Hybrid Powertrain Optimization for Plug-In Microgrid Power Generation

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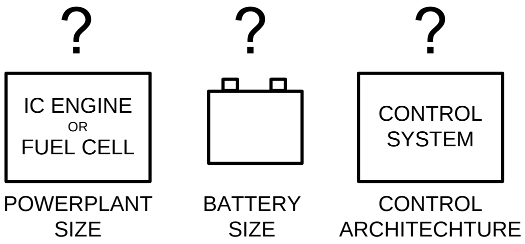
Introduction & Motivation

Vision – Vehicle to Grid (V2G)

Use plug-in hybrid electric vehicles (PHEV) to provide ancillary services to autonomous electric microgrid systems (e.g. hospital backup power, military bases)

Obstacles

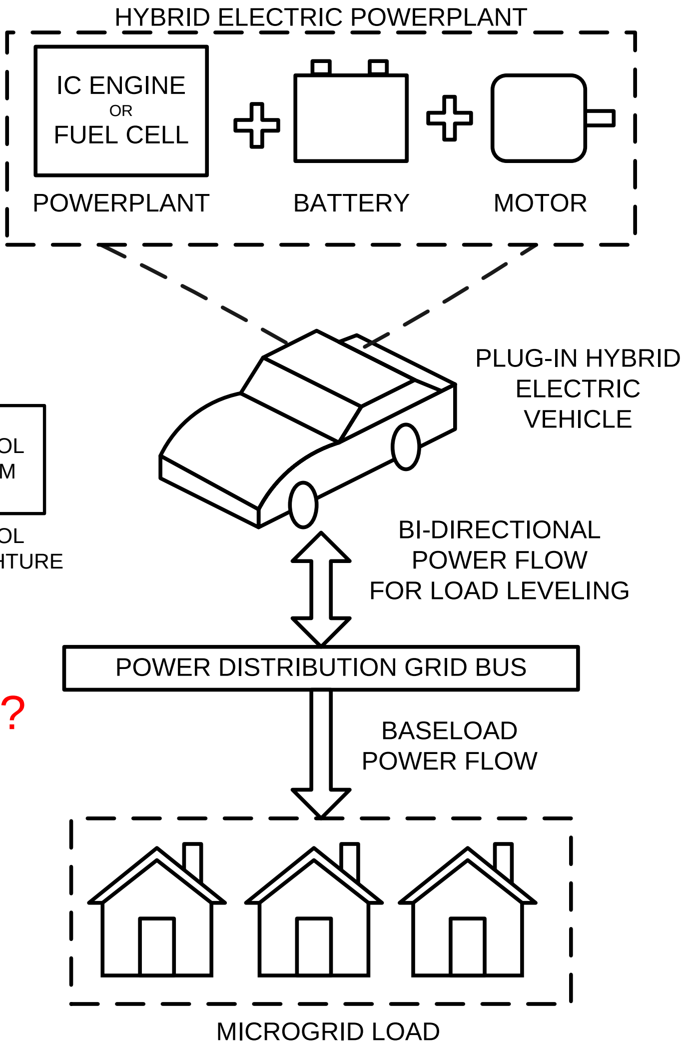
Current PHEVs do not capitalize on V2G technology



1. What is the optimal design and control?
2. Does an optimal system provide significant benefits?

Proposed Solution

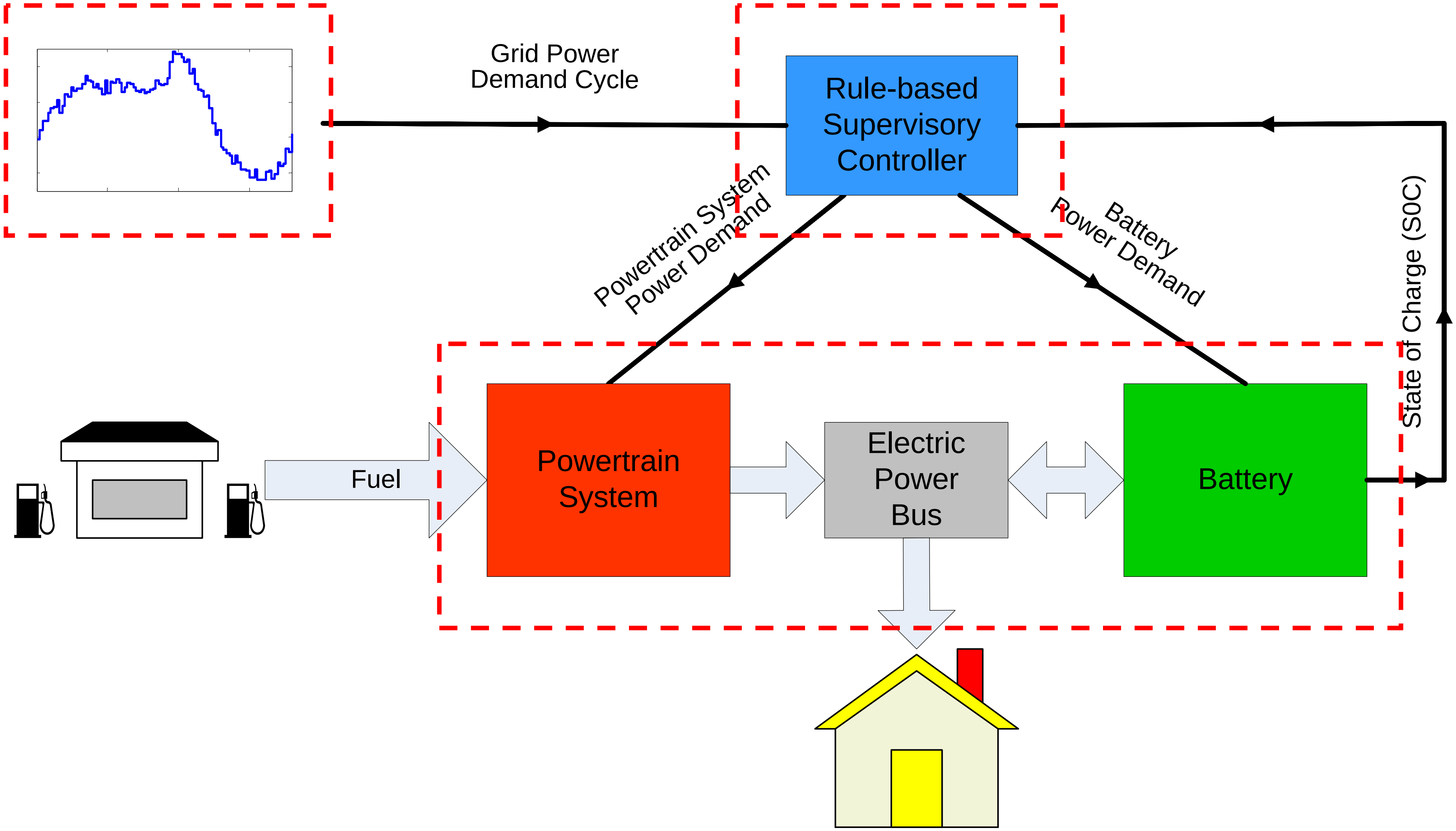
Develop an optimization approach for the design and control of a PHEV powertrain for microgrid power generation to minimize fuel consumption



Outline

- Introduction & Motivation
- Powertrain System Modeling
- Optimization Study
- Constraint Tightening
- Discussion of Results
- Conclusions

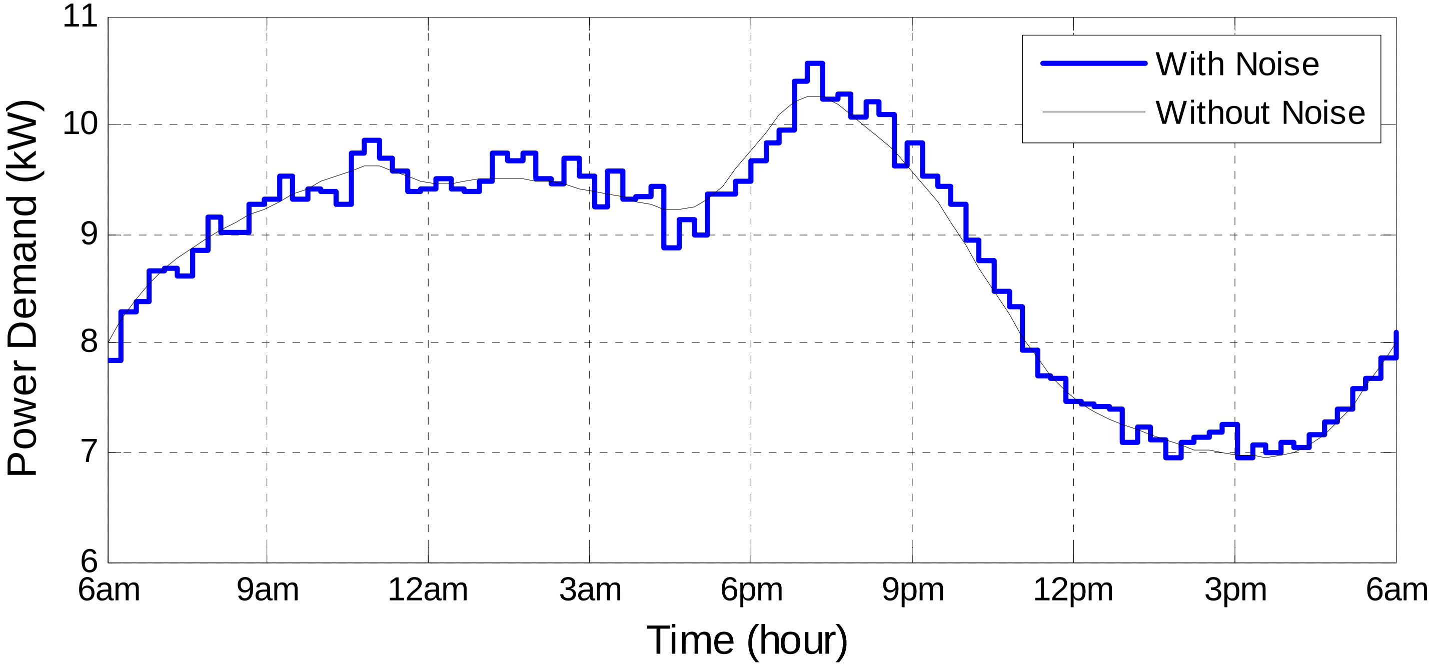
System Level Block Diagram



Grid Power Demand Cycle Modeling

Representative grid power demand cycle

- Adapted from CAISO daily demand forecast data [1]
- Applied cubic spline curve fit
- Augmented with white Gaussian noise – models stochastic behavior
- Scaled for medium size office or apartment complex

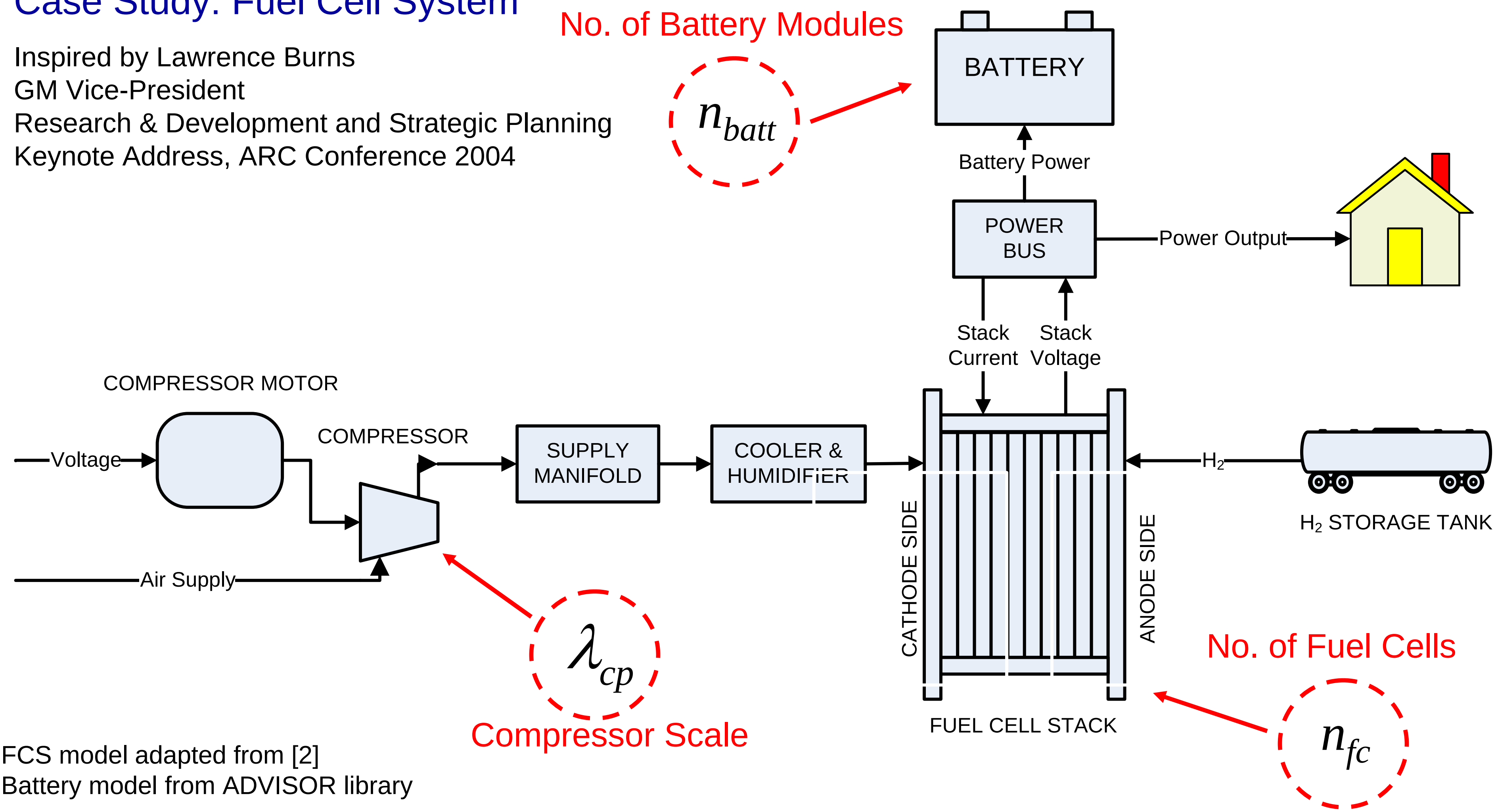


[1] California ISO: System Status. http://www.caiso.com/outlook/outlook.html

Powertrain System Model

Case Study: Fuel Cell System

Inspired by Lawrence Burns
GM Vice-President
Research & Development and Strategic Planning
Keynote Address, ARC Conference 2004

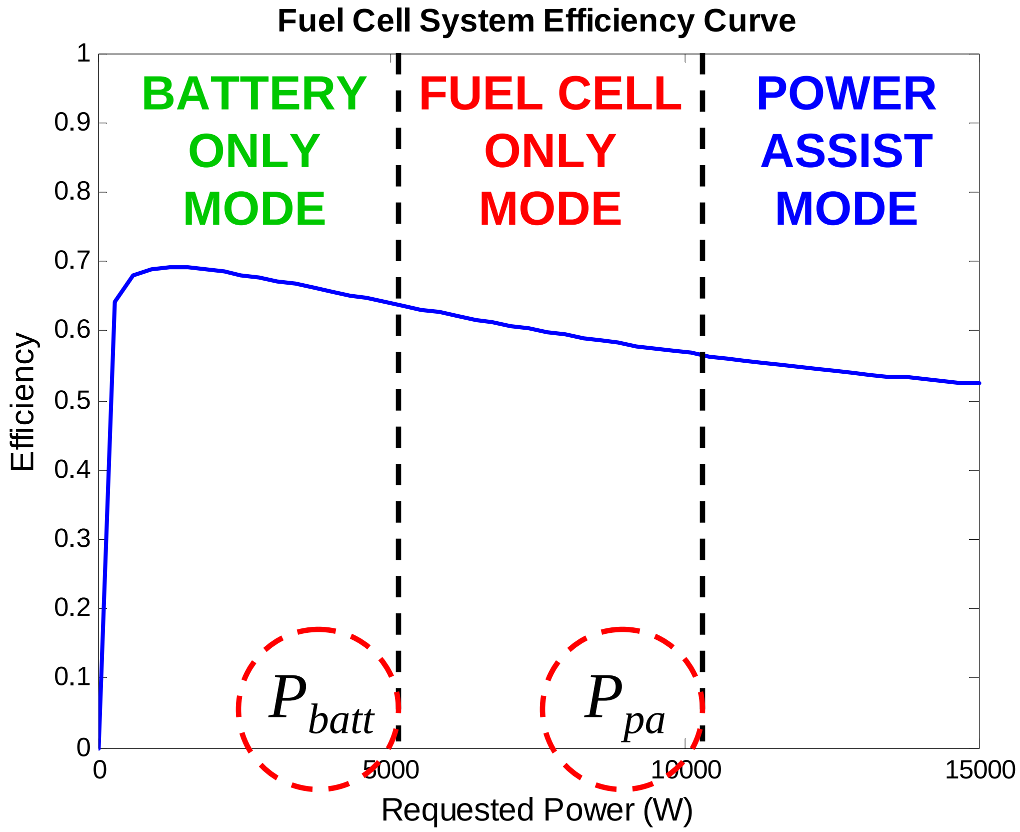


FCS model adapted from [2]
Battery model from ADVISOR library

[2] J. T. Pukrushpan, A. G. Stefanopoulou and H. Peng, *Control of Fuel Cell Power Systems: Principles, Modeling, Analysis and Feedback Design.* , vol. XVII, Springer, 2004, pp. 161.

Rule-Based Supervisory Controller

Concept: Use battery to minimize fuel cell operation, yet ensure desirable efficiency



BATTERY ONLY MODE

$$P_{fc} = 0$$

$$P_{batt} = P_{dem}$$

FUEL CELL ONLY MODE

$$P_{fc} = P_{dem} + P_{charge}$$

$$P_{batt} = -P_{charge}$$

POWER ASSIST MODE

$$P_{fc} = P_{pa\_mode}$$

$$P_{batt} = P_{dem} - P_{pa\_mode}$$

where $P_{charge} = K_{ch}\left(SOC - SOC_{des}\right)$

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Optimization Problem Formulation

Minimize hydrogen fuel consumption

$$\min\ f(\mathbf{x}) = m_{H_2}\left(n_{fc}, n_{fc}, \lambda_{cp}, P_{pa}, P_{batt}, K_{ch}\right)$$

with respect to

6 Design Variables

- Number of fuel cells in stack, n_{fc}
- Number of battery modules, n_{batt}
- Compressor size, λ_{cp}

Component Sizes

- Power Assist (PA) mode threshold, P_{pa}
- Battery mode threshold, P_{batt}
- Controller Gain, K_{ch}

Control Parameters

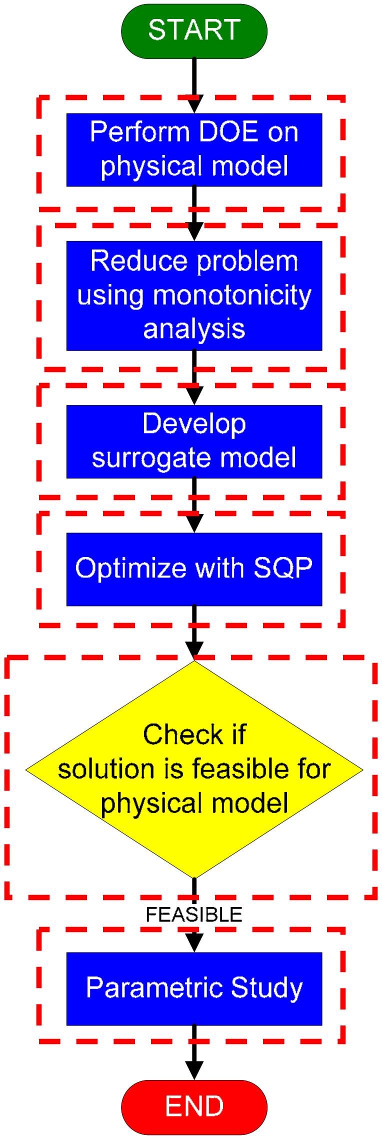
subject to

10 Constraints

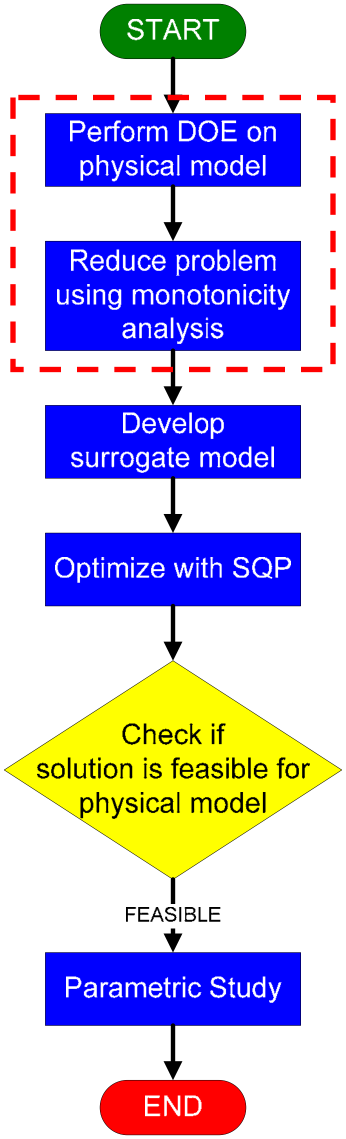
- Fuel cell stack length
- eight
- Stack heat generation
- Parasitic losses
- Fuel cell efficiency
- excess ratio
- SOC
- Start/End SOC deviation

Optimization Algorithm

1. Run multiple experiments to collect data on physical model
2. Perform monotonicity analysis to determine trends, optima, and reduce the problem
3. Use data to develop a surrogate model (e.g. LSM, ANN, Kriging)
4. Optimize with Sequential Quadratic Programming (SQP)
5. Cross-check solution feasibility with physical model
6. Analyze tradeoff between battery cost and fuel consumption by performing a parametric study



Optimization Algorithm



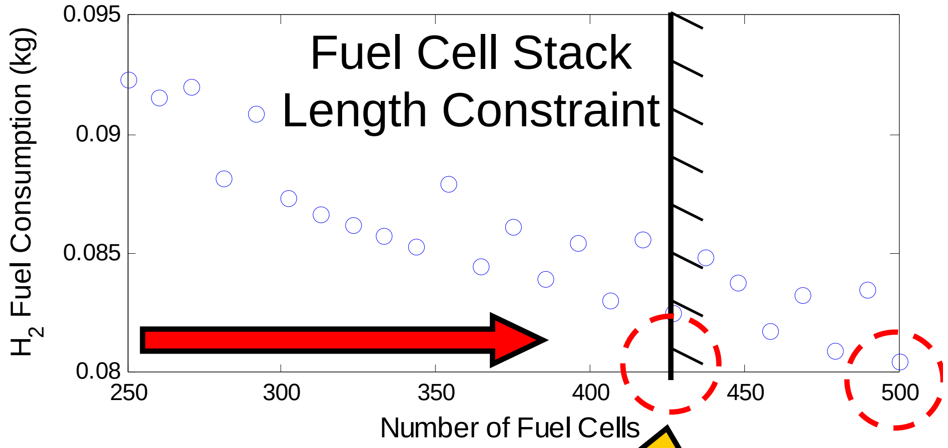
Steps1 & 2: DOE & Monotonicity Analysis

Model Reduction

Number of Fuel Cells

n_{fc}^{*} = 422 fuel cells

Problem reduces to 5 design variables



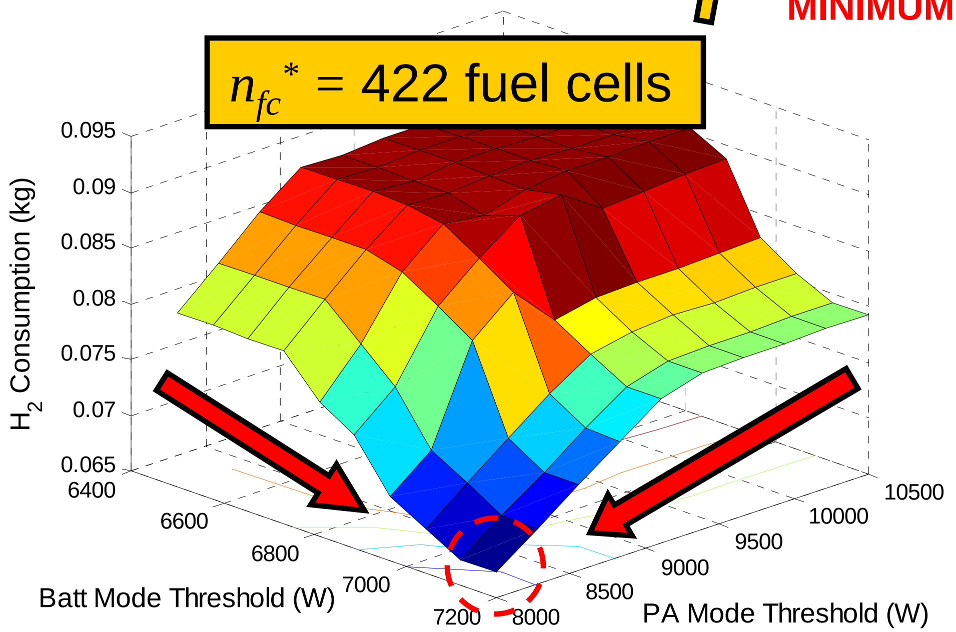
MINIMUM

Identifying Trends

Power Threshold Values

Several constraints may bound P_{pa} and P_{batt}

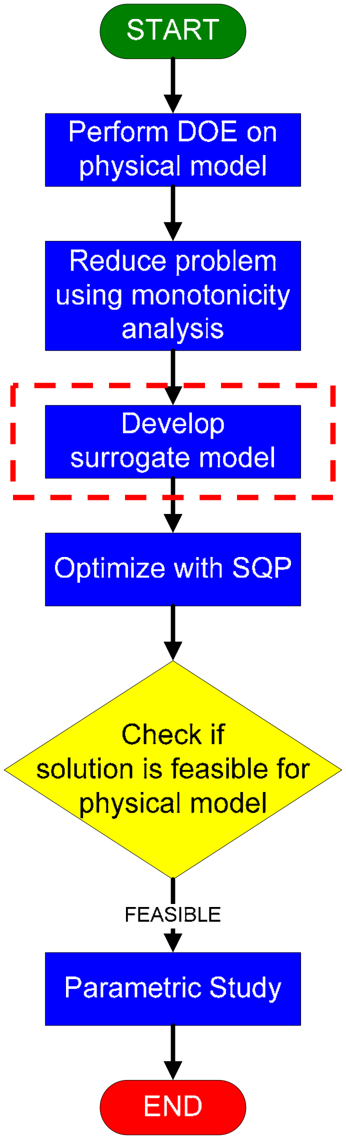
At least two constraints must be active



n_{fc}^{*} = 422 fuel cells

MINIMUM

Optimization Algorithm



START

Perform DOE on physical model

Reduce problem using monotonicity analysis

Develop surrogate model

Optimize with SQP

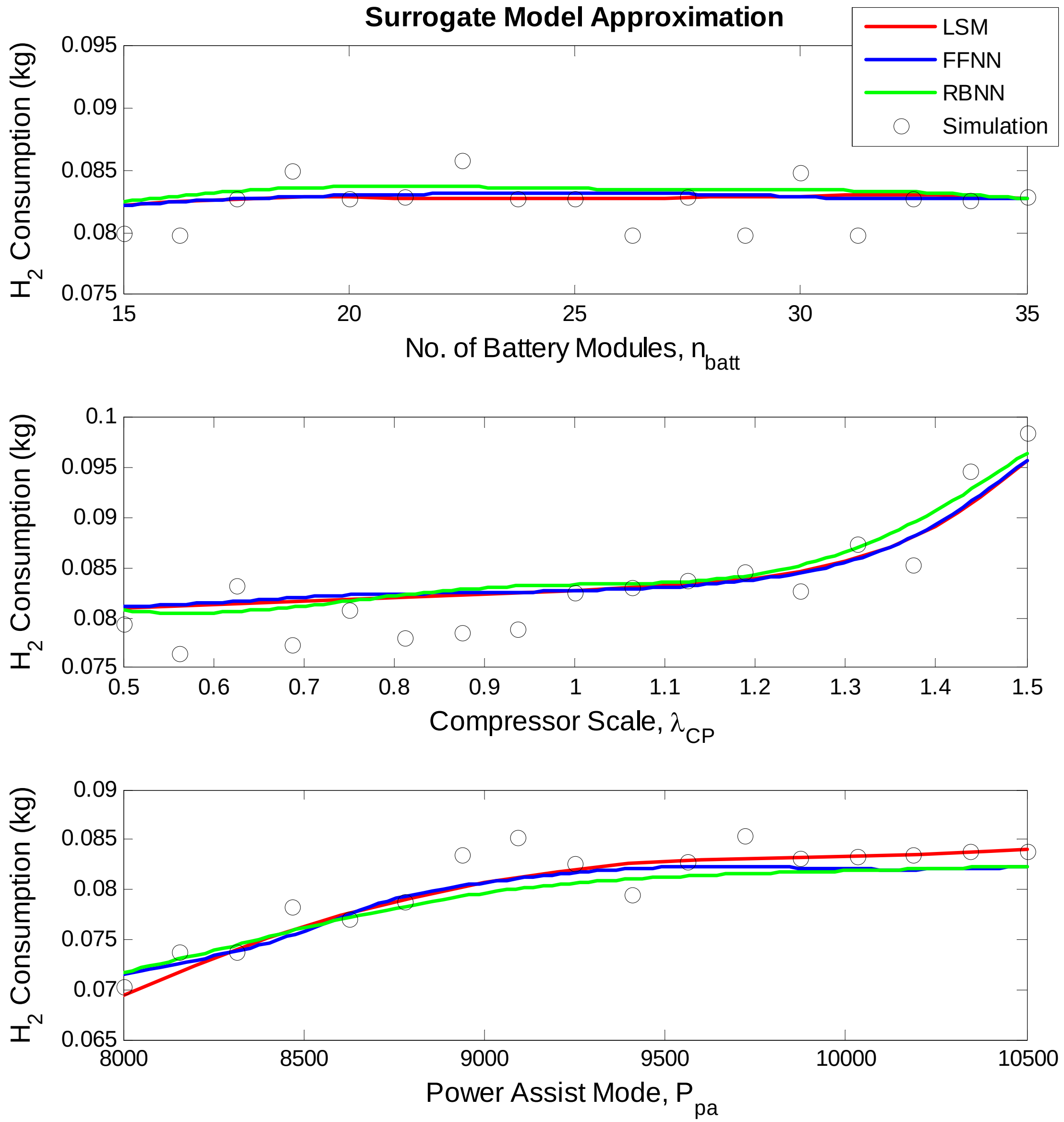
Check if solution is feasible for physical model

FEASIBLE

Parametric Study

END

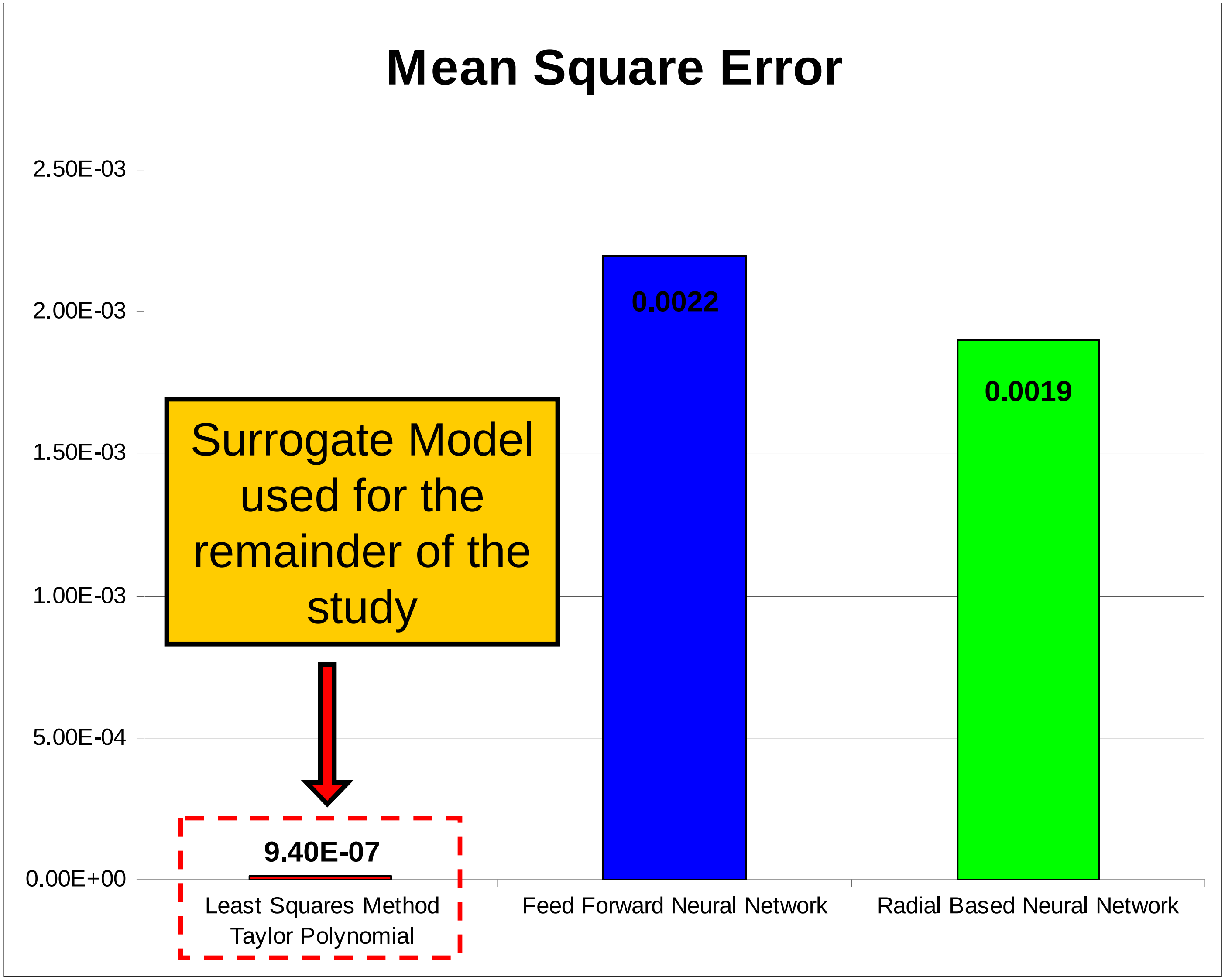
Surrogate Modeling Methods



- Least Squares Method – 4th order Taylor Polynomial
- Feedforward ANN
- Radial Based ANN

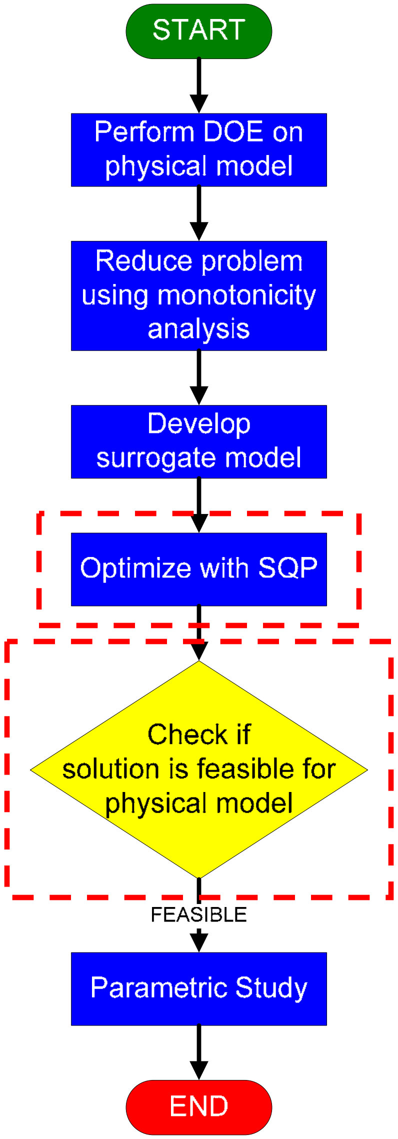
Which surrogate model is best?

Step 3: Surrogate Model Evaluation



Surrogate Model used for the remainder of the study

Optimization Algorithm



Step 4: Feasibility Analysis

Determine if the surrogate model solution is feasible for the actual simulation

Constraints	**Surrogate**
Battery Weight	🟩 **56 lbs**
Stack Heat Generation	🟩 **6094 W**
Parasitic Losses	🟩 **2.69 %**
Fuel Cell Efficiency	🟩 **57.7 %**
Oxygen Excess Ratio	🟨 **3.00**
Max SOC	🟩 **0.7**
Min SOC	🟩 **0.666**
Max SOC Deviation	🟨 **0.01**

🟩 FEASIBLE 🟨 ACTIVE CONSTRAINT 🟥 INFEASIBLE

Recall that 2 constraints need to be active to properly bound P_{pa} and P_{batt}

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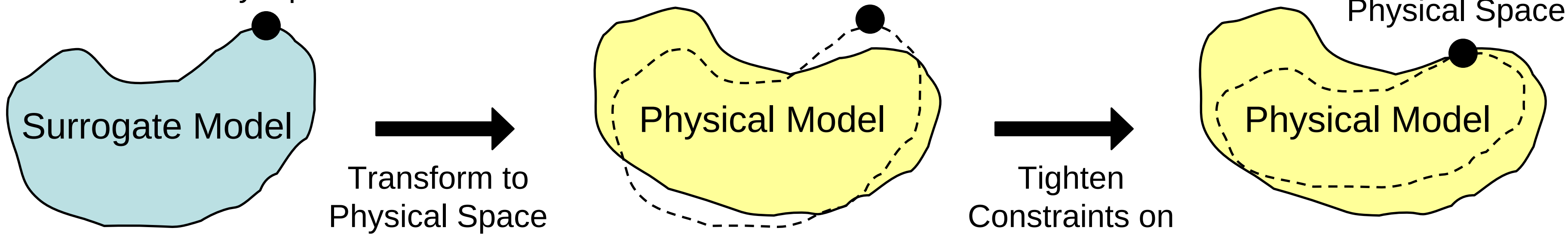
Constraint Tightening

Proposed Solution: Make violated constraints more aggressive for the surrogate model to compensate for modeling error

Case 1: Oxygen Excess Ratio



Boundary Optimum

Surrogate Model

Transform to Physical Space

Infeasible in Physical Space

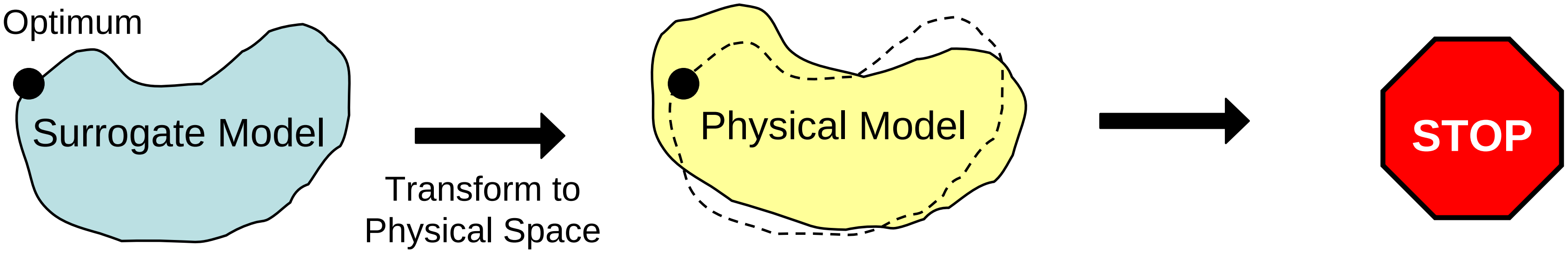
Physical Model

Tighten Constraints on Surrogate Model

Feasible in Physical Space

Physical Model

Case 2: Max SOC Deviation



Boundary Optimum

Surrogate Model

Transform to Physical Space

Feasible in Physical Space

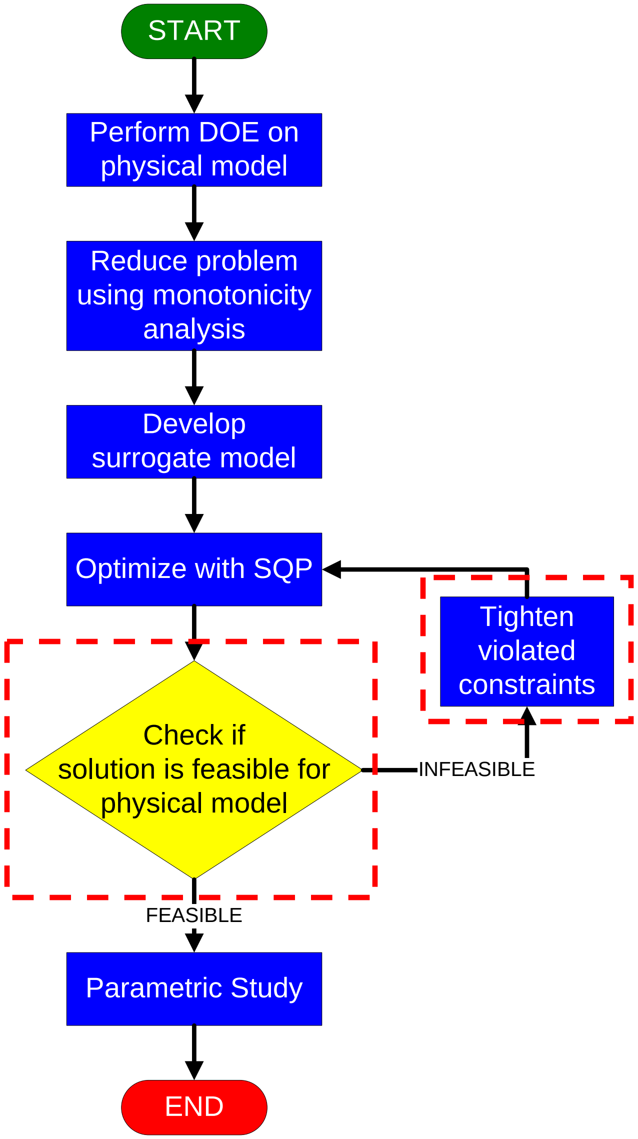
Physical Model

STOP

[4] A. Parkinson, "Robust mechanical design using engineering models," *Journal of Mechanical Design,* vol. 117B, pp. 48-54, 1995.

Optimization Algorithm with Constraint Tension

1. Run multiple experiments to collect data on physical model
2. Perform monotonicity analysis to determine trends, optima, and reduce the problem
3. Use data to develop a surrogate model (e.g. LSM, ANN, Kriging)
4. Optimize with Sequential Quadratic Programming (SQP)
5. Cross-check solution feasibility with physical model
6. If solution is not feasible, tighten the violated constraints and go to Step 4
7. Analyze tradeoff between battery cost and fuel consumption by performing a parametric study


START

Perform DOE on physical model

Reduce problem using monotonicity analysis

Develop surrogate model

Optimize with SQP

Check if solution is feasible for physical model

INFEASIBLE

Tighten violated constraints

FEASIBLE

Parametric Study

END

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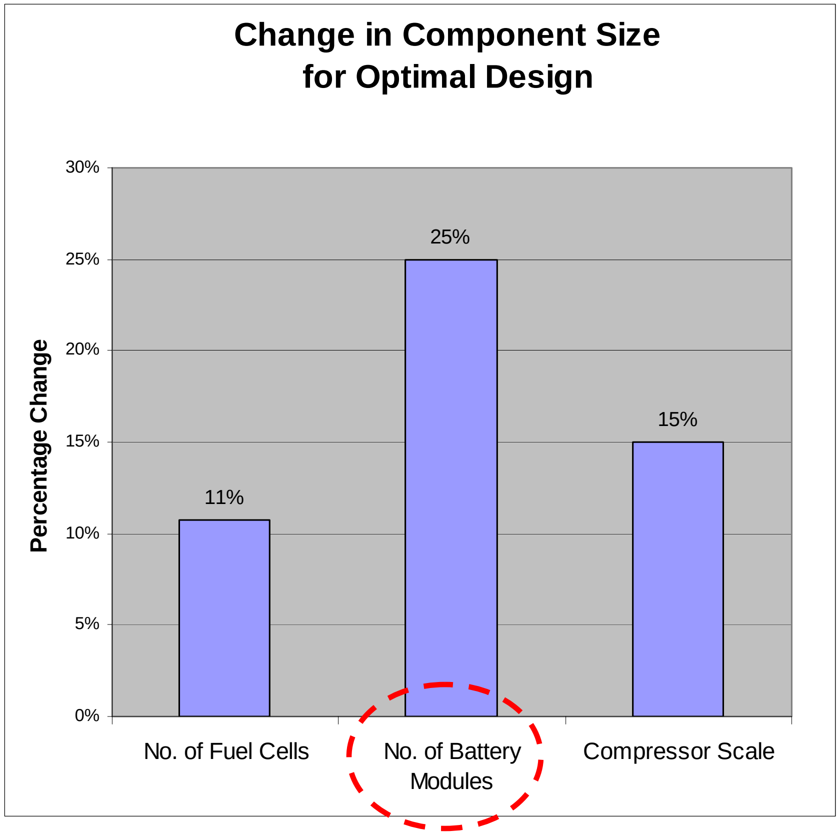
Nominal vs. Optimal Designs

55% decrease in fuel consumption per month



- Combined design/control optimization significantly increases fuel efficiency
- All components increase in size
- Number of fuel cells is constrained only by total stack length
- Battery size increases the most

Parametric Study on Battery Size

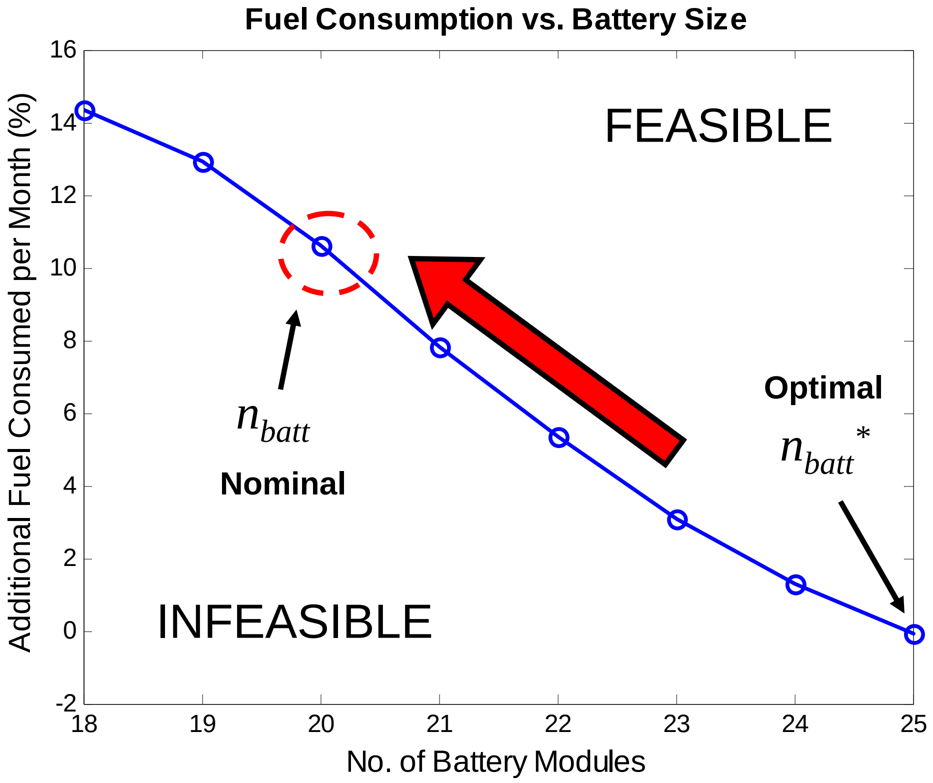
What is the optimal solution that also minimizes battery size?

Formulate Multi-objective Optimization Problem

- Parameterize the number of battery modules

Observations

- Decreasing battery size sacrifices fuel economy
- 20% reduction in battery size
  11% increase in fuel consumption
- Tradeoff between battery cost and fuel consumption



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Conclusions

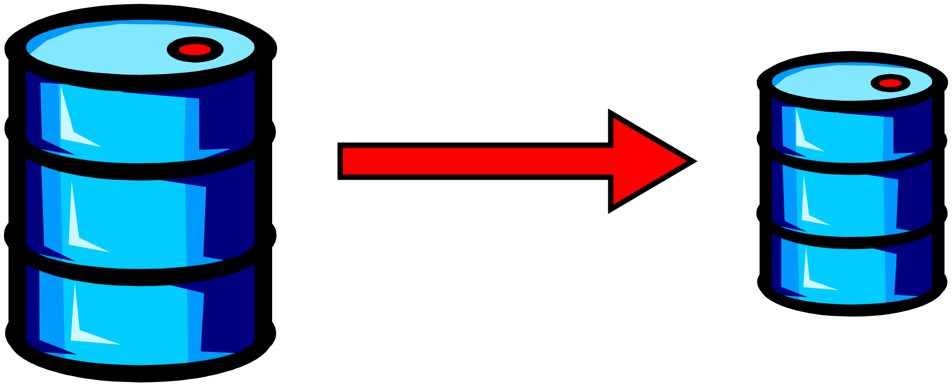
What is the optimal control & design?

- Increase component sizes
- Maximize battery participation

Note: component costs are not considered

Does an optimal system provide significant benefits?

- 55% decrease in fuel consumption per month



Summary & Future Work

Summary

- Developed combined design/control optimization algorithm for PHEV powertrain supplying microgrid power generation
- Applied constraint tightening concept to ensure solution feasibility
- Analyzed tradeoff between fuel consumption and battery cost

Future Work

- Include component cost metrics
- Integrate optimal control algorithm to replace rule-based construction
- Generalize case study for any powertrain type and load demand

Acknowledgements & References

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- Jeongwoo Han
- Panos Y. Papalambros
- Huei Peng
- Michael Kokkolaras
- James Allison

Key References

[1] S. J. Moura, D. Kum. “Plant/Control Optimization of a PEM Hybrid Fuel Cell Vehicle to Grid (V2G) System.” Design Optimization (ME 555). http://www-personal.umich.edu/~sjmoura/projects.html Professor Panos Y. Papalambros. University of Michigan, Ann Arbor. April 19, 2007.

[2] A. Parkinson, "Robust mechanical design using engineering models," *Journal of Mechanical Design,* vol. 117B, pp. 48-54, 1995.

[3] J. Han., Optimal design of hybrid and non-hybrid fuel cell vehicles M.S. Thesis, University of Michigan, Ann Arbor, 2000.

[4] J. T. Pukrushpan, A. G. Stefanopoulou and H. Peng, *Control of Fuel Cell Power Systems: Principles, Modeling, Analysis and Feedback Design.* , vol. XVII, Springer, 2004, pp. 161.

[5] P. Y. Papalambros and D. Wilde. *Principles of Optimal Design*. Cambridge University Press., 2nd edition, 2000.

QUESTIONS?