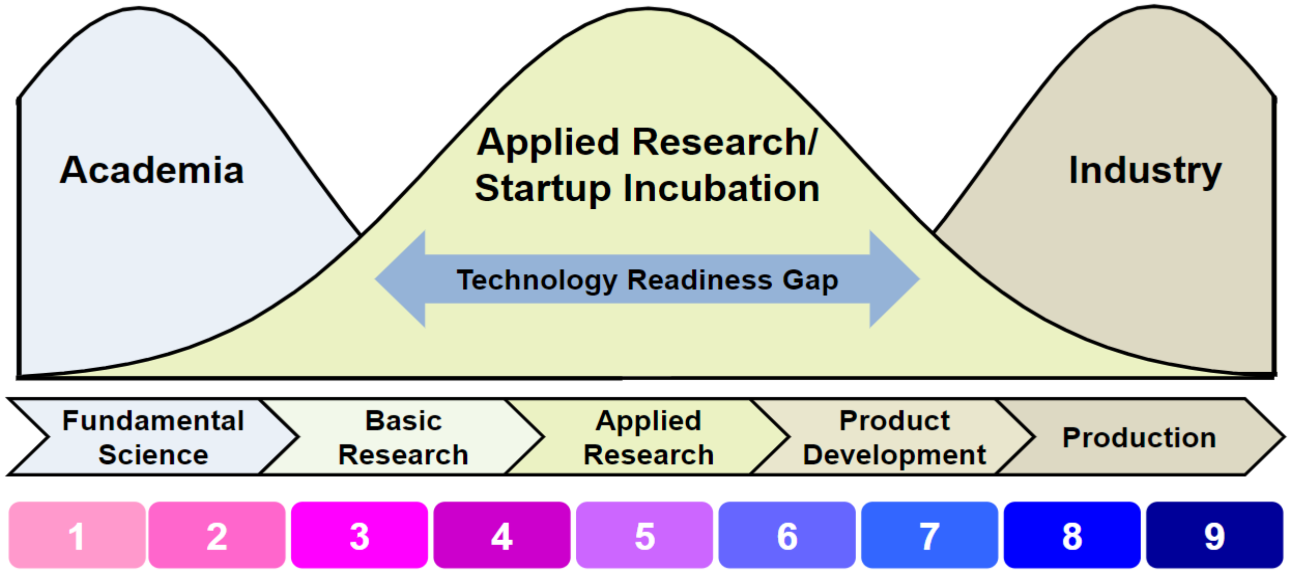
Energy-based Control

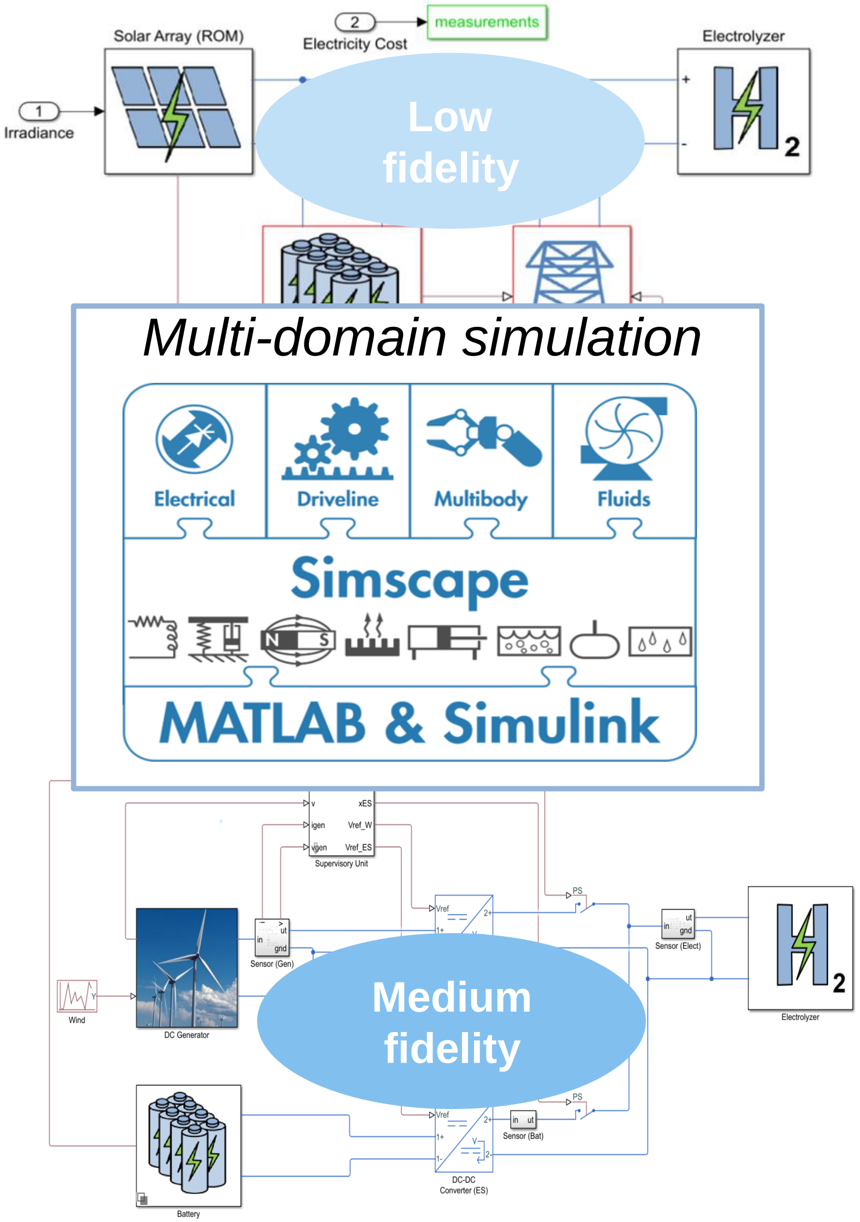




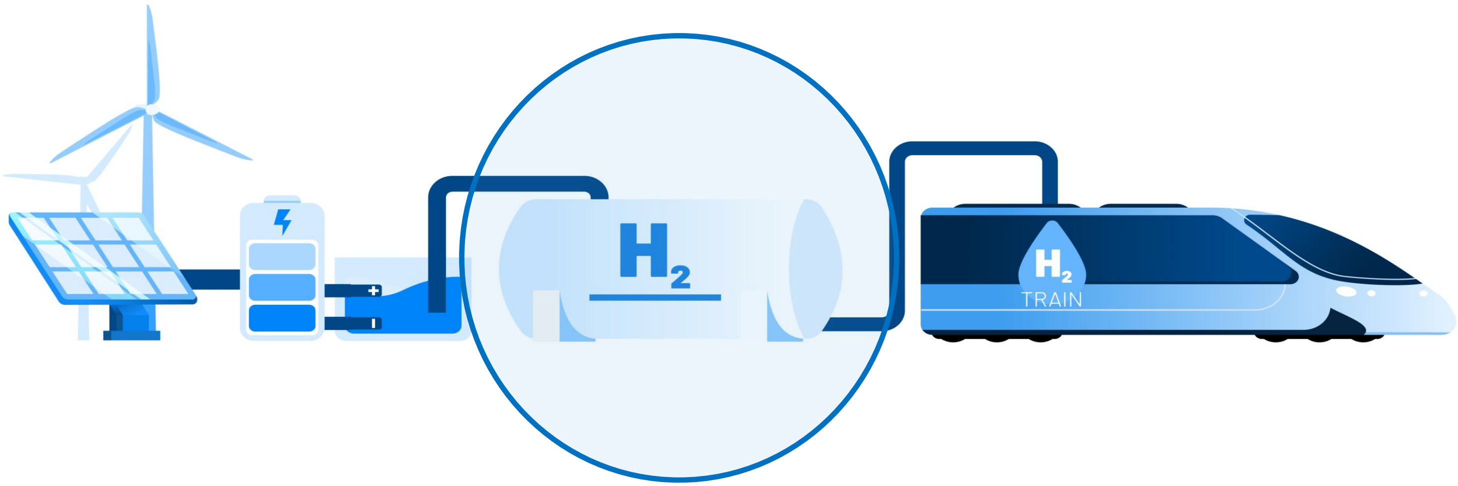
Recap of Green Hydrogen Production

- Assert feasibility
  - Techno-economic analyses
  - Proven concept





Stage 2. Hydrogen Distribution (from tank to consumers)



Enabling Green Hydrogen – Challenges H2 Handling and Usage

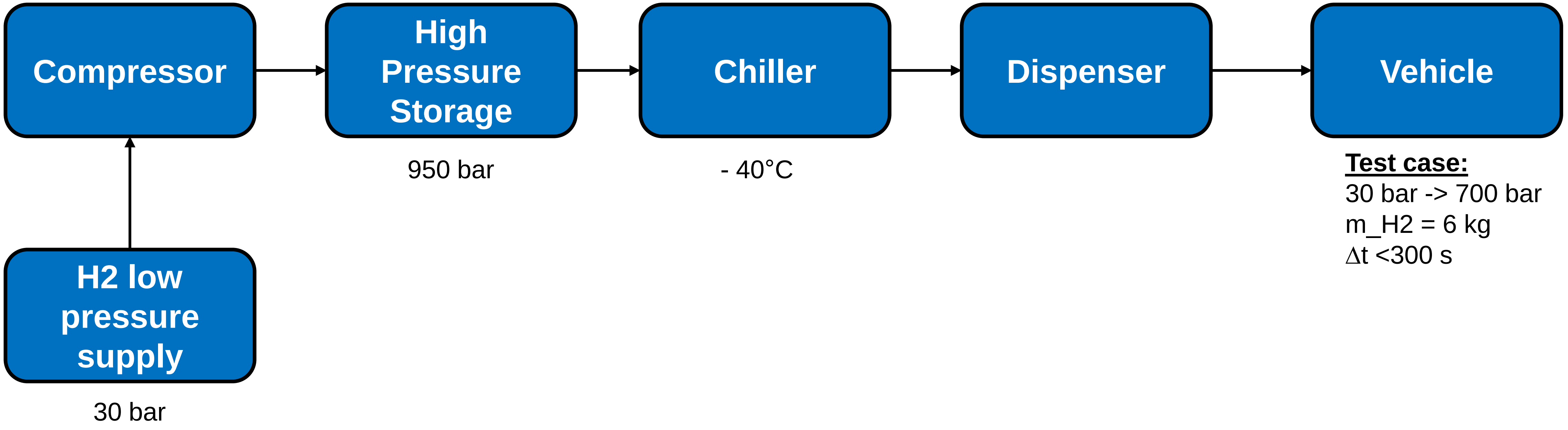
(Stage 2)

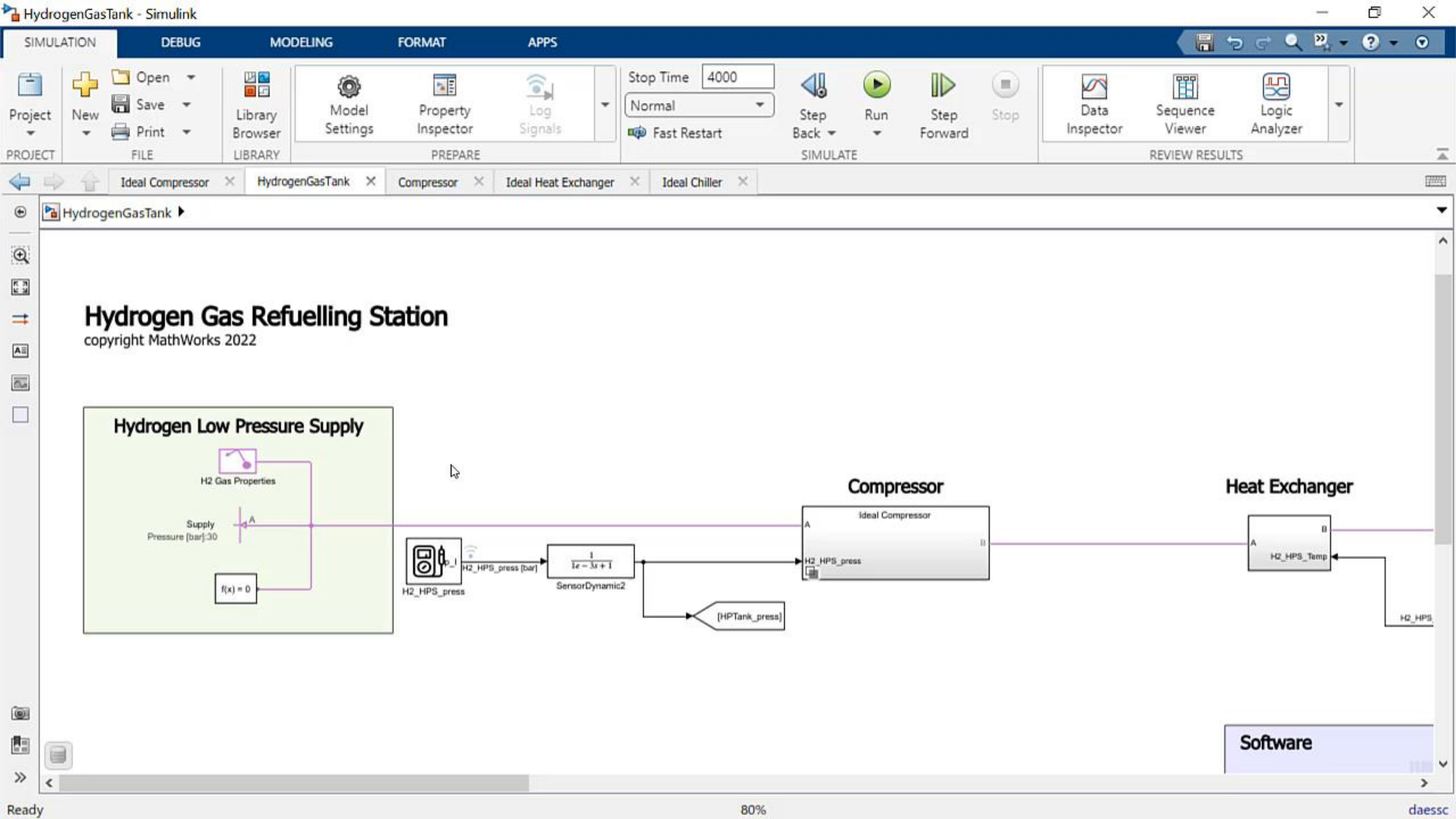
Transfer
(tank-to-cell)

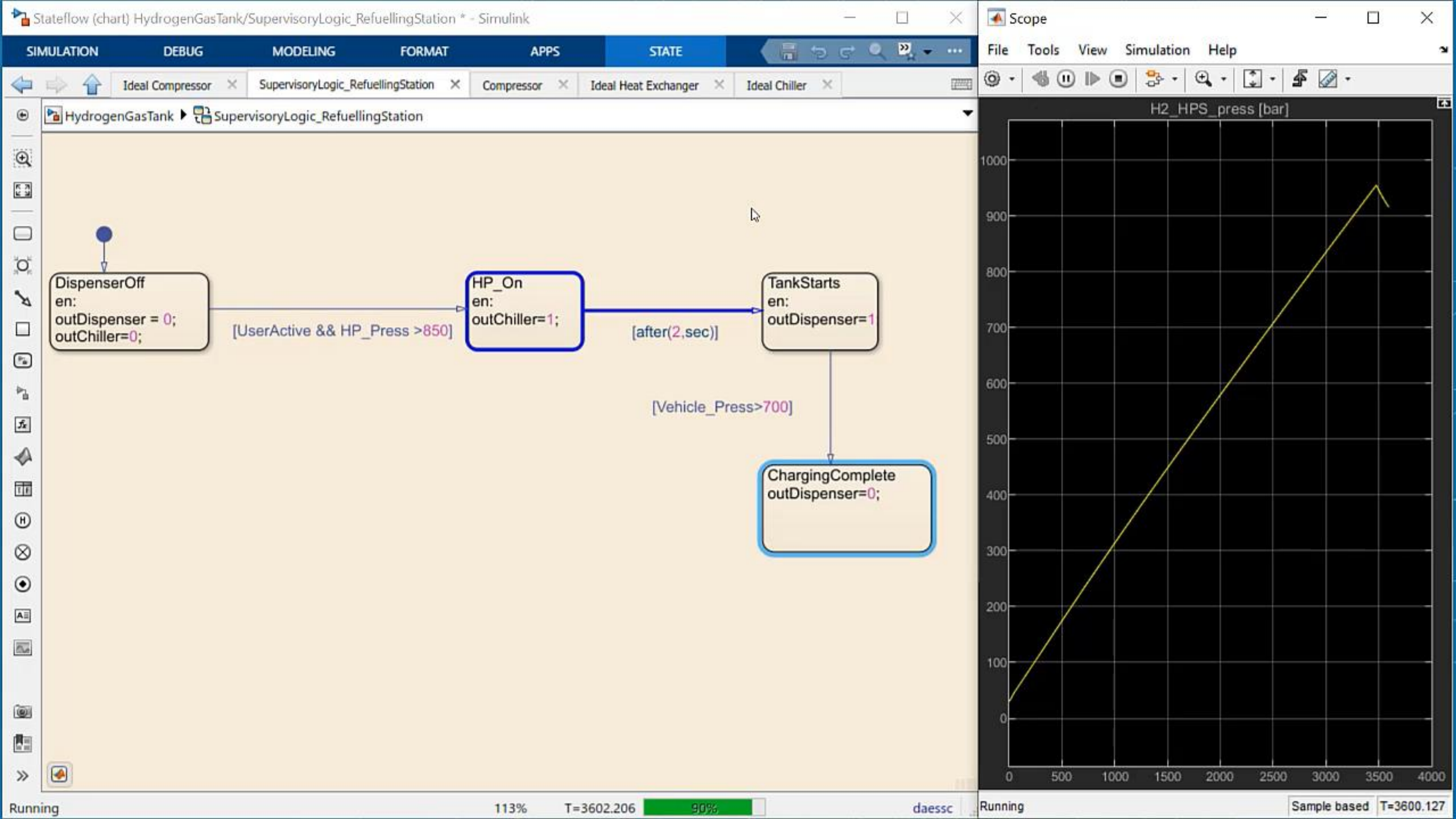
- Optimal components sizing (cooling, storage, compressors)
- Reliable 24/7 software operation
- Meet critical safety requirements

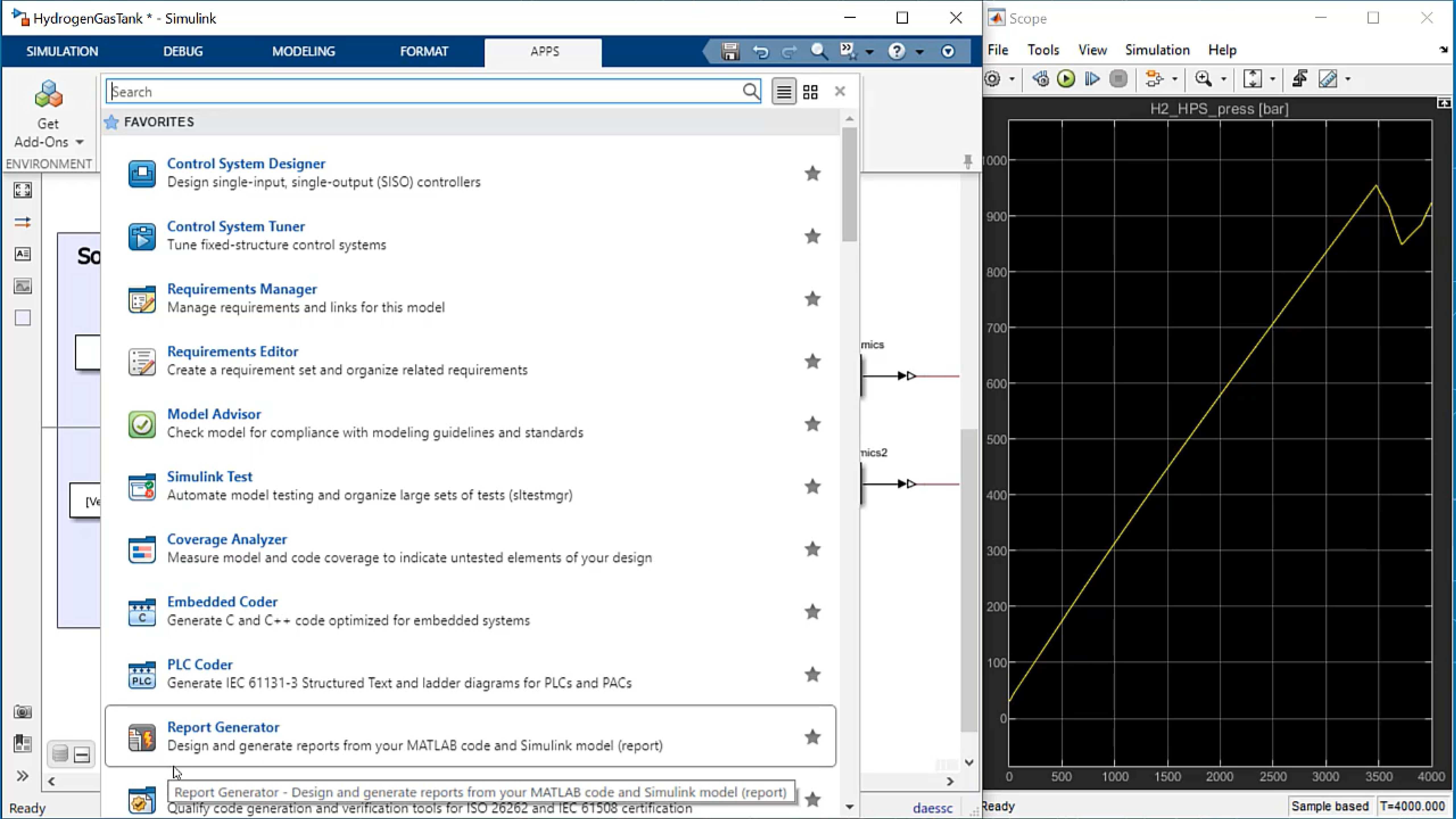
Modeling Gas Systems with Simscape

- Case study: Hydrogen Refueling Station



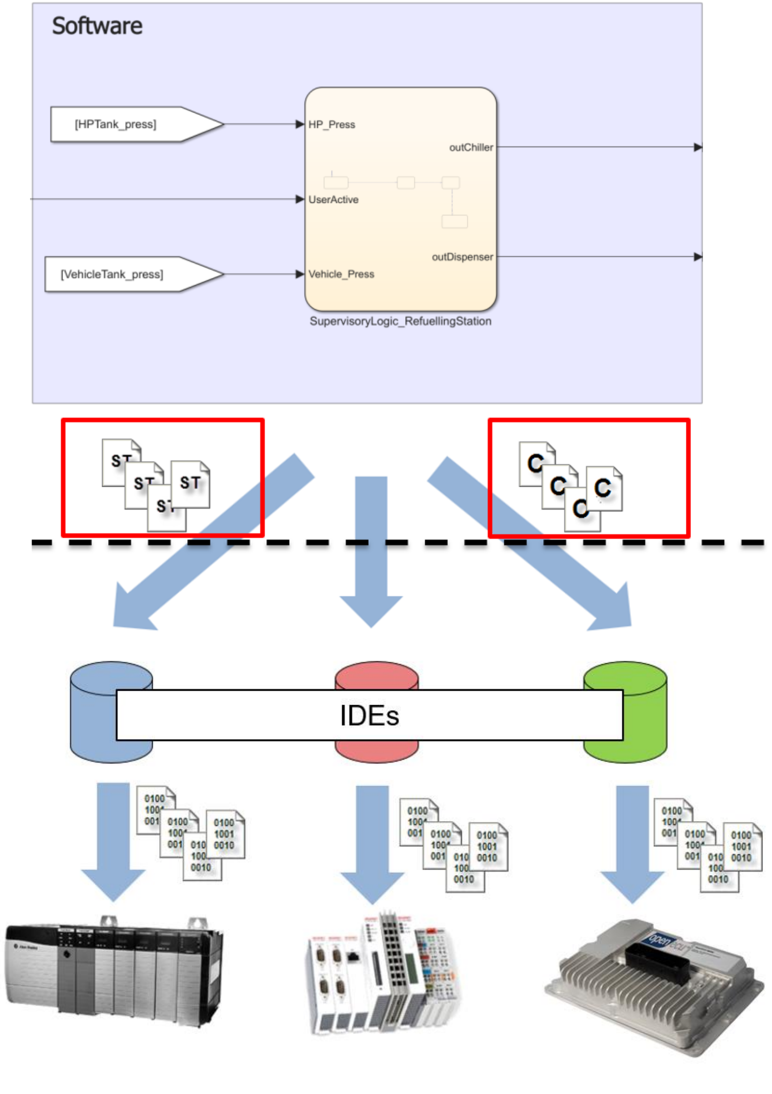

HydrogenGasTank - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
APPS
Project
New
Open
Save
Print
Library Browser
Model Settings
Property Inspector
Log Signals
Stop Time
4000
Normal
Fast Restart
Step Back
Run
Step Forward
Stop
Data Inspector
Sequence Viewer
Logic Analyzer
PROJECT
FILE
LIBRARY
PREPARE
SIMULATE
REVIEW RESULTS
Ideal Compressor
HydrogenGasTank
Compressor
Ideal Heat Exchanger
Ideal Chiller
HydrogenGasTank
Hydrogen Gas Refuelling Station
copyright MathWorks 2022
Hydrogen Low Pressure Supply
H2 Gas Properties
Supply
Pressure [bar]:30
f(x) = 0
H2_HPS_press
H2_HPS_press [bar]
SensorDynamic2
[HPTank_press]
Compressor
Ideal Compressor
H2_HPS_press
Heat Exchanger
H2_HPS_Temp
Software
Ready
80%
daessc


Stateflow (chart) HydrogenGasTank/SupervisoryLogic_RefuellingStation * - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
APPS
STATE
Ideal Compressor
SupervisoryLogic_RefuellingStation
Compressor
Ideal Heat Exchanger
Ideal Chiller
HydrogenGasTank
SupervisoryLogic_RefuellingStation
DispenserOff
en:
outDispenser = 0;
outChiller=0;
[UserActive && HP_Press >850]
HP_On
en:
outChiller=1;
[after(2,sec)]
TankStarts
en:
outDispenser=1
[Vehicle_Press>700]
ChargingComplete
outDispenser=0;
Running
113%
T=3602.206
90%
daessc
Scope
File
Tools
View
Simulation
Help
H2_HPS_press [bar]
1000
900
800
700
600
500
400
300
200
100
0
0
500
1000
1500
2000
2500
3000
3500
4000
Running
Sample based
T=3600.127


HydrogenGasTank * - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
APPS
Get Add-Ons
ENVIRONMENT
Search
FAVORITES
Control System Designer
Design single-input, single-output (SISO) controllers
Control System Tuner
Tune fixed-structure control systems
Requirements Manager
Manage requirements and links for this model
Requirements Editor
Create a requirement set and organize related requirements
Model Advisor
Check model for compliance with modeling guidelines and standards
Simulink Test
Automate model testing and organize large sets of tests (sltestmgr)
Coverage Analyzer
Measure model and code coverage to indicate untested elements of your design
Embedded Coder
Generate C and C++ code optimized for embedded systems
PLC Coder
Generate IEC 61131-3 Structured Text and ladder diagrams for PLCs and PACs
Report Generator
Design and generate reports from your MATLAB code and Simulink model (report)
Report Generator - Design and generate reports from your MATLAB code and Simulink model (report)
Qualify code generation and verification tools for ISO 26262 and IEC 61508 certification
Ready
daessc
Scope
File
Tools
View
Simulation
Help
H2_HPS_press [bar]
1000
900
800
700
600
500
400
300
200
100
0
0
500
1000
1500
2000
2500
3000
3500
4000
Ready
Sample based
T=4000.000

Algorithm Model and Deployment on Real-time Controller

- Automatic code generation from models
- Reduced coding time & errors
- Hardware independent source code
- Know-how captured in single source (model)



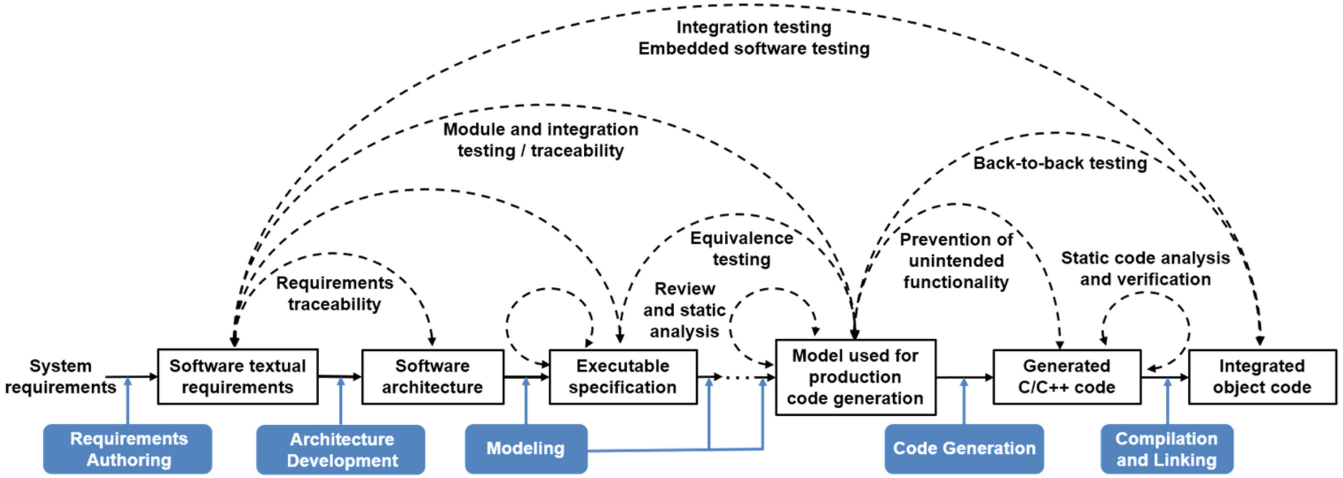
PLCs, ECU, custom hardware

All relevant PLCs supported

Vendor	IDE	IEC 61131-3	C/C++	Connections Partner
3S - Smart Software Solutions	CODESYS	✓		✓
B&R Industrial Automation	Automation Studio	✓	✓	✓
Bachmann Electronic	SolutionCenter	✓	✓	✓
Beckhoff Automation	TwinCAT	✓	✓	✓
Bosch Rexroth	IndraWorks	✓	✓	✓
Mitsubishi Electric	CW Workbench		✓	✓
Omron	Sysmac Studio	✓		✓
Phoenix Contact	PC WORX	✓	✓	✓
Rockwell Automation	RSLogix / Studio 5000	✓		✓
Siemens	TIA Portal / STEP 7	✓	✓	✓

Scalable to Certification Workflows Ensuring Highest Quality & Safety

- IEC 61508 - Safety-related systems
- ISO 26262 - Automotive / Motorcycle
- ISO 25119 - Agriculture and Forestry
- EN 50128 - Rail
- IEC 62304 - Medical
- IEC 61511 - Process Control
- DO-178 & DO-254



[MATLAB and Simulink](#)
[For Verification, Validation and Test](#)

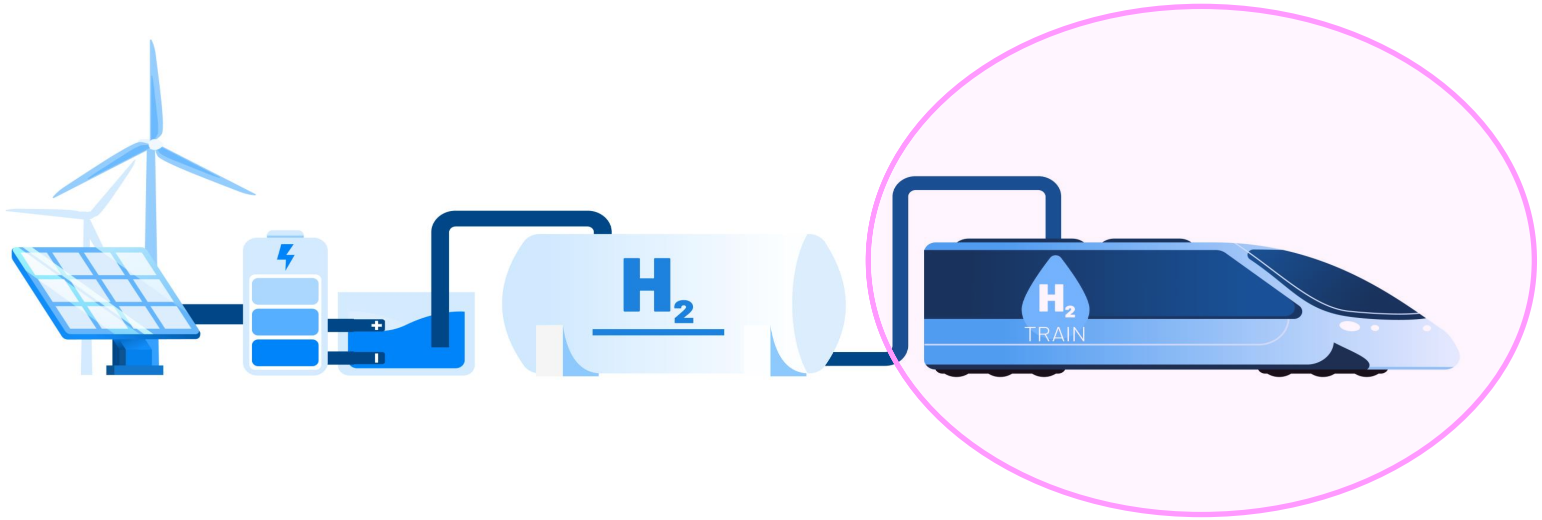
Enabling Green Hydrogen – Challenges H2 Handling and Usage

(Stage 2)

Transfer
(tank-to-cell)

- Optimal components sizing
  (cooling, storage, compressors)
  - Leverage multi-domain simulation platform
- Reliable 24/7 software operation
  - Develop supervisory logic
    with state-of-the-art V&V capabilities
- Meet critical safety requirements
  - Model-Based Design streamline certification of your embedded systems

Stage 3. Hydrogen Consumption (e-mobility, electrification)



Enabling Green Hydrogen – Challenges H2 Handling and Usage

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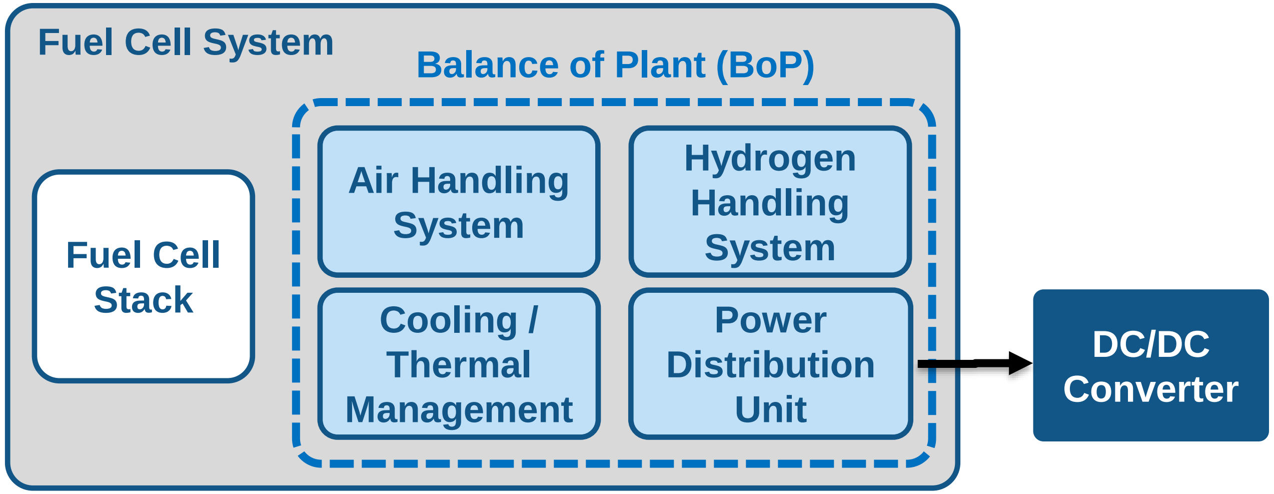
  - Develop supervisory logic with state-of-the-art V&V capabilities
- Meet critical safety requirements
  - Model-Based Design streamline certification of your embedded systems

(Stage 3)

Consumption
(E-mobility)

- Component-level vs system-level simulation
- Optimal system architecture (e.g., fuel cell multi-stack, battery)
- Expensive physical prototype testing

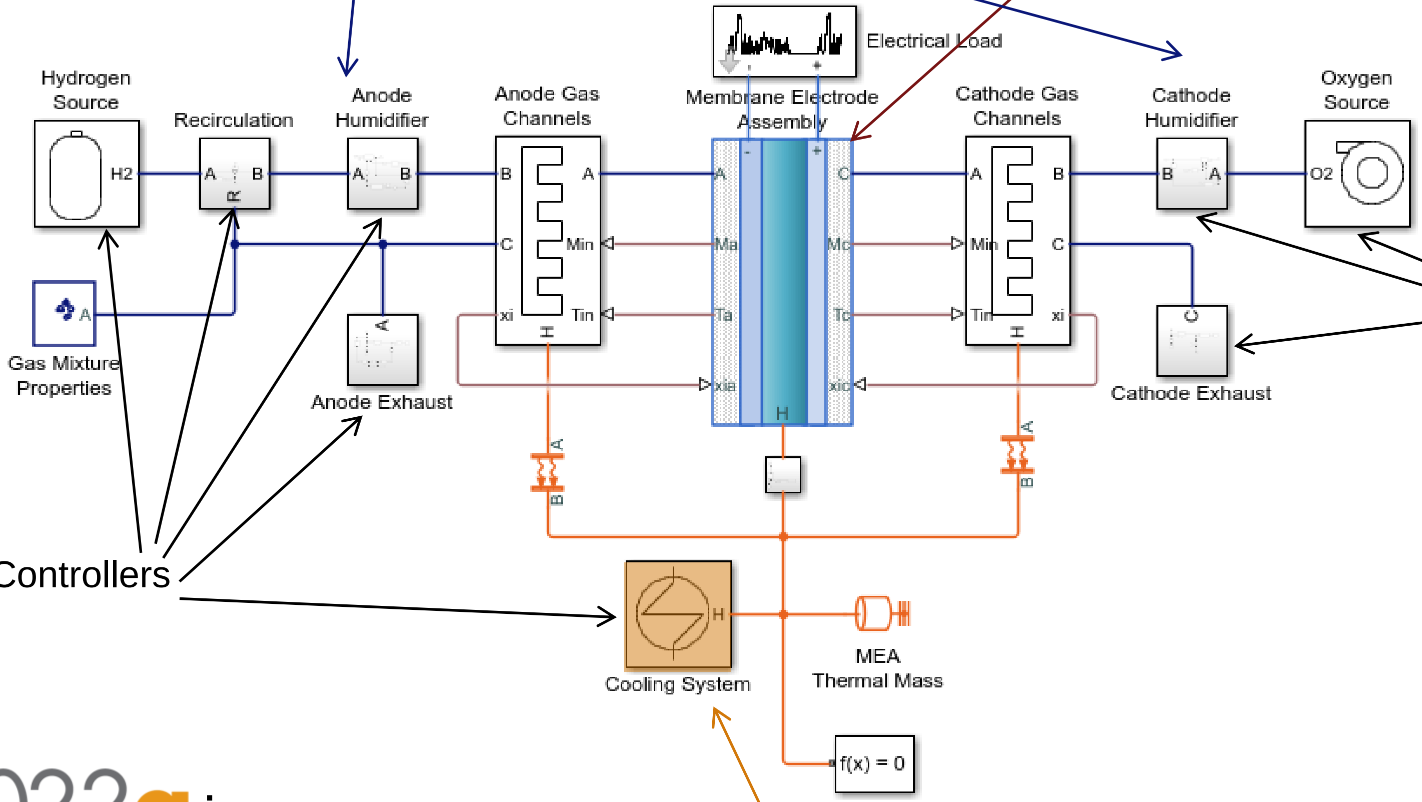
Fuel Cell System in Vehicle



Multiple Domains Used to Simulate Fuel Cell Systems….

Custom Fuel Cell Domain
Multispecies gas network
for N_2,O_2,H_2, H_2O

Membrane
Exchange species and generate elec. power & heat, N_2 diffusion



Controllers

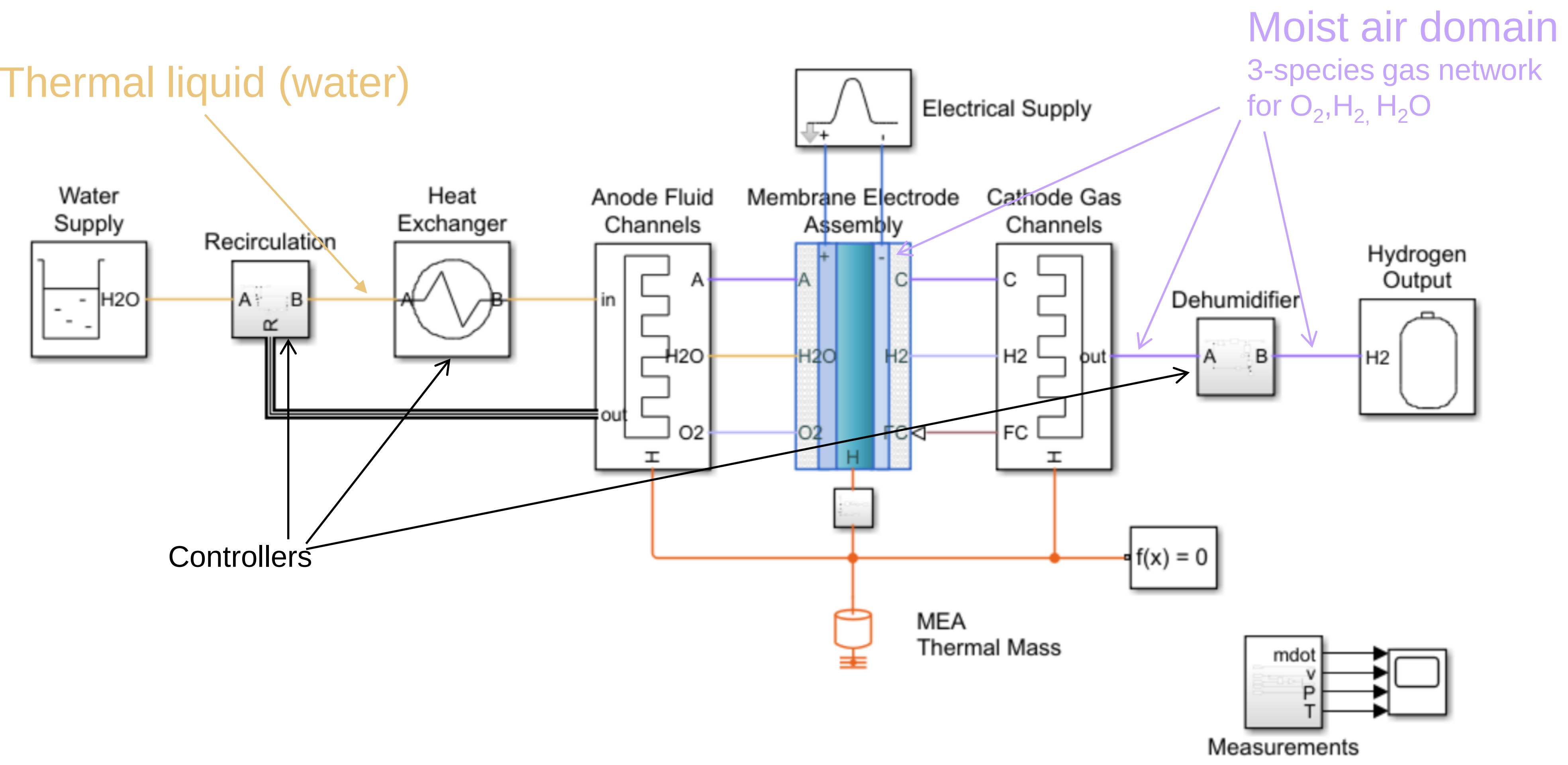
Controllers

Liquid cooling system

Try it out in R2022a:

```
>> sscfluids_fuel_cell
```

… and Electrolyzers!



Try it out in R2022a:

```
>> ssc_electrolyzer
```

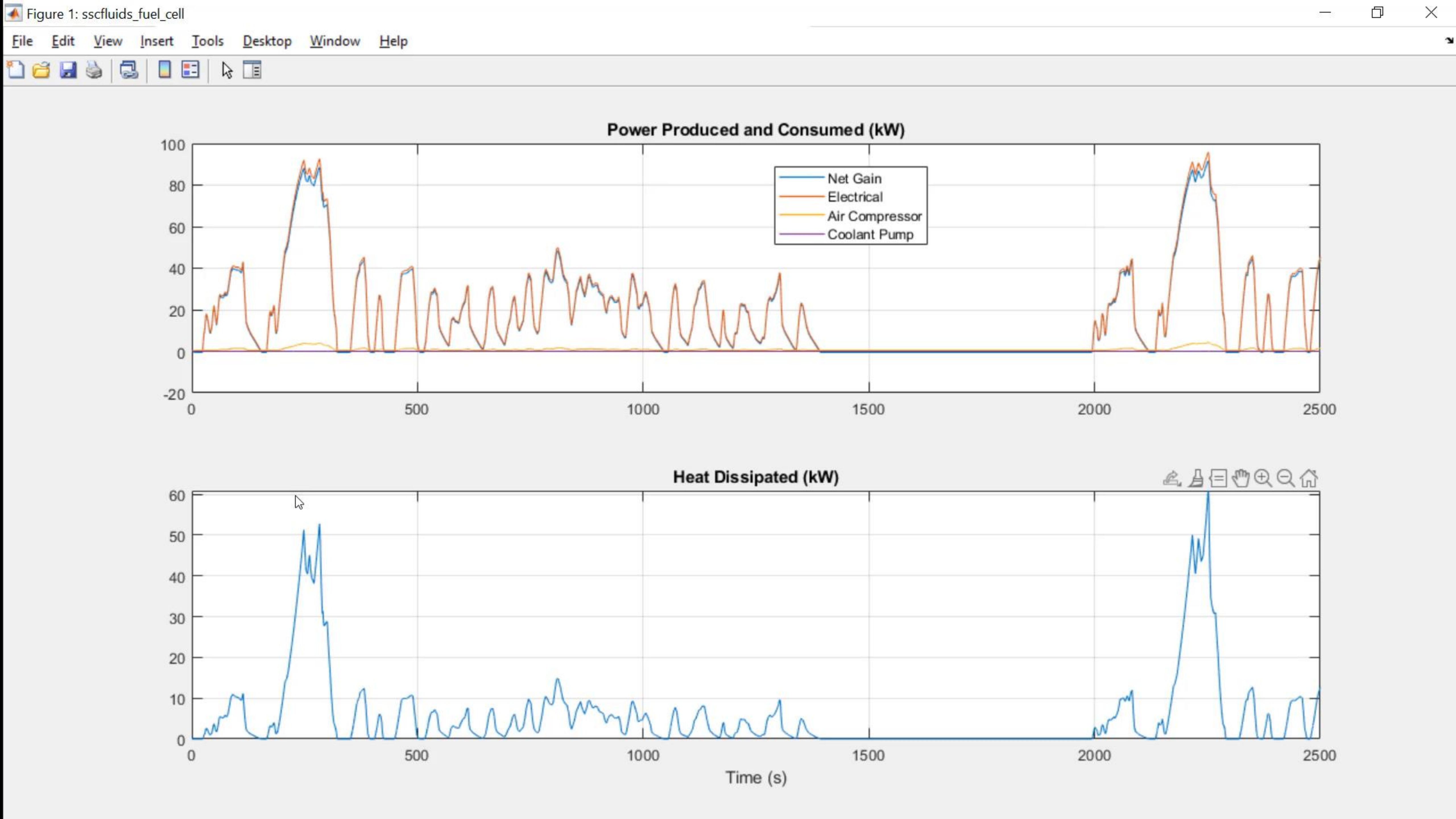
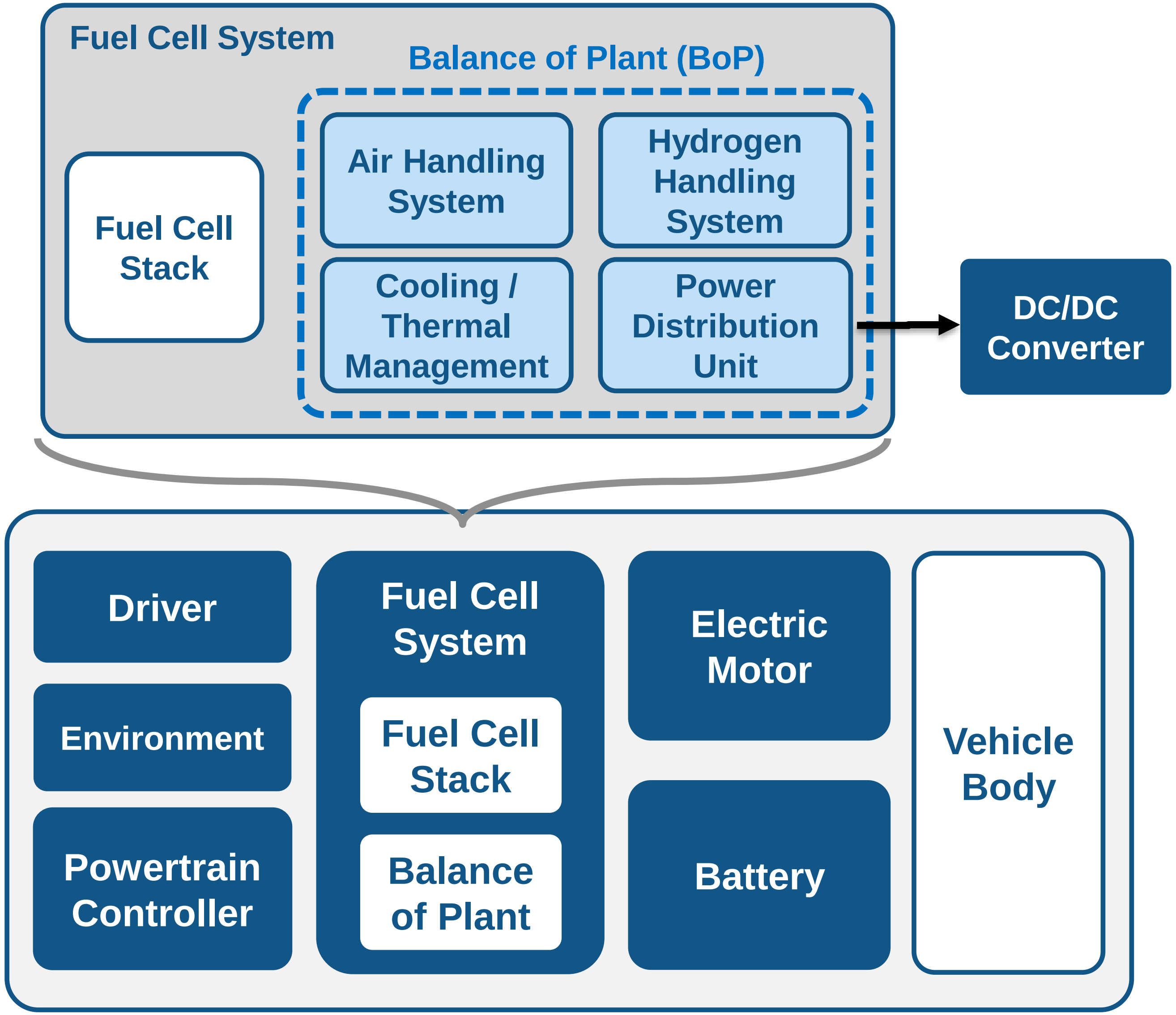


Figure 1: sscfluids_fuel_cell
File Edit View Insert Tools Desktop Window Help
Power Produced and Consumed (kW)
Net Gain
Electrical
Air Compressor
Coolant Pump
100
80
60
40
20
0
-20
0
500
1000
1500
2000
2500
Heat Dissipated (kW)
60
50
40
30
20
10
0
0
500
1000
1500
2000
2500
Time (s)

Fuel Cell System in Vehicle



Fuel cell system operation in an FCV

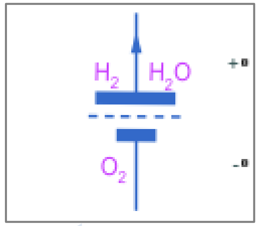
- Determine instantaneous power demand
- Convert power demand to current demand
- Translate current command to H2 / Air flow commands
- Distribute current demand between battery and fuel cell

Choose the Appropriate Fidelity Level for Fuel Cell System Modeling

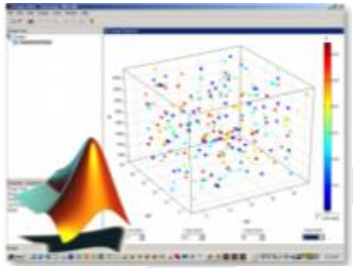
Model what you need …
when you need it

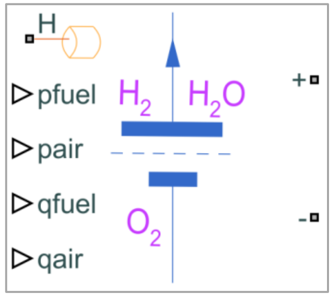
Computational Time

Voltage vs.
current curve

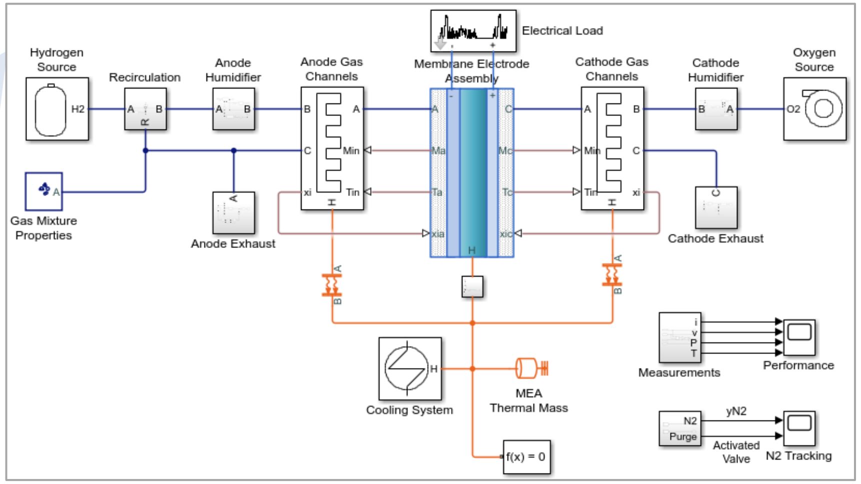


Lookup-table
statistical model
no dynamics



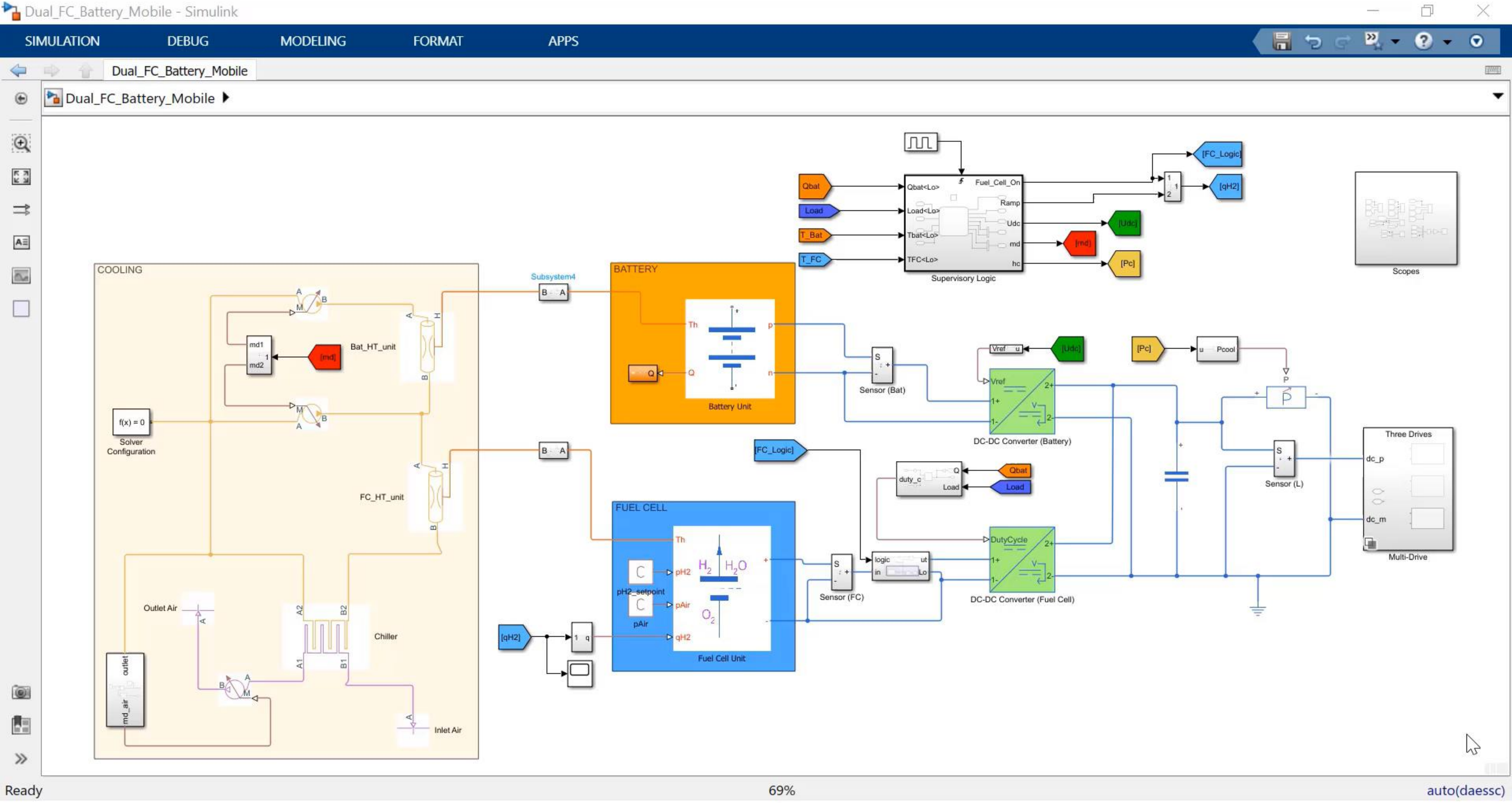


Detailed first principles
model without
gas dynamics

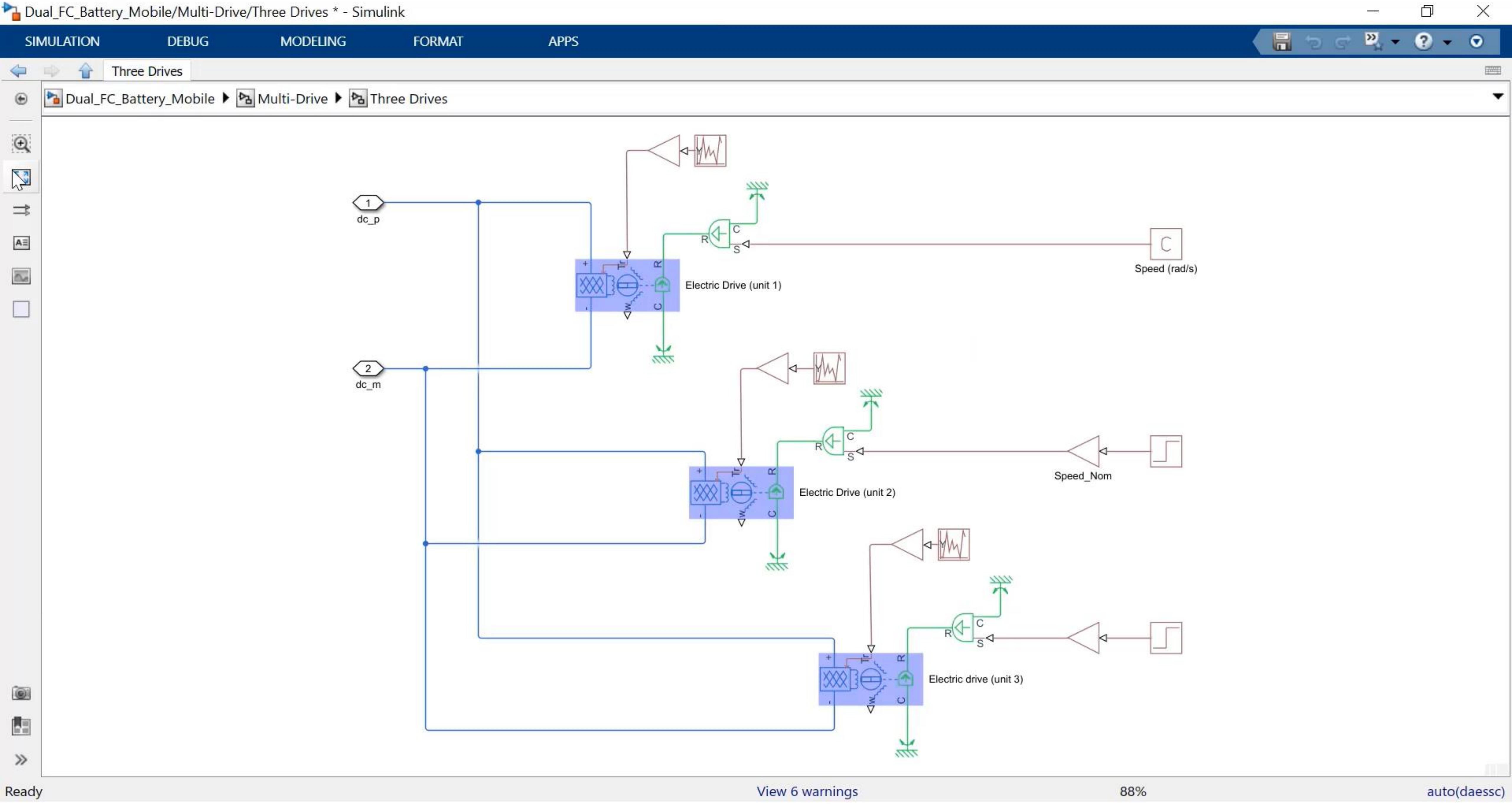


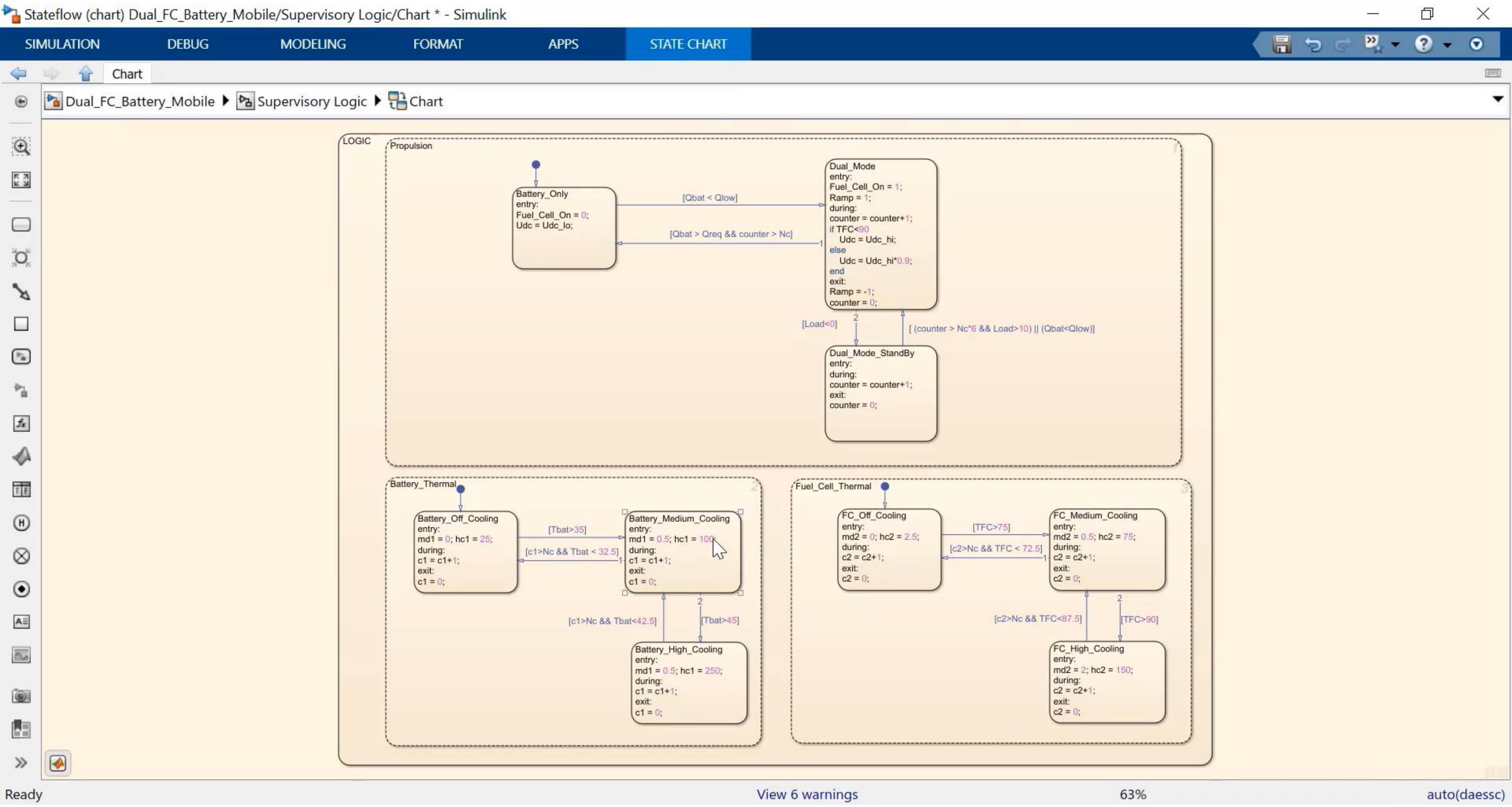
Detailed first principles
model with gas dynamics

Model Complexity and Details


Dual_FC_Battery_Mobile - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
APPS
Dual_FC_Battery_Mobile
COOLING
BATTERY
FUEL CELL
Subsystem4
Bat_HT_unit
FC_HT_unit
Solver Configuration
Outlet Air
Inlet Air
Chiller
Battery Unit
Fuel Cell Unit
pH2_setpoint
pAir
Supervisory Logic
Qbat
Load
T_Bat
T_FC
Fuel_Cell_On
Ramp
Udc
Scopes
Sensor (Bat)
Sensor (FC)
Sensor (L)
DC-DC Converter (Battery)
DC-DC Converter (Fuel Cell)
Three Drives
Multi-Drive
[FC_Logic]
[qH2]
[Udc]
[md]
[Pc]
Ready
69%
auto(daessc)

MATLAB EXPO


Dual_FC_Battery_Mobile/Multi-Drive/Three Drives * - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
APPS
Three Drives
Dual_FC_Battery_Mobile
Multi-Drive
Three Drives
1
dc_p
2
dc_m
Electric Drive (unit 1)
Speed (rad/s)
Electric Drive (unit 2)
Speed_Nom
Electric drive (unit 3)
Ready
View 6 warnings
88%
auto(daessc)



Stateflow (chart) Dual_FC_Battery_Mobile/Supervisory Logic/Chart * - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
APPS
STATE CHART
Chart
Dual_FC_Battery_Mobile
Supervisory Logic
Chart
LOGIC
Propulsion
Battery_Only
entry:
Fuel_Cell_On = 0;
Udc = Udc_lo;
[Qbat < Qlow]
[Qbat > Qreq && counter > Nc]
Dual_Mode
entry:
Fuel_Cell_On = 1;
Ramp = 1;
during:
counter = counter+1;
if TFC<90
Udc = Udc_hi;
else
Udc = Udc_hi*0.9;
end
exit:
Ramp = -1;
counter = 0;
[Load<0]
[(counter > Nc*6 && Load>10) || (Qbat<Qlow)]
Dual_Mode_StandBy
entry:
during:
counter = counter+1;
exit:
counter = 0;
Battery_Thermal
Battery_Off_Cooling
entry:
md1 = 0; hc1 = 25;
during:
c1 = c1+1;
exit:
c1 = 0;
[Tbat>35]
[c1>Nc && Tbat < 32.5]
Battery_Medium_Cooling
entry:
md1 = 0.5; hc1 = 100;
during:
c1 = c1+1;
exit:
c1 = 0;
[c1>Nc && Tbat<42.5]
[Tbat>45]
Battery_High_Cooling
entry:
md1 = 0.5; hc1 = 250;
during:
c1 = c1+1;
exit:
c1 = 0;
Fuel_Cell_Thermal
FC_Off_Cooling
entry:
md2 = 0; hc2 = 2.5;
during:
c2 = c2+1;
exit:
c2 = 0;
[TFC>75]
[c2>Nc && TFC < 72.5]
FC_Medium_Cooling
entry:
md2 = 0.5; hc2 = 75;
during:
c2 = c2+1;
exit:
c2 = 0;
[c2>Nc && TFC<87.5]
[TFC>90]
FC_High_Cooling
entry:
md2 = 2; hc2 = 150;
during:
c2 = c2+1;
exit:
c2 = 0;
Ready
View 6 warnings
63%
auto(daessc)

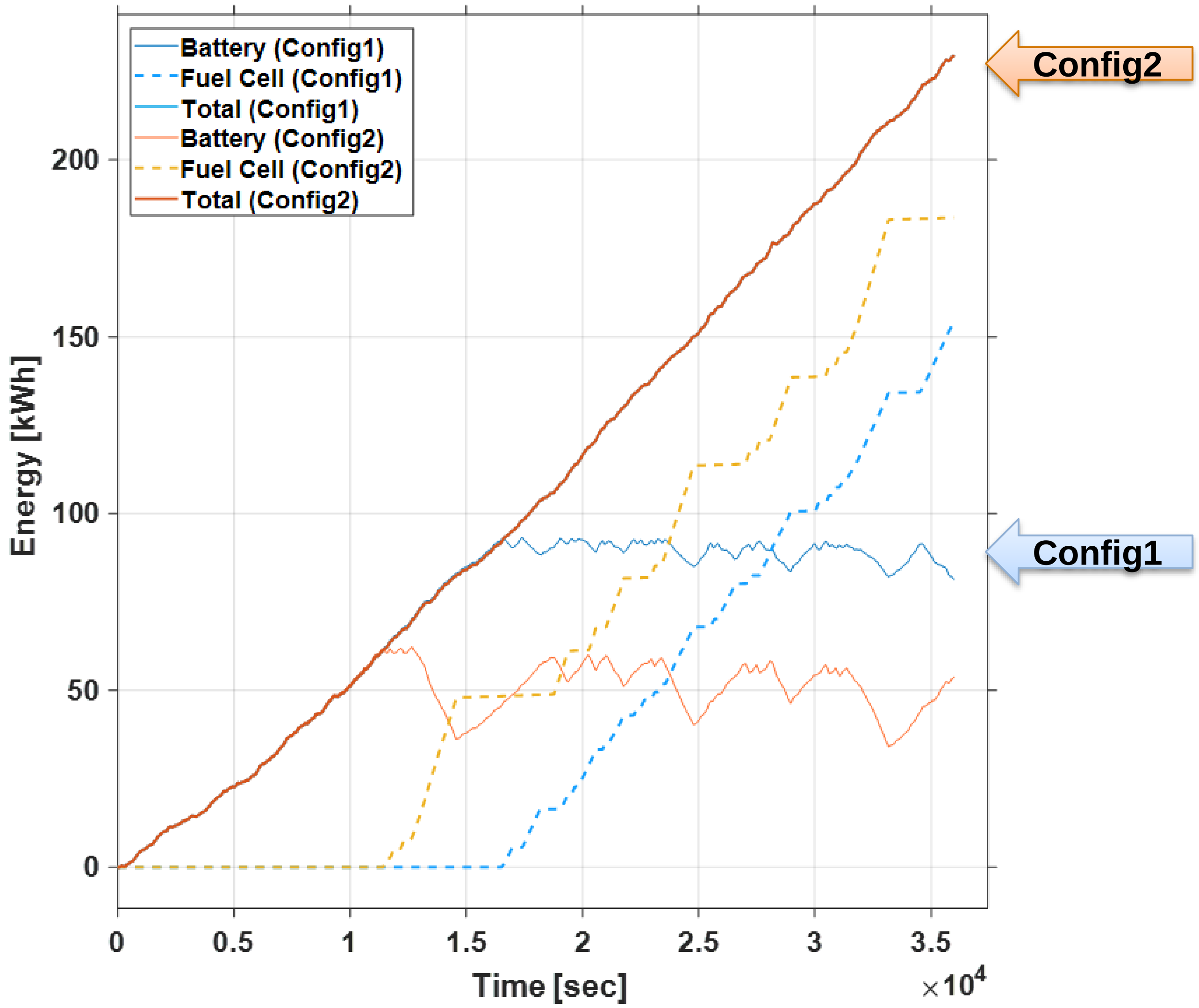
System Level Electrified Propulsion Unit

- Explore design space
  - Example:

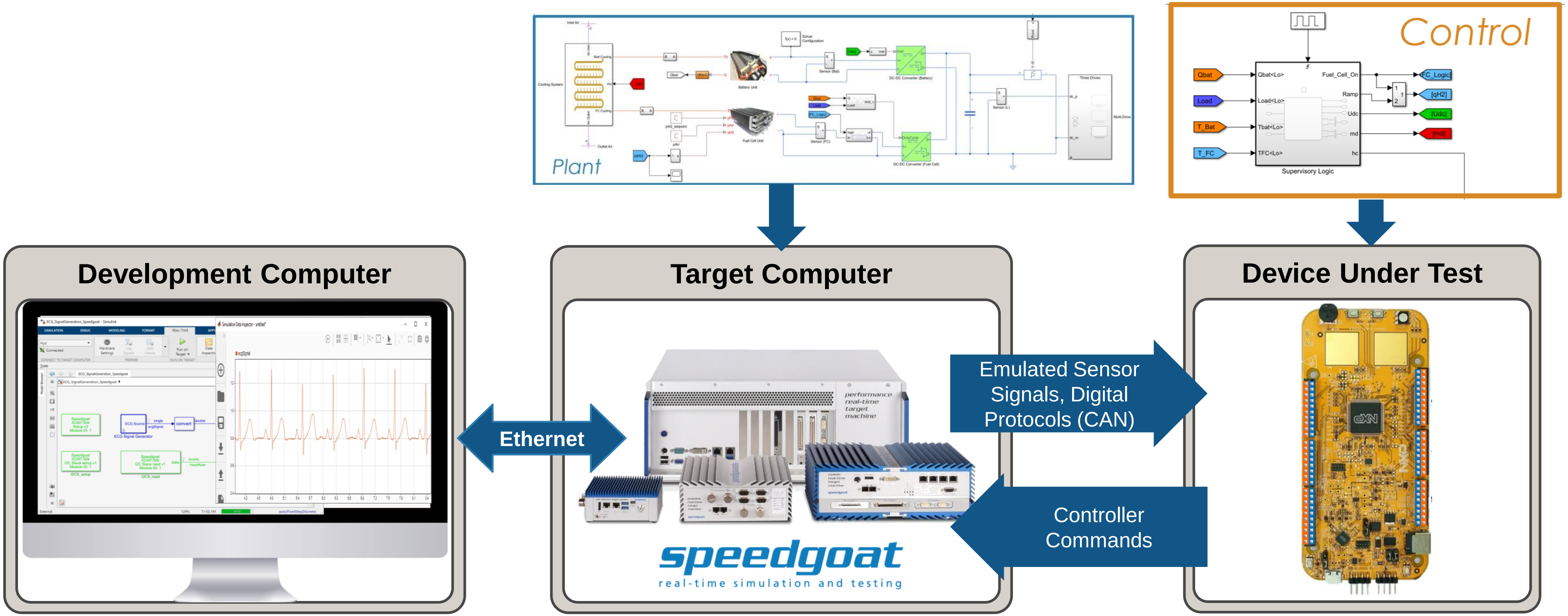
Config1 — **3 Battery Modules, 2 Fuel Cell Stacks**

vs

Config2 — **2 Battery Modules, 3 Fuel Cell Stacks**



Hardware-in-the-Loop



Enabling Green Hydrogen – Challenges H2 Handling and Usage

(Stage 2)

Transfer (tank-to-cell)

- Optimal components sizing (cooling, storage, compressors)
  - ➢ Leverage multi-domain simulation platform
- Reliable 24/7 software operation
  - ➢ Develop supervisory logic with state-of-the-art V&V capabilities
- Meet critical safety requirements
  - ➢ Model-Based Design streamline certification of your embedded systems

(Stage 3)

Consumption (E-mobility)

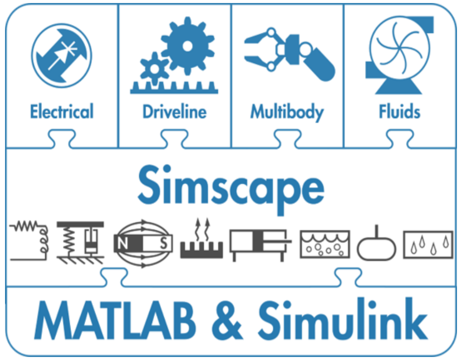
- Component-level vs system-level simulation
  - ➢ Flexible modelling and simulation platform
- Optimal system architecture (e.g., fuel cell multi-stack, battery)
  - ➢ Perform trade-off analysis and monte carlo simulations
- Expensive physical prototype testing
  - ➢ Reduce physical prototypes, reuse models for Hardware-in-the-Loop tests

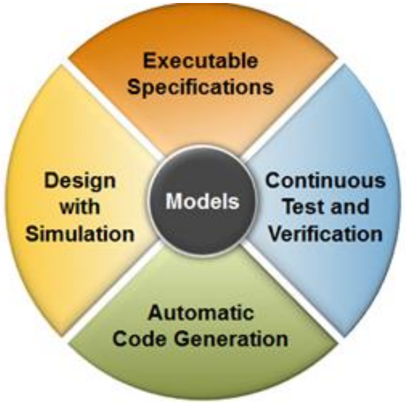
User Testimonial – Nuvera Cells

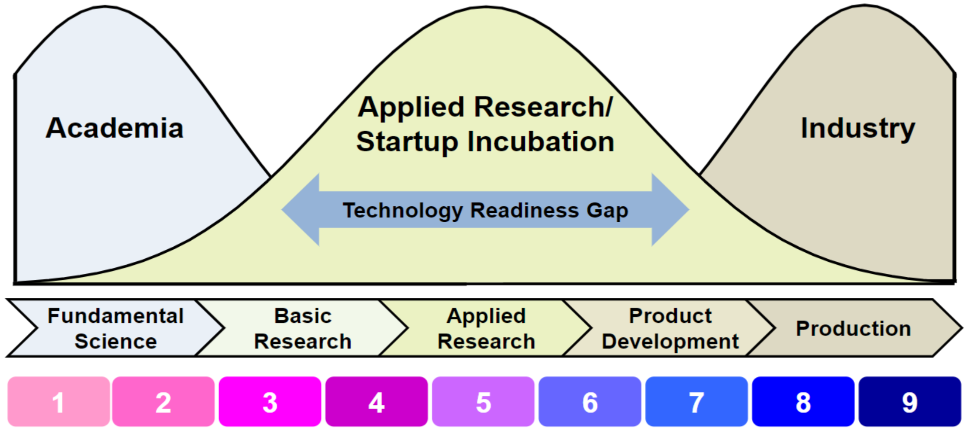
[Hydrogen Is the New Diesel: Electrifying Heavy-Duty Vehicles with Nuvera Fuel Cells Video]

*" Using **modeling** and **real-time simulation** enables Nuvera's engineers to iterate on their design **quickly** and allows for experimentation without putting a real engine **at risk**. "*

Enabling Green Hydrogen - Conclusions







- Assert feasibility
  - techno-economic analyses
  - concept evaluation
- Secure sustainable and robust operation
  - design automation
  - optimization

Call to Action

- Developing Hydrogen Production and Fuel Cell Applications with MATLAB and Simulink
  - In-depth videos & resources
  - Customer references
- Additional resources
  - MATLAB and Simulink for the Utilities and Energy Industry
  - MATLAB and Simulink for Electric Vehicle Development
  - MATLAB and Simulink for Developing Power Generation and Transmission Equipment
  - MATLAB and Simulink for Verification, Validation and Test
- Shipping examples
  - PEM Fuel Cell System (2022a)
  - PEM Electrolysis System (2022a)

MATLAB EXPO

Thank you

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