MathWorks
AUTOMOTIVE CONFERENCE 2022
North America

Multi-Stack Fuel Cell Electric Vehicle Modeling and Applications

Jason Rodgers, MathWorks

Graham Dudgeon, MathWorks

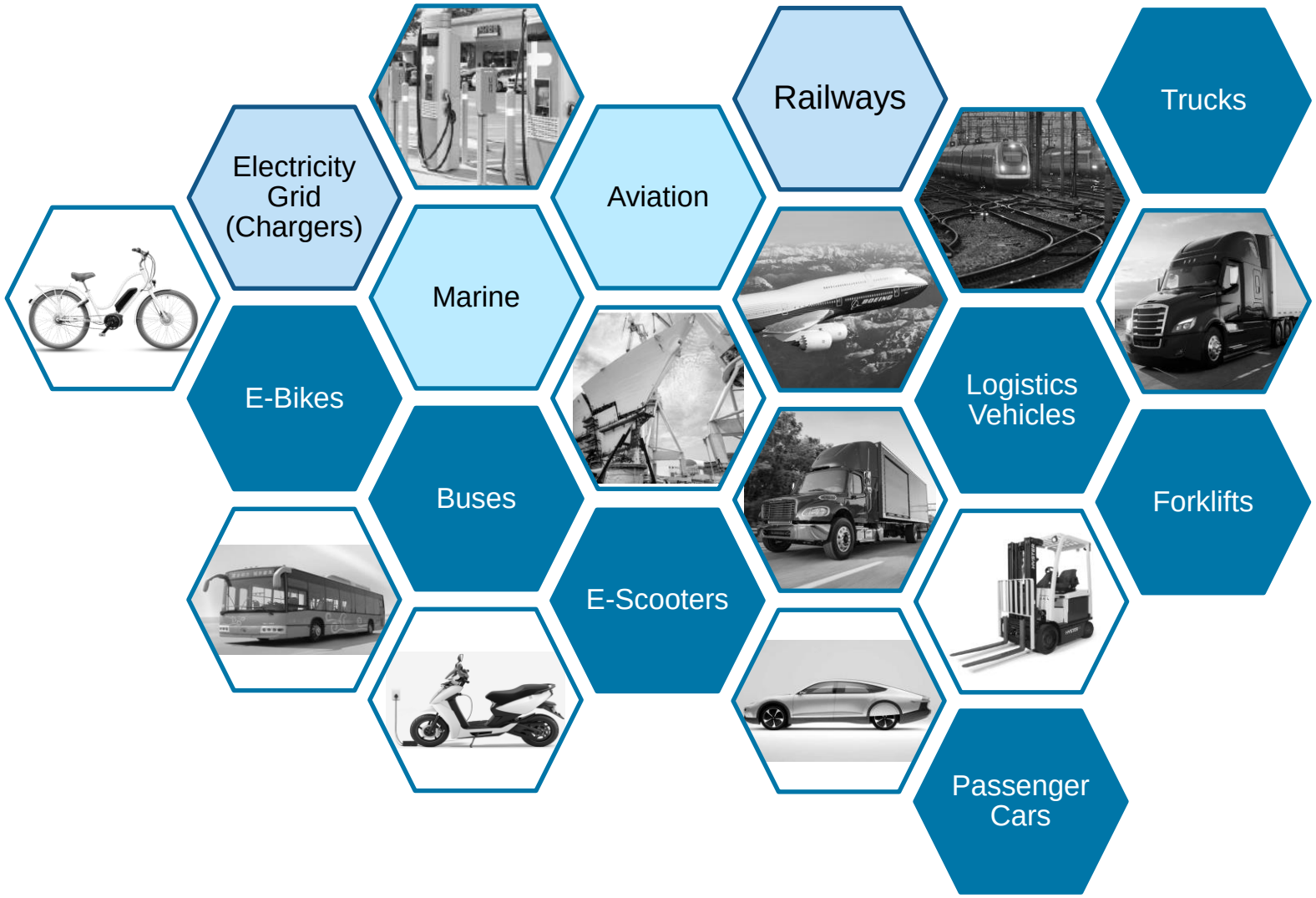
MathWorks

Key Takeaways

- Multi-Stack fuel cell **virtual vehicle** models enabled by MathWorks tools
  - Realistic environment and testing scenarios
  - Analysis, control design and optimization of components and full vehicle simulation

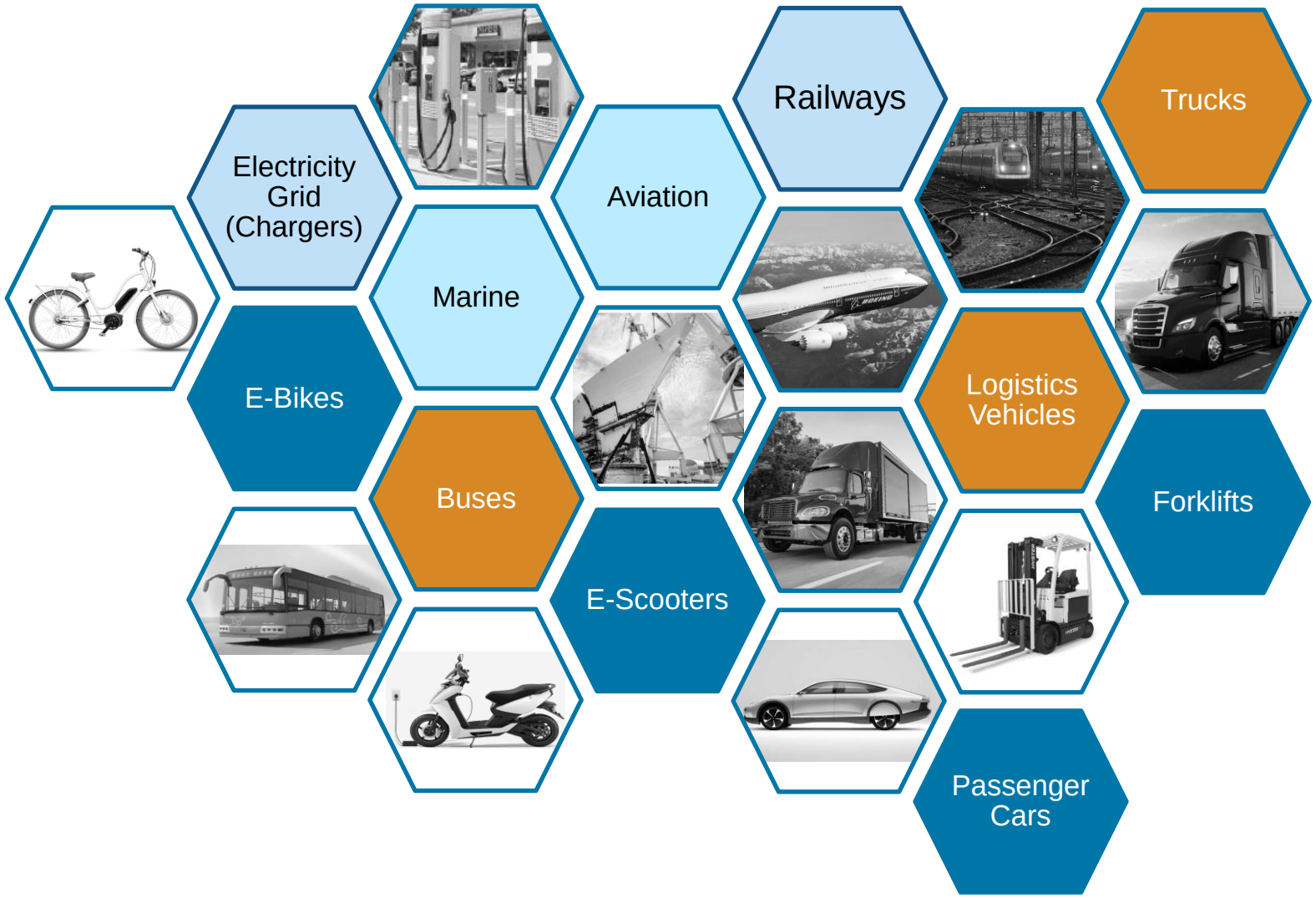
- Methodology and workflows for modeling **subsystem** level fuel cell systems
  - Build out fidelity and complexity incrementally
  - Focus on specific design tasks and minimize the time taken to perform design iterations.
  - Utilize first-principles and data-driven/statistical approaches for appropriate tasks

What is Electrification?



Electrification is the increasing use of electrical technology and energy management to achieve enhanced efficiency, performance and reliability in transportation, industrial systems, consumer and professional equipment, and power generation and transmission.

What is Electrification?



How to tackle high power requirement of heavy-duty vehicles?

Problem Statement

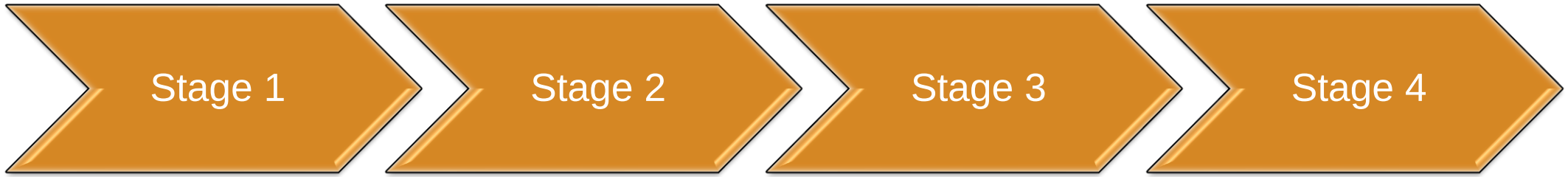
What is the problem?

- PEM based multi-stack fuel cell vehicles can meet **heavy duty** vehicle power requirements
- Given two different stack systems, how to best decide power split control to meet wheel power demand **efficiently**?

Process for Control Development

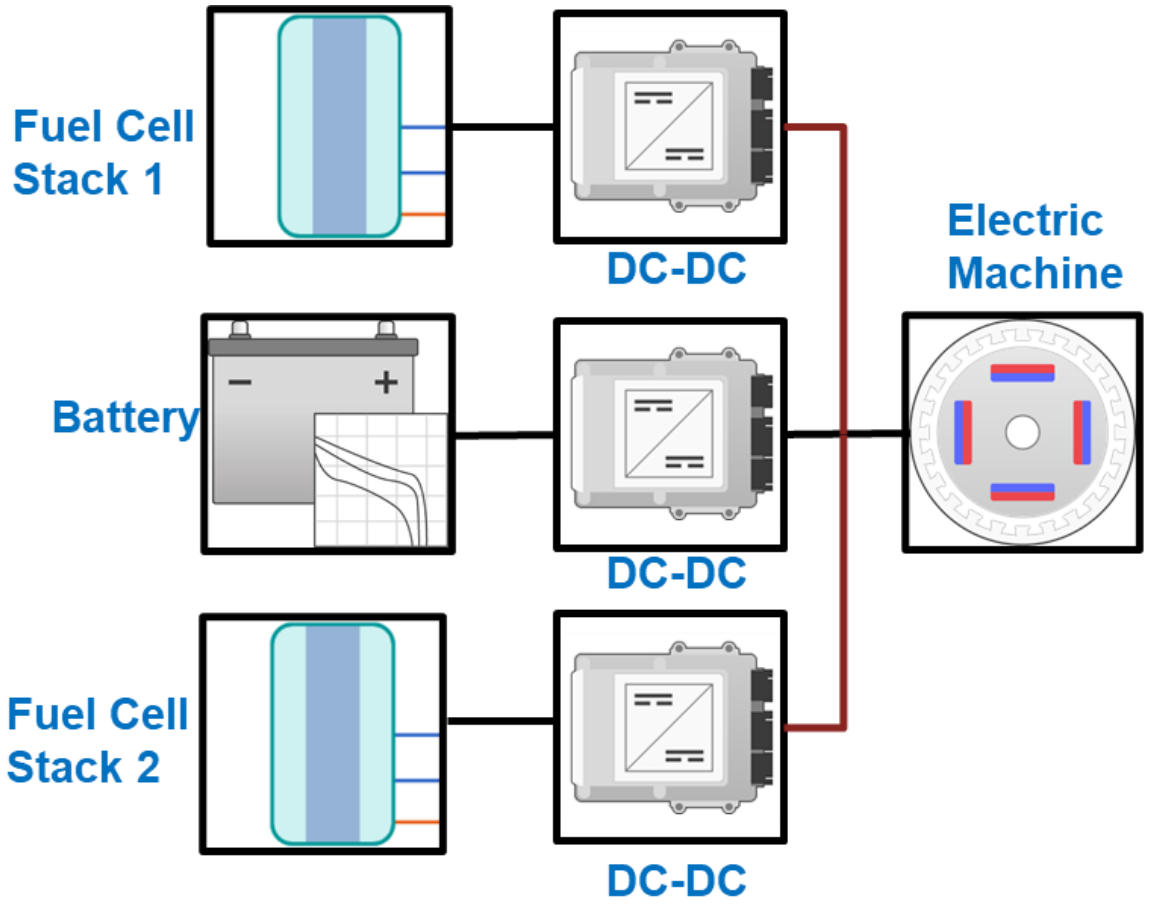
How do we solve this?

- Use a four-stage process to facilitate fast control development
- Build out fidelity and complexity incrementally focusing on specific design tasks to minimize the time taken to perform design iterations



- Develop low fidelity electrical system architecture
- Optimize power sharing
- Confirm functional response on high fidelity electrical system.
- Check system level integration

Stage 1: Develop Electrical System Architecture



What are we doing at this stage?

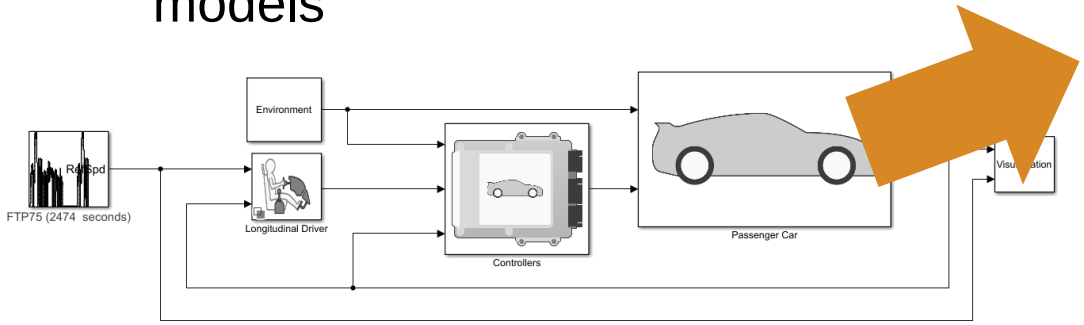
- Isolate electrical system
  - FC stacks
  - DCDC converters
  - Battery
  - Electric machine
- Use simple Thevenin equivalents for power sources
- Electrical system is modeled using Simscape components

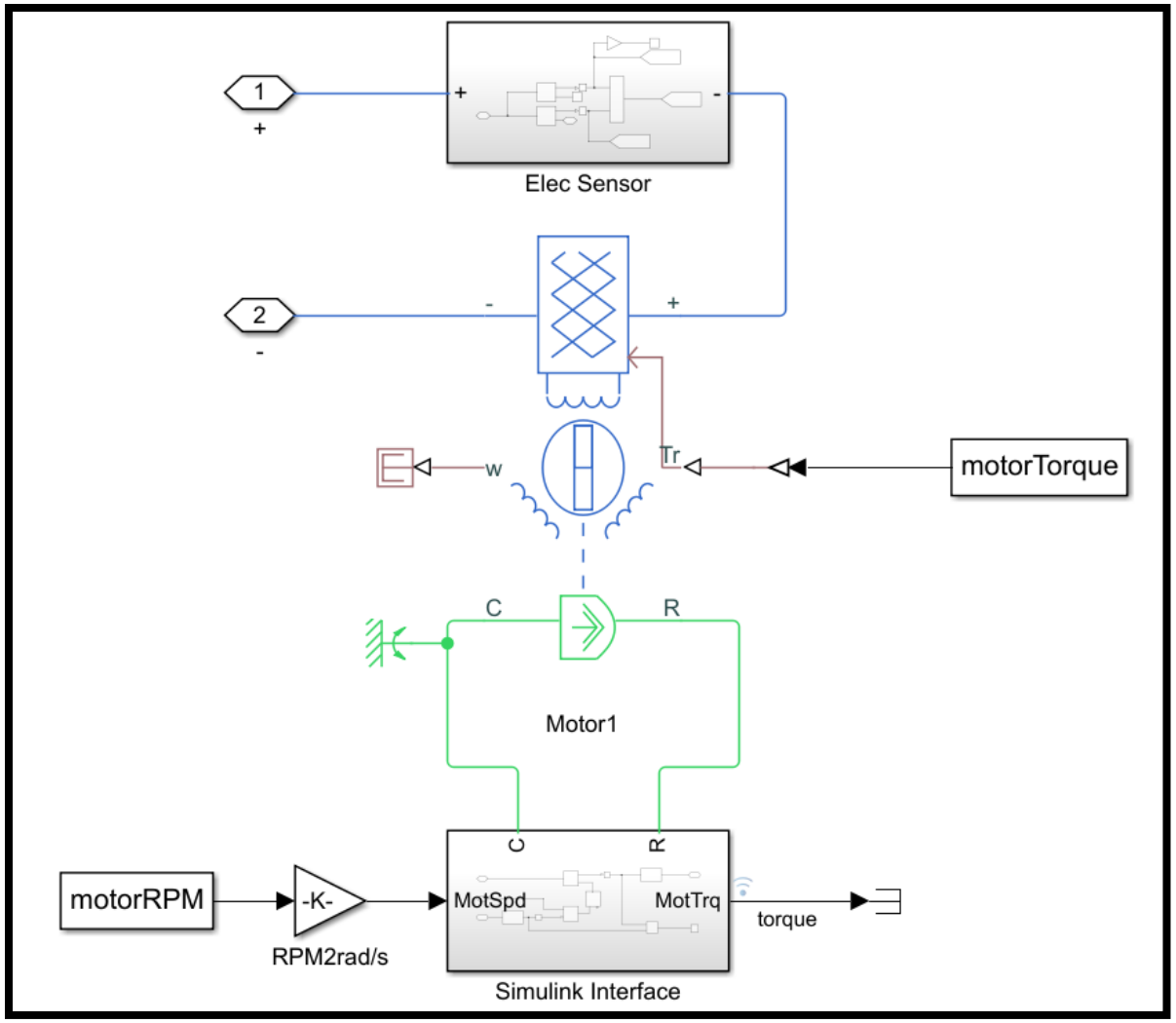
Why do this?

- Reduces model complexity
- Allows for rapid design iterations.
- Simscape allows for design style modeling

Stage 1: Develop Electrical System Architecture

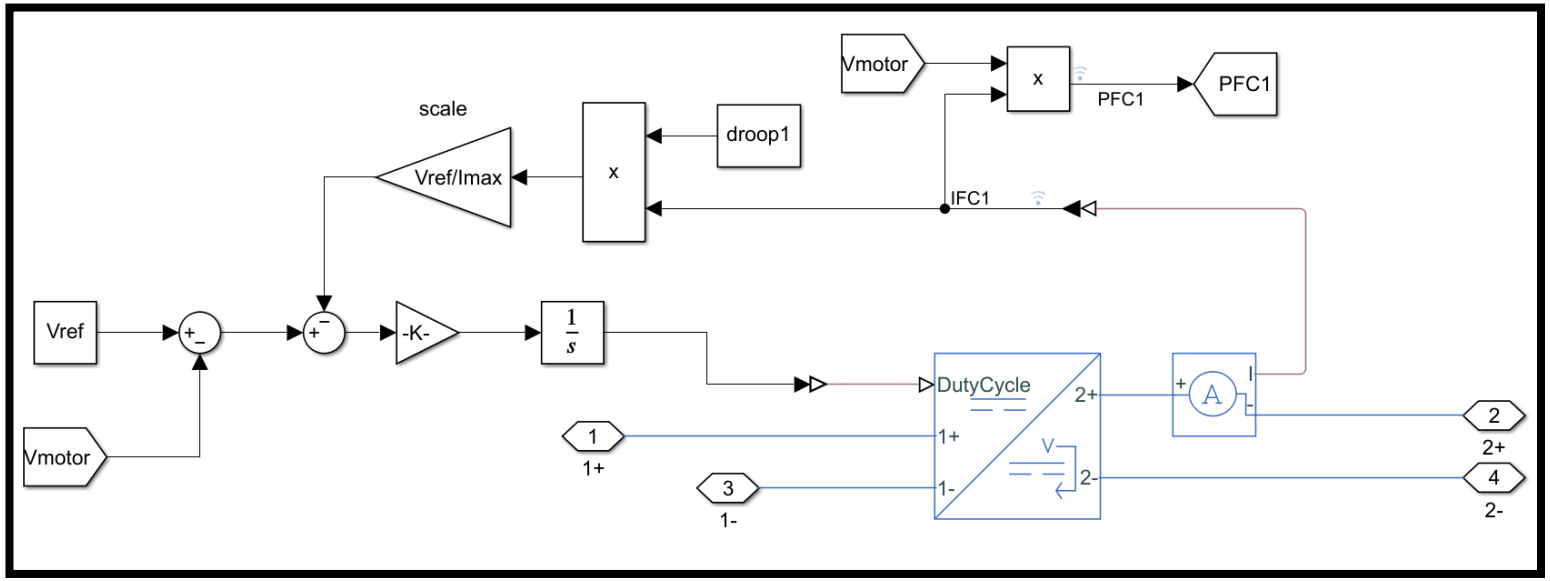
- Use Powertrain Blockset Fuel Cell reference application
  - Same motor and battery specs
  - Simulated FTP75 drive cycle for system power demand and motor speeds
  - Powertrain model is combination of Simscape and Simulink-based models



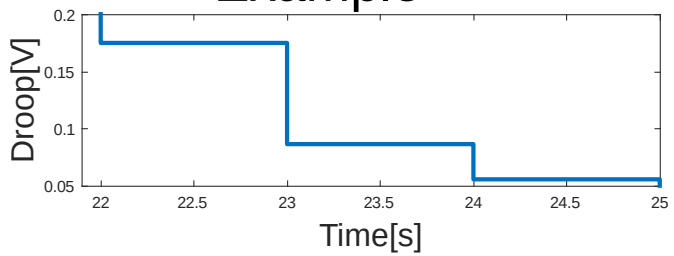


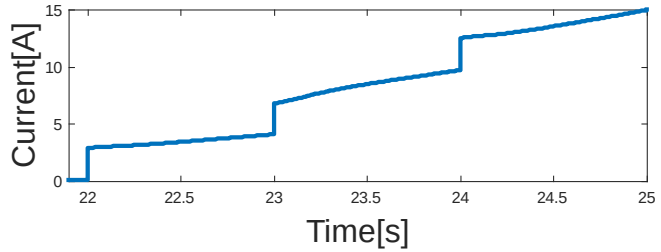
Stage 1: Develop Electrical System Architecture

- DCDC converters adjust duty-cycle
  - Voltage droop control
- **Voltage droop** is a traditional mechanism for power sharing control on DC electrical systems

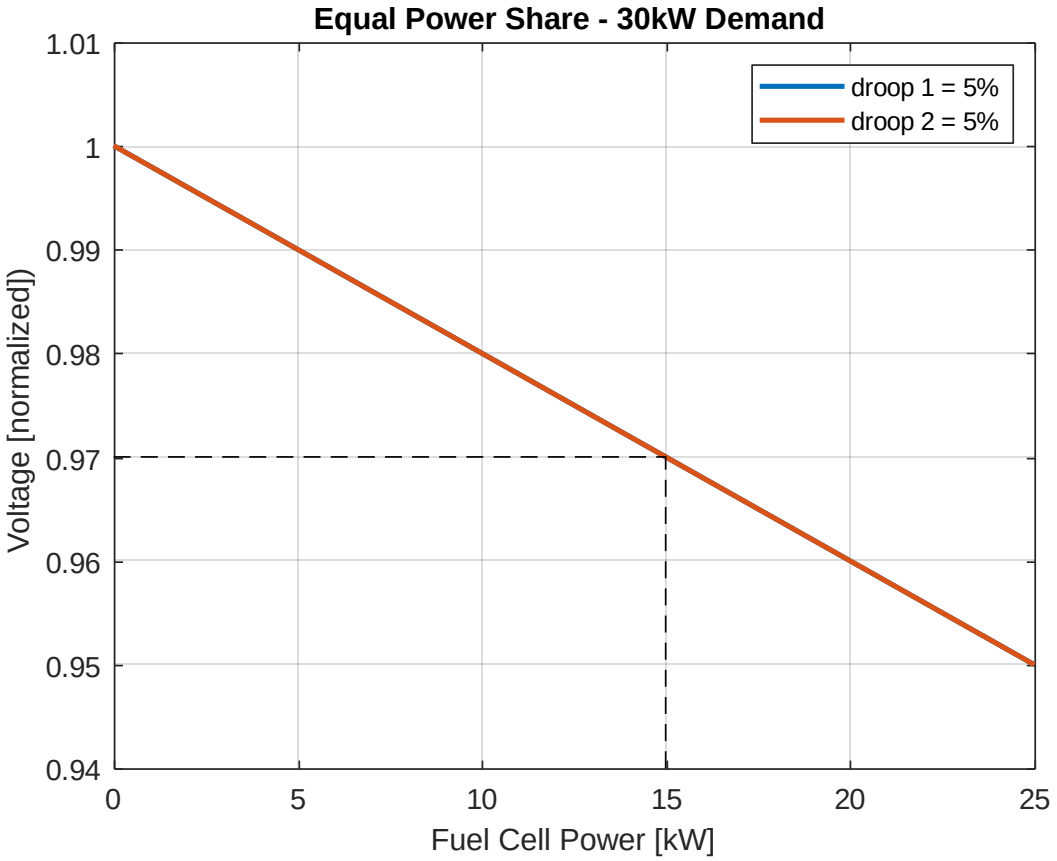


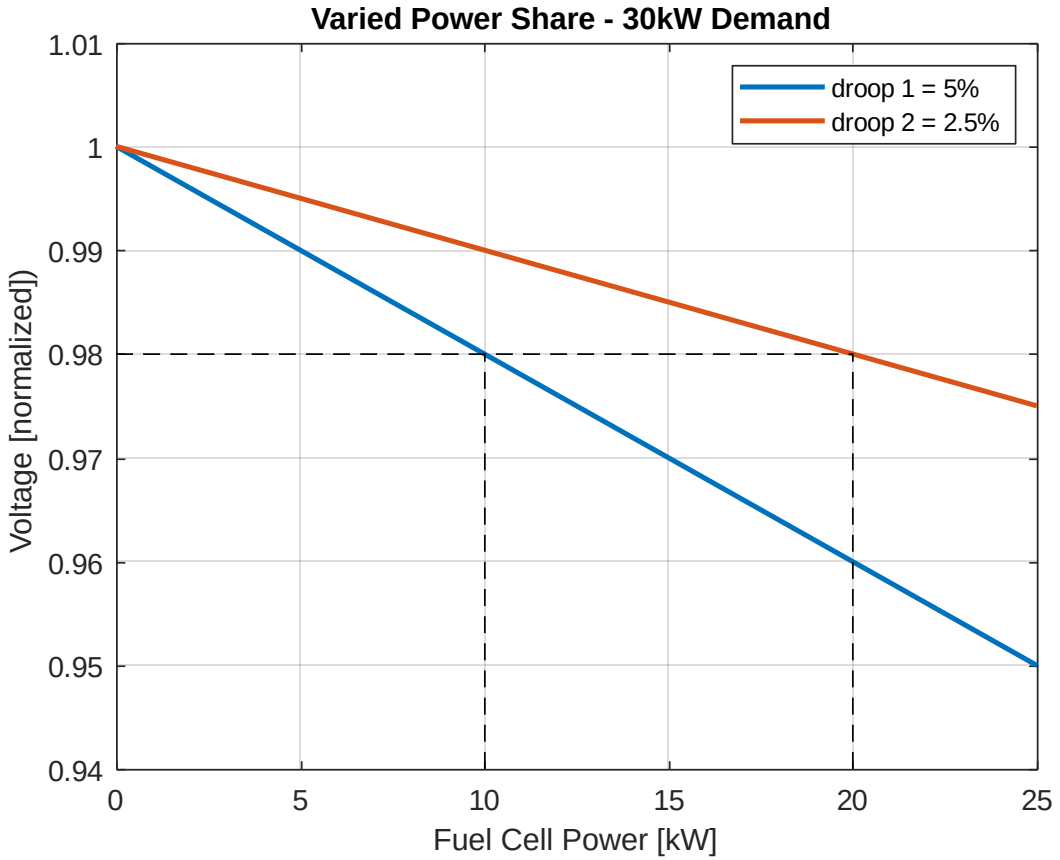
Example





Stage 1: Develop Electrical System Architecture

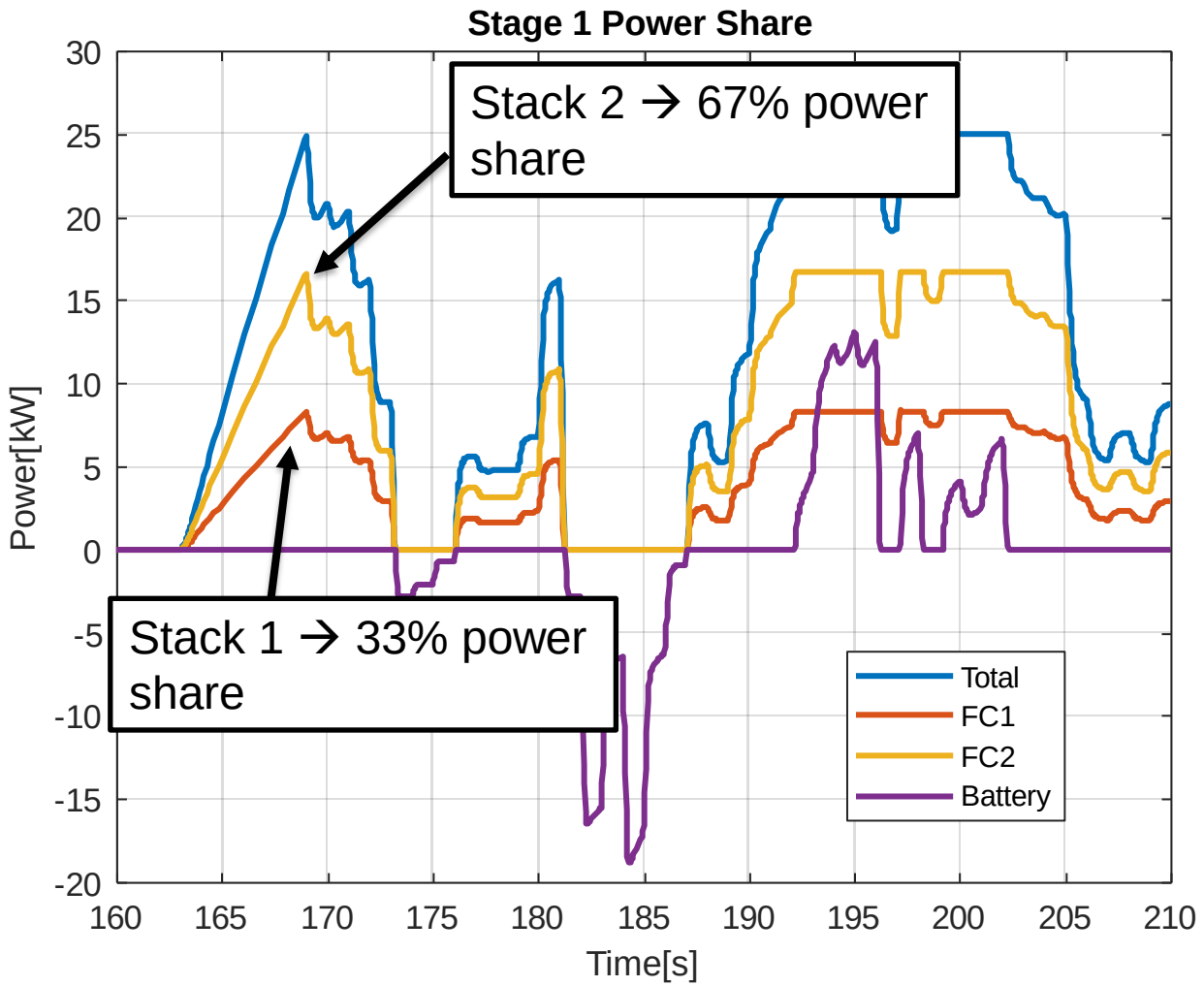




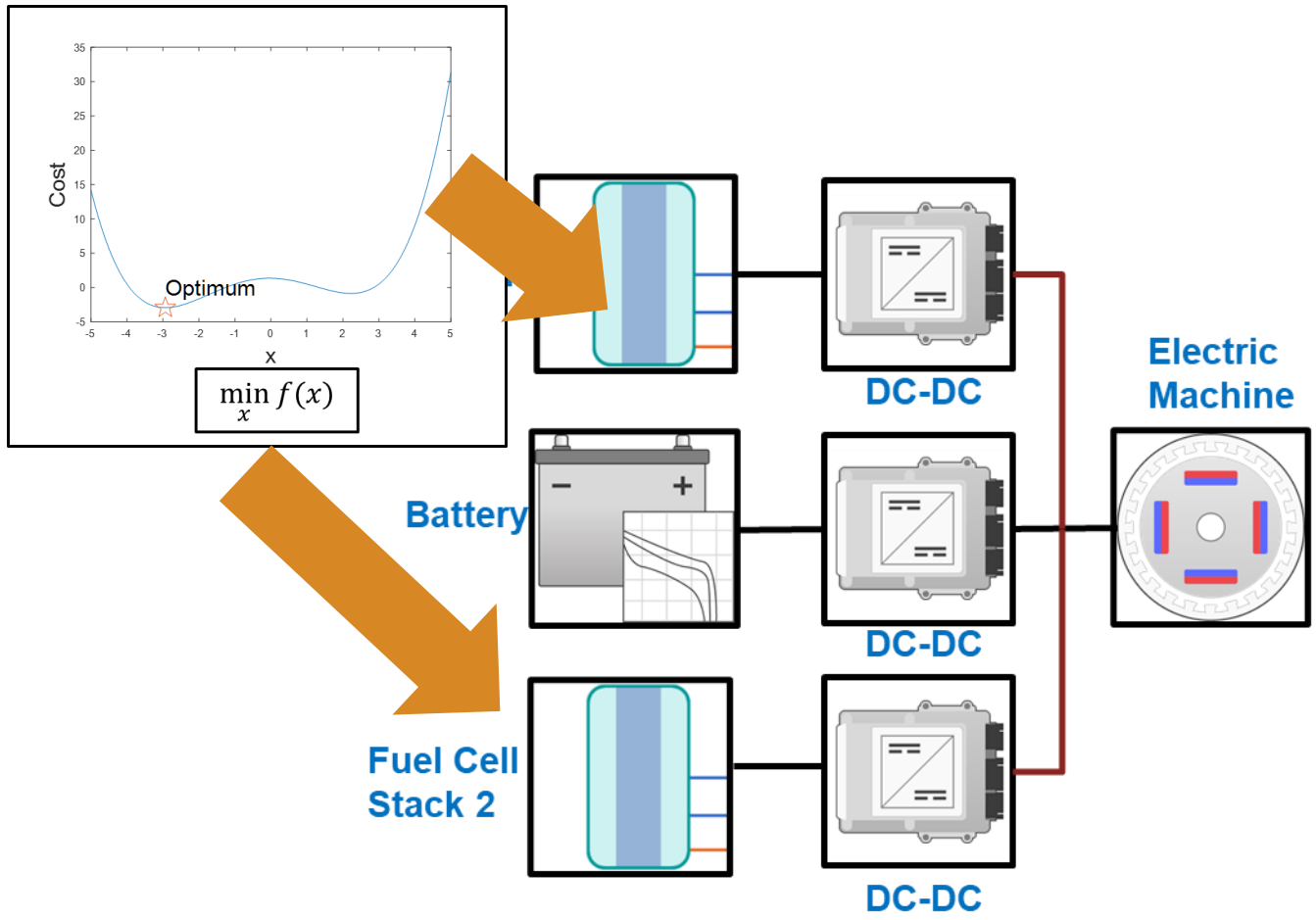
- Commanding equal droop leads to equal power share
- Commanding lower droop in stack 2 leads to higher power share from stack 1

Stage 1: Develop Electrical System Architecture

- Electrical system behaves as expected.
  - The example on the right shows droop 1 at 5% and droop 2 at 2.5%
- The battery absorbs regenerated power and provides motor power beyond 25kW



Stage 2: Optimization of Power Sharing



What are we doing at this stage?

- Implement a power share algorithm that will optimize power share based on efficiency curves of each fuel cell
- Thevenin models are still used for control development

Why do this?

- Use fast running models to design optimal control algorithm
- Confirm control behaves as expected

Stage 2: Optimization of Power Sharing

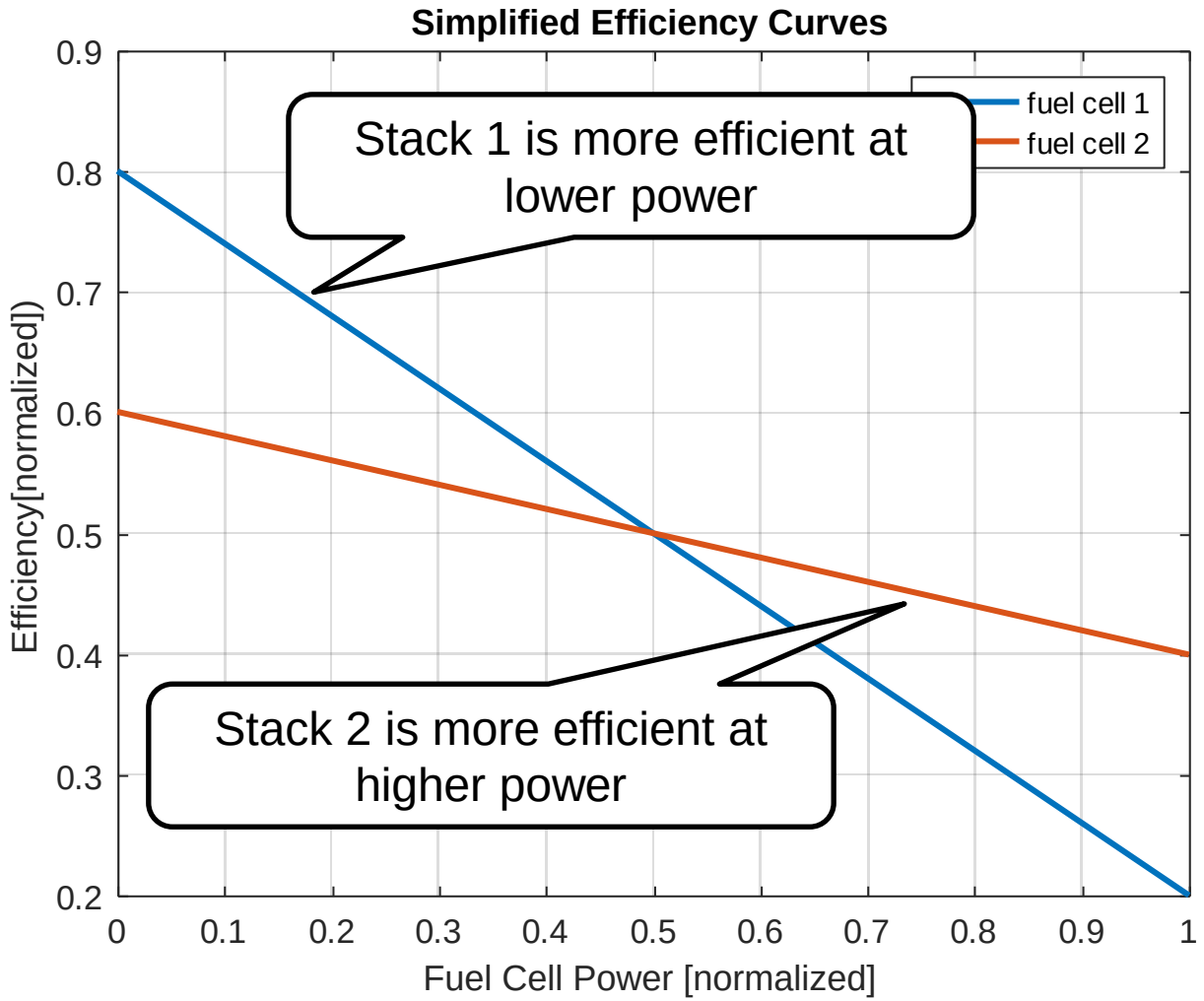
- Want to minimize the total power required to meet power demand

$$\min_{P_{FC1},P_{FC2}} \frac{P_{FC1}}{\eta_{FC1}} + \frac{P_{FC2}}{\eta_{FC2}}$$

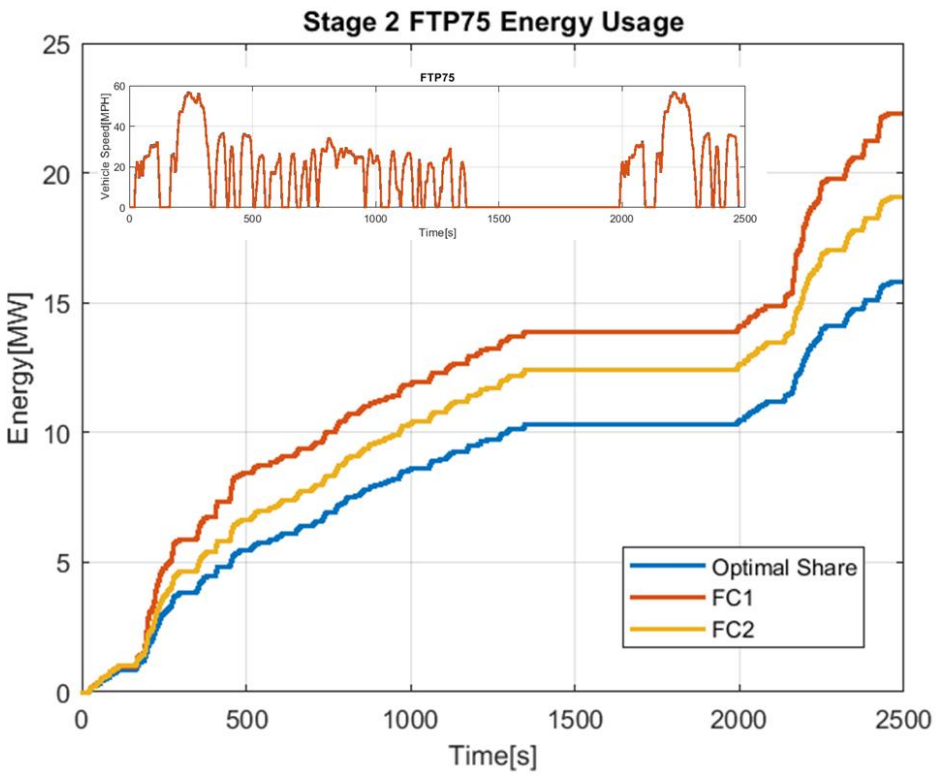
$$s.t. P_{total} = P_{FC1} + P_{FC2}$$

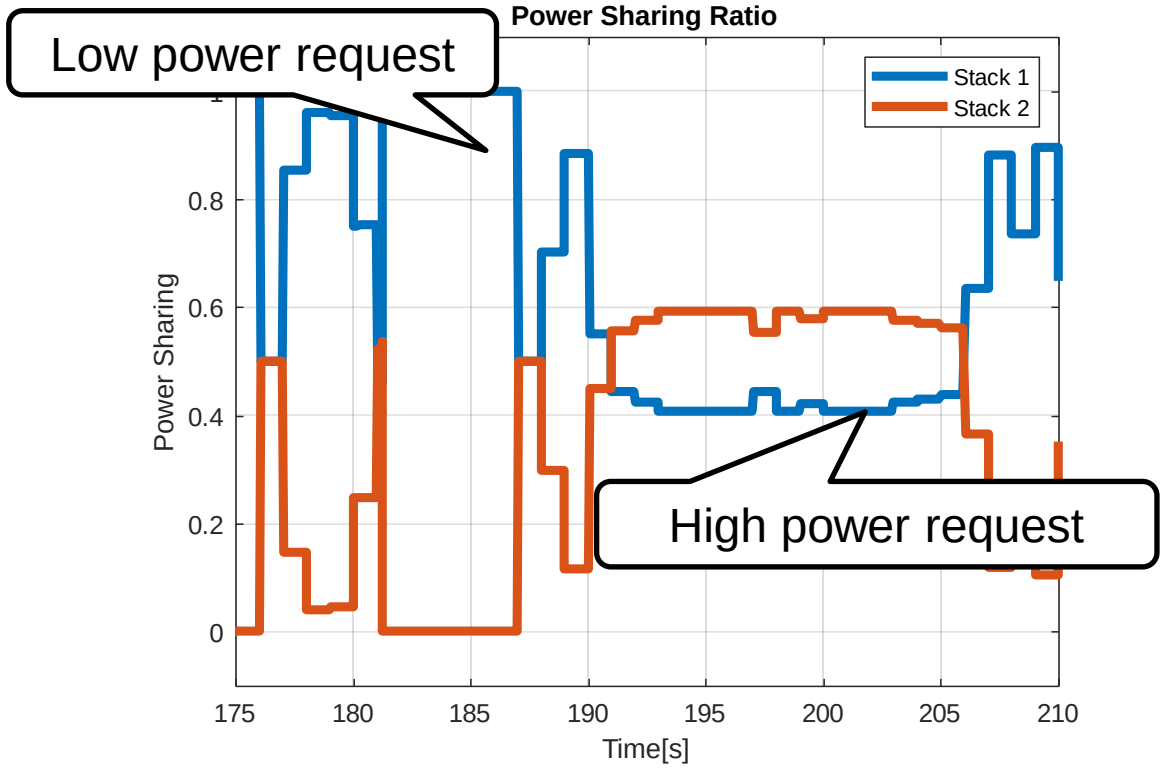
$$P = power$$
$$\eta = efficiency$$
$$FC_i = ith\ fuel\ cell$$

- fmincon is used to solve this problem at each time step



Stage 2: Optimization of Power Sharing

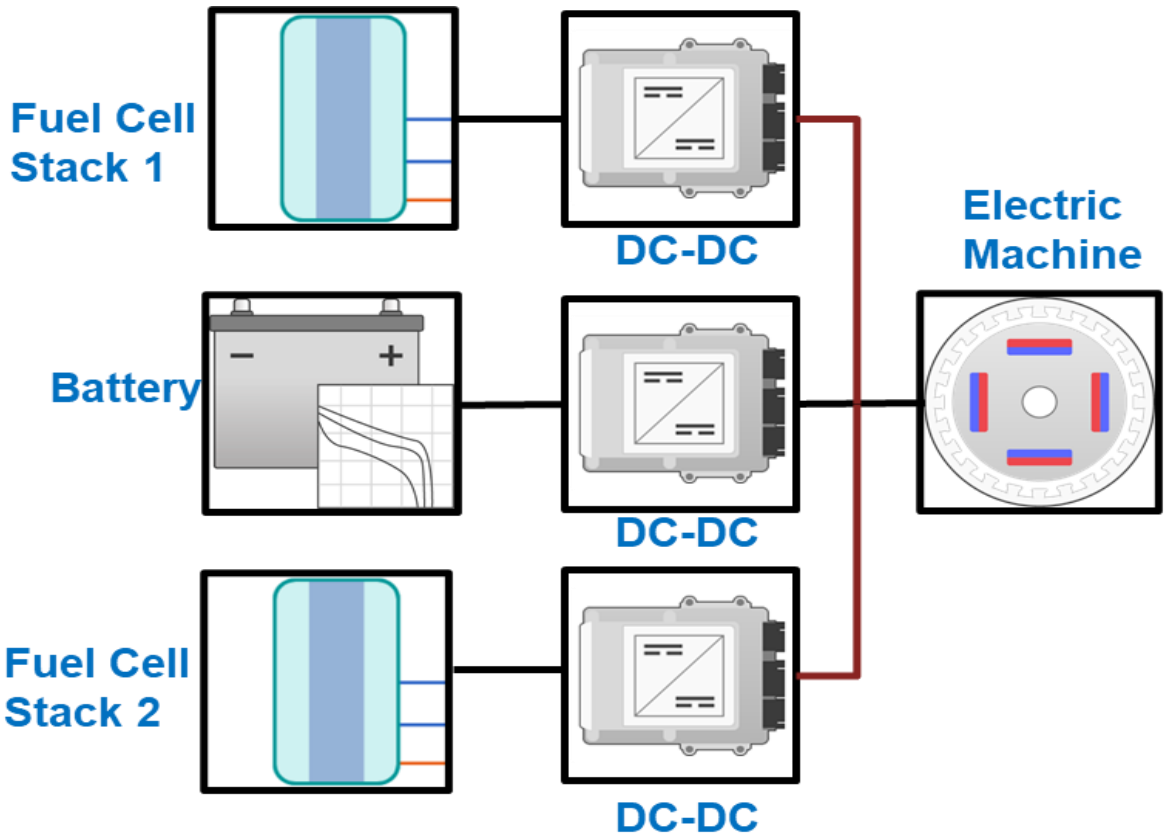




- Optimized control shows improved performance
  - 30% improved over stack 1 only
  - 17% improved over stack 2 only

- Power sharing is as expected
  - Stack 1 supplies more power at low load
  - Stack 2 supplies more power at high load

Stage 3: Confirm Functional Response



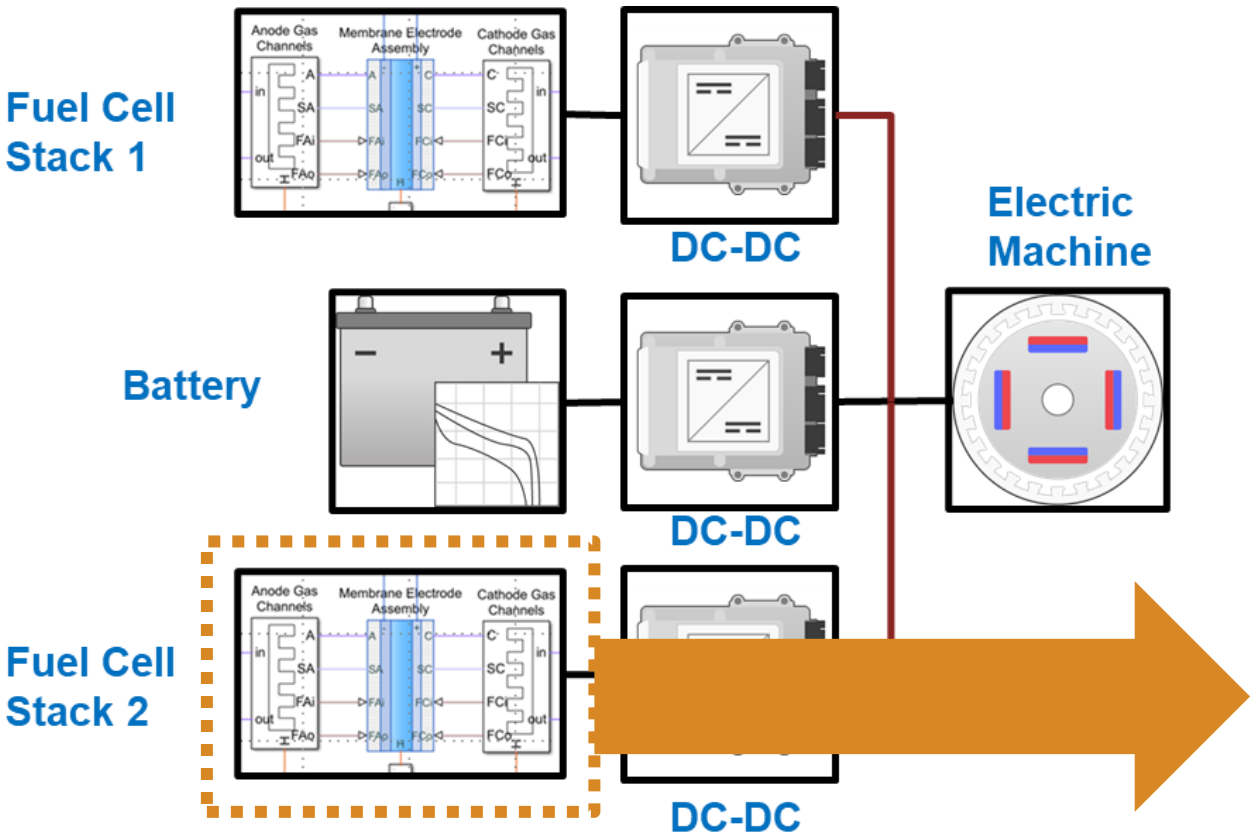
What are we doing at this stage?

- Add in more detailed physics to electrical system

Why do this?

- Confirm functional response of electrical system

Stage 3: Confirm Functional Response

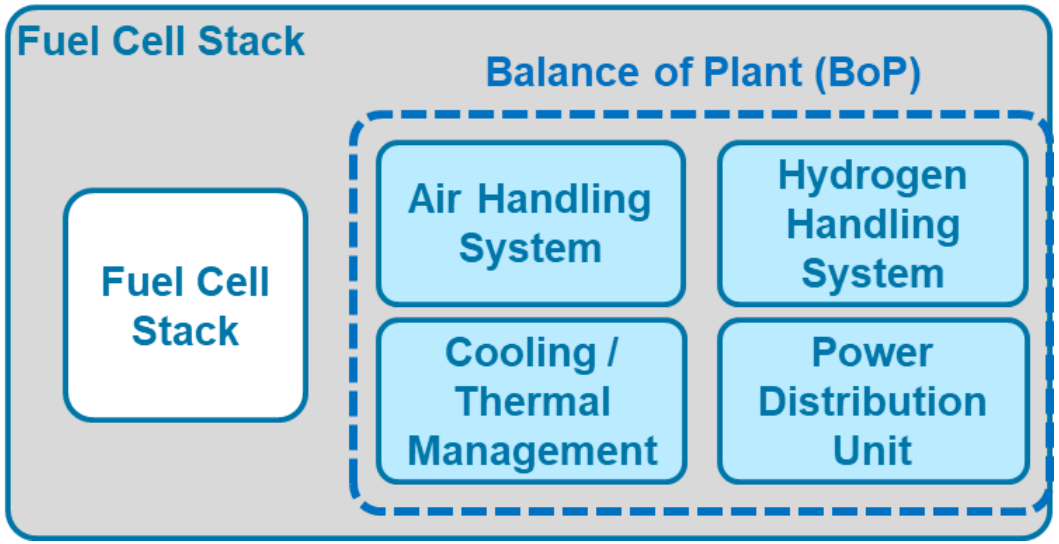


What are we doing at this stage?

- Add in more detailed physics to electrical system

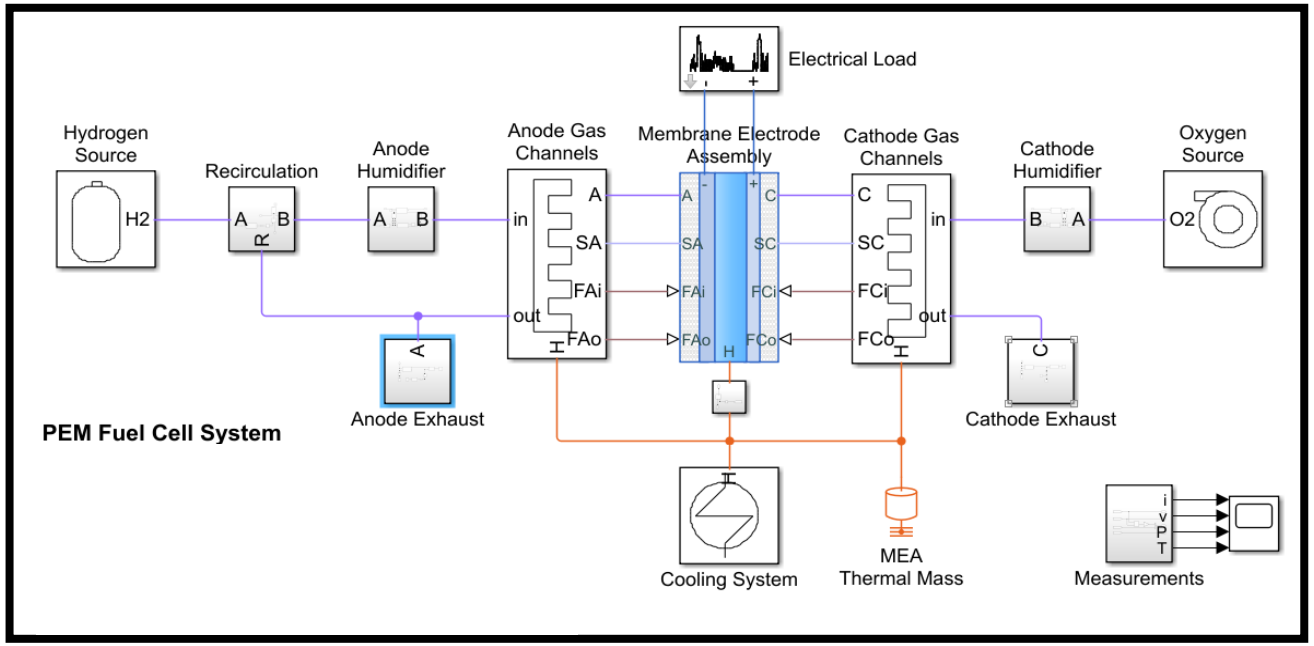
Why do this?

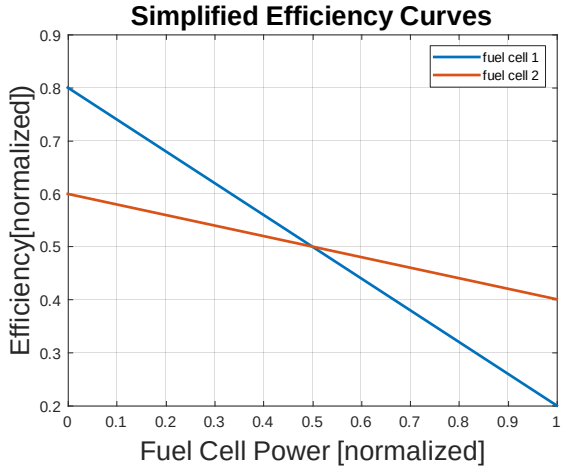
- Confirm functional response of electrical system

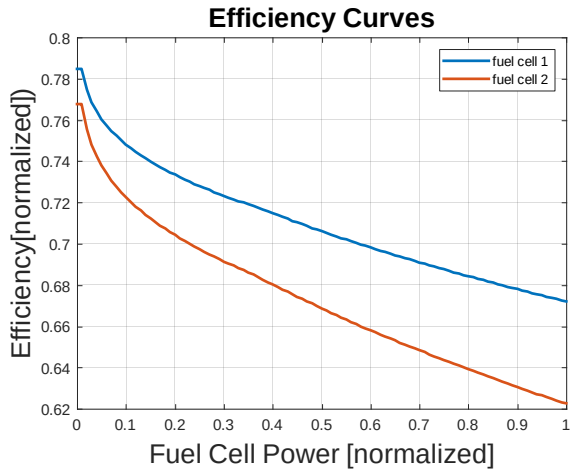


Stage 3: Confirm Functional Response

- Fuel Cell Stacks
  - Implemented in Simscape language
  - Multiple species tracking
- Balance of Plant
  - Compressor
  - Humidifier
  - Cooling system
  - H2 recirculation
  - Water management

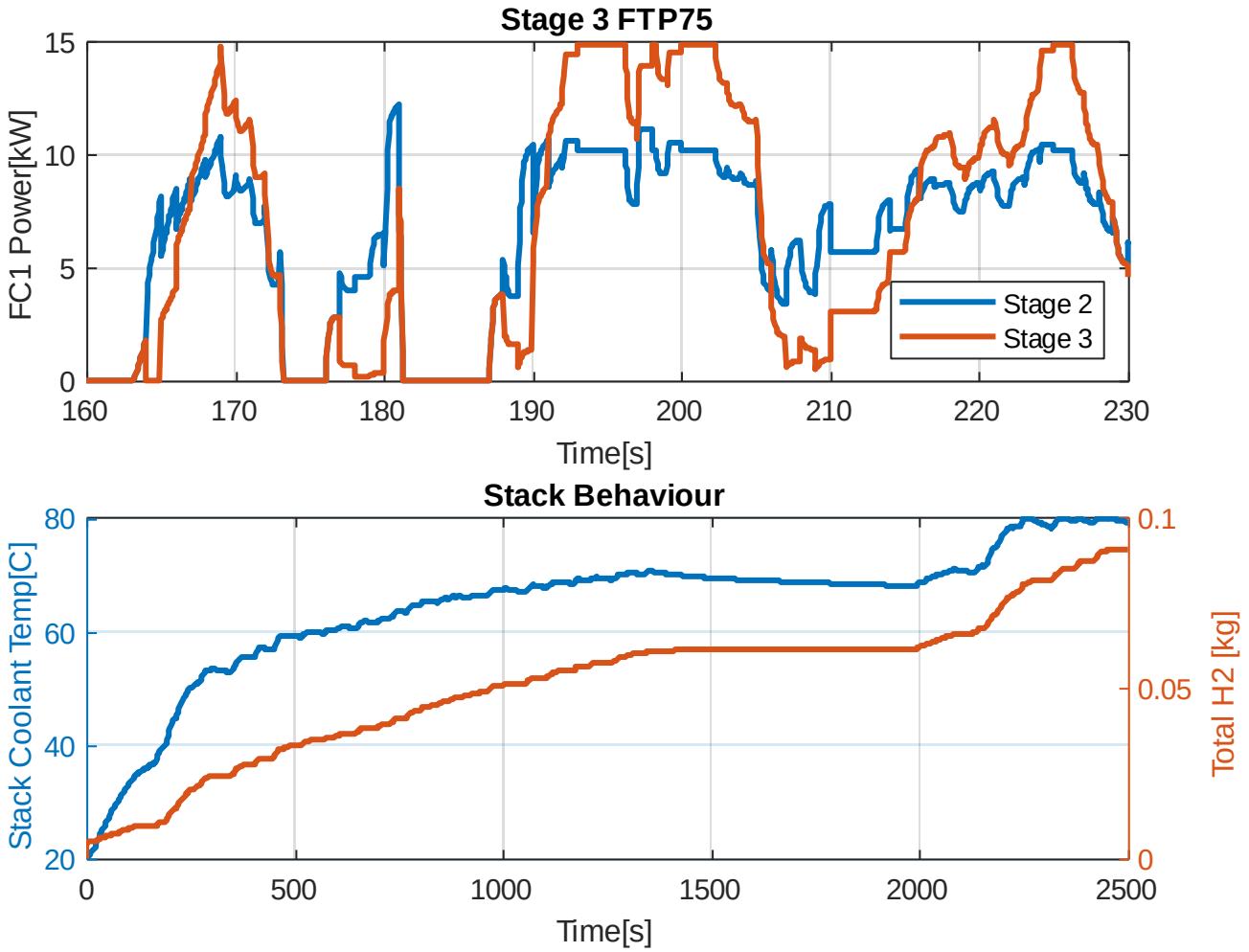




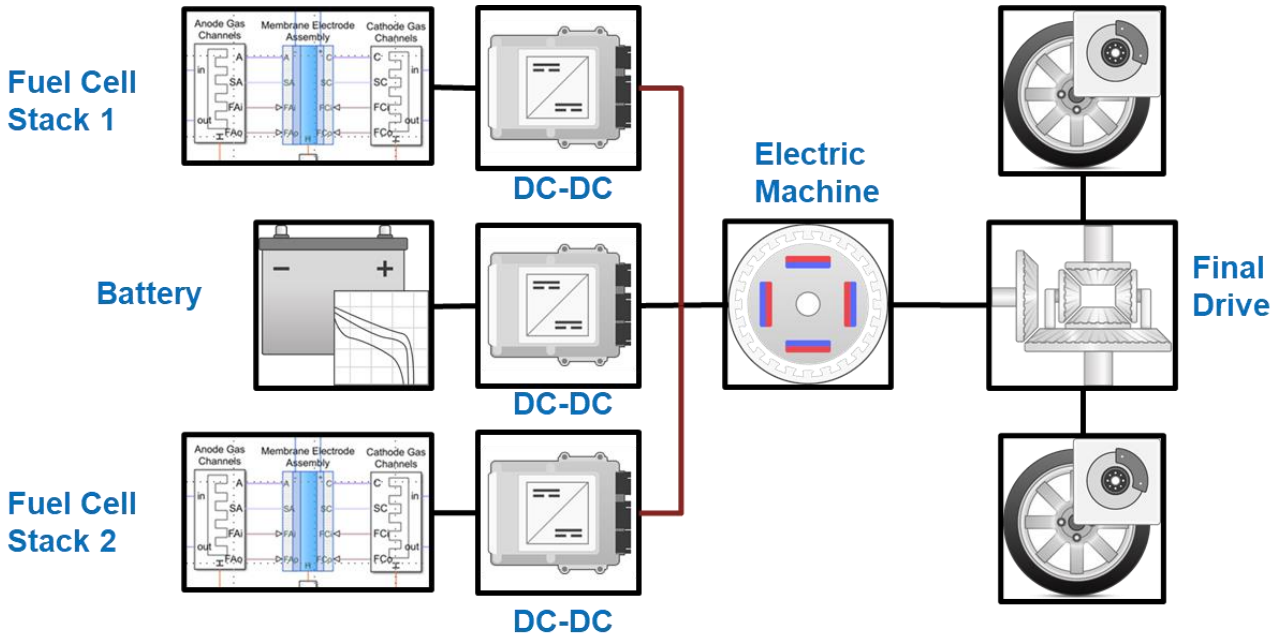


Stage 3: Confirm Functional Response

- Some difference between stage 2 and stage 3 controlled behavior
  - Expected as now we are modeling more detailed physics
- Can begin to look more detailed response
  - Stack coolant temperature
  - Total Hydrogen usage
  - Etc.



Stage 4: System Level Simulation



What are we doing at this stage?

- Implement the electrical system into a full powertrain model

Why do this?

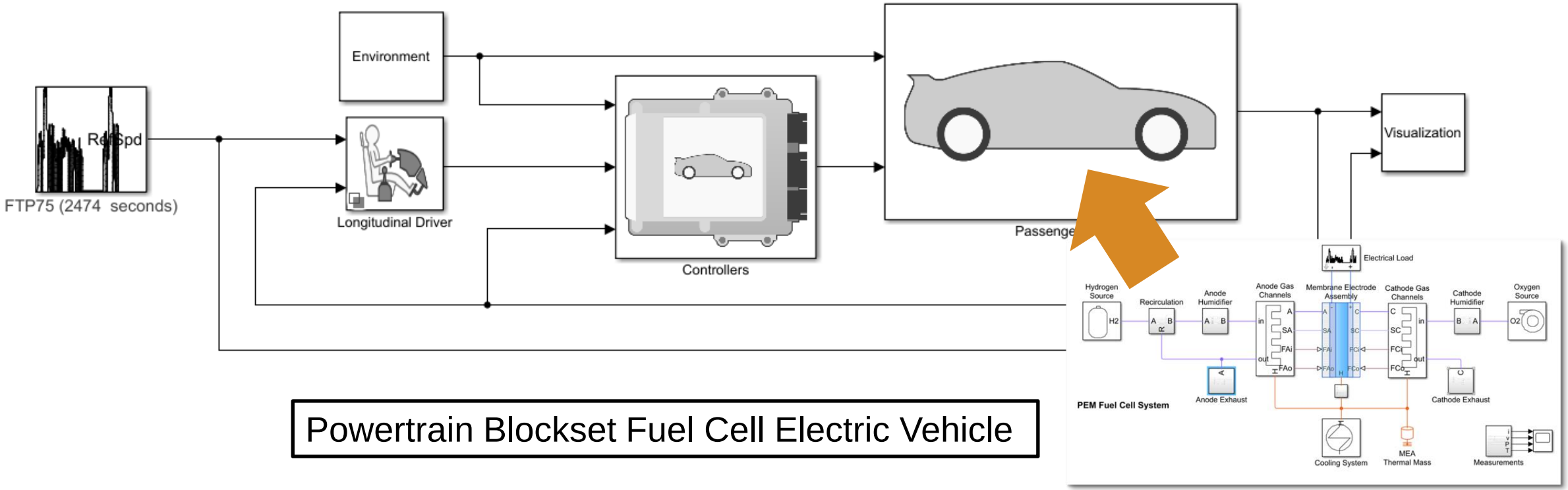
- Confirm system level response for untested drive cycles
- Look at system level metrics such as MPGe, acceleration performance, etc
- Confirm power sharing control behavior when interfacing with other control systems

Stage 4: System Level Simulation

model fuel cells, electrified powertrain and virtual vehicle

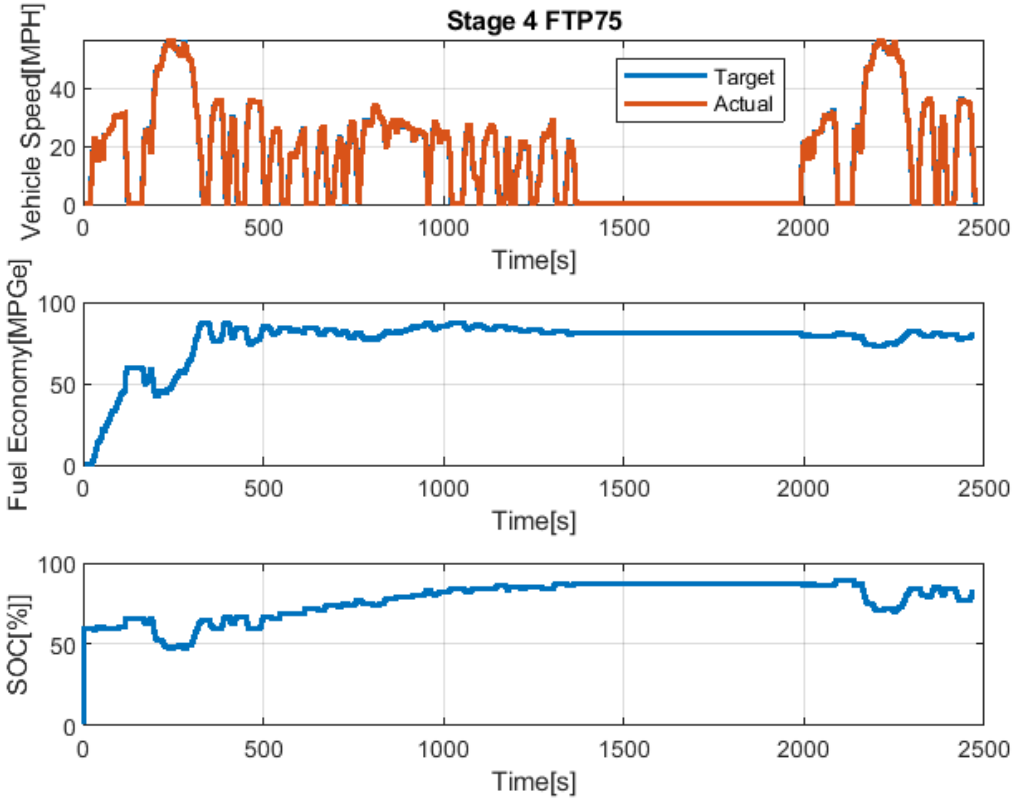
integrate fuel cell in virtual vehicle models

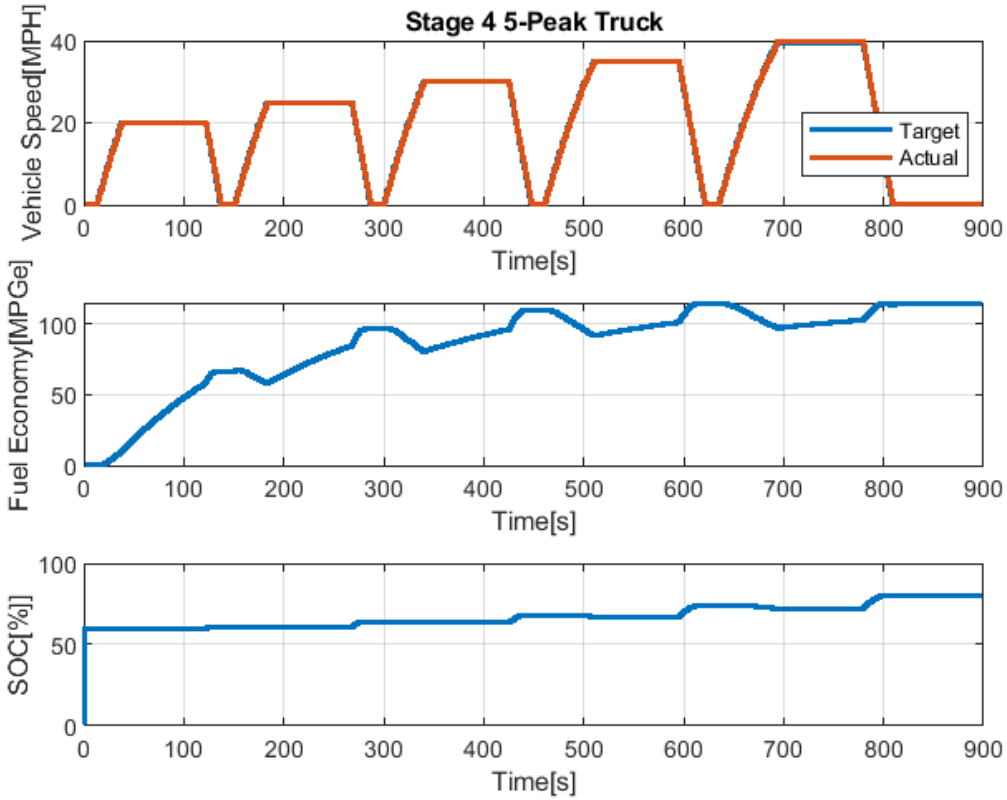
calibrate and **analyze** fuel cell virtual vehicles



Powertrain Blockset Fuel Cell Electric Vehicle

Stage 4: System Level Simulation

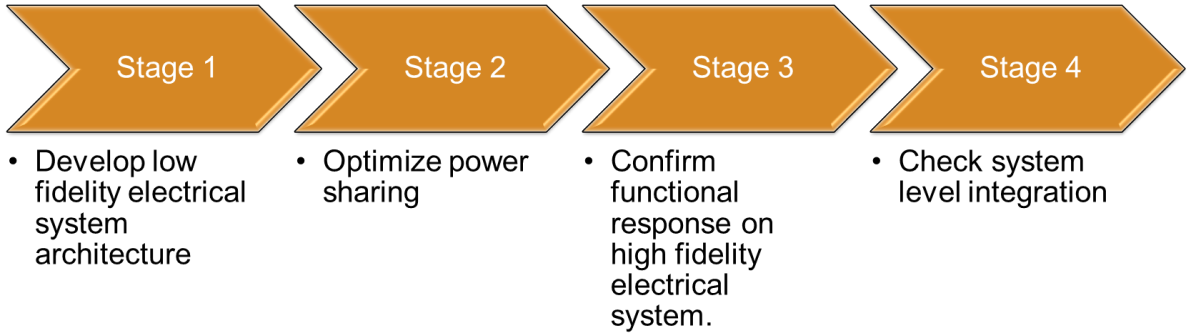


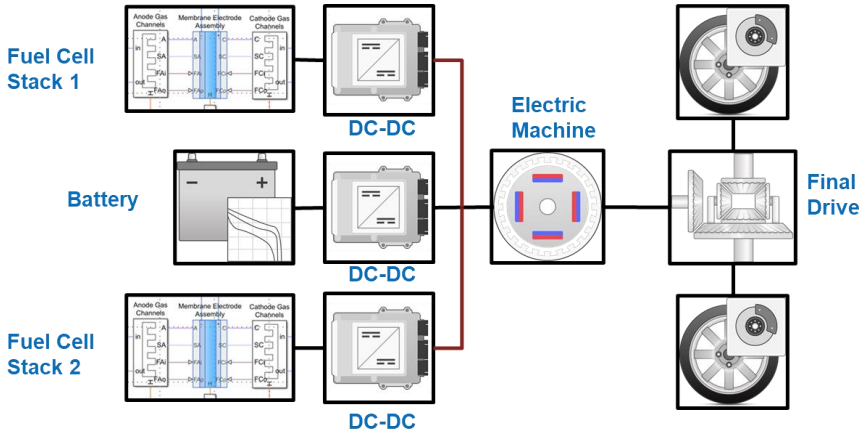


- System level simulation confirms controller performance
- Load control could use some fine tuning to balance SOC

Conclusion

- Multi-Stack fuel cell **virtual vehicle** models enabled by MathWorks tools
  - Realistic environment and testing scenarios
  - Analysis, control design and optimization of components and full vehicle simulation
- Methodology and workflows for modeling **subsystem** level fuel cell systems
  - Build out fidelity and complexity incrementally
  - Focus on specific design tasks and minimize the time taken to perform design iterations.
  - Utilize first-principles and data-driven/statistical approaches for appropriate tasks





MathWorks
AUTOMOTIVE CONFERENCE 2022
North America

Thank you

© 2022 The MathWorks, Inc. MATLAB and Simulink are registered trademarks of The MathWorks, Inc. See *mathworks.com/trademarks* for a list of additional trademarks. Other product or brand names may be trademarks or registered trademarks of their respective holders.