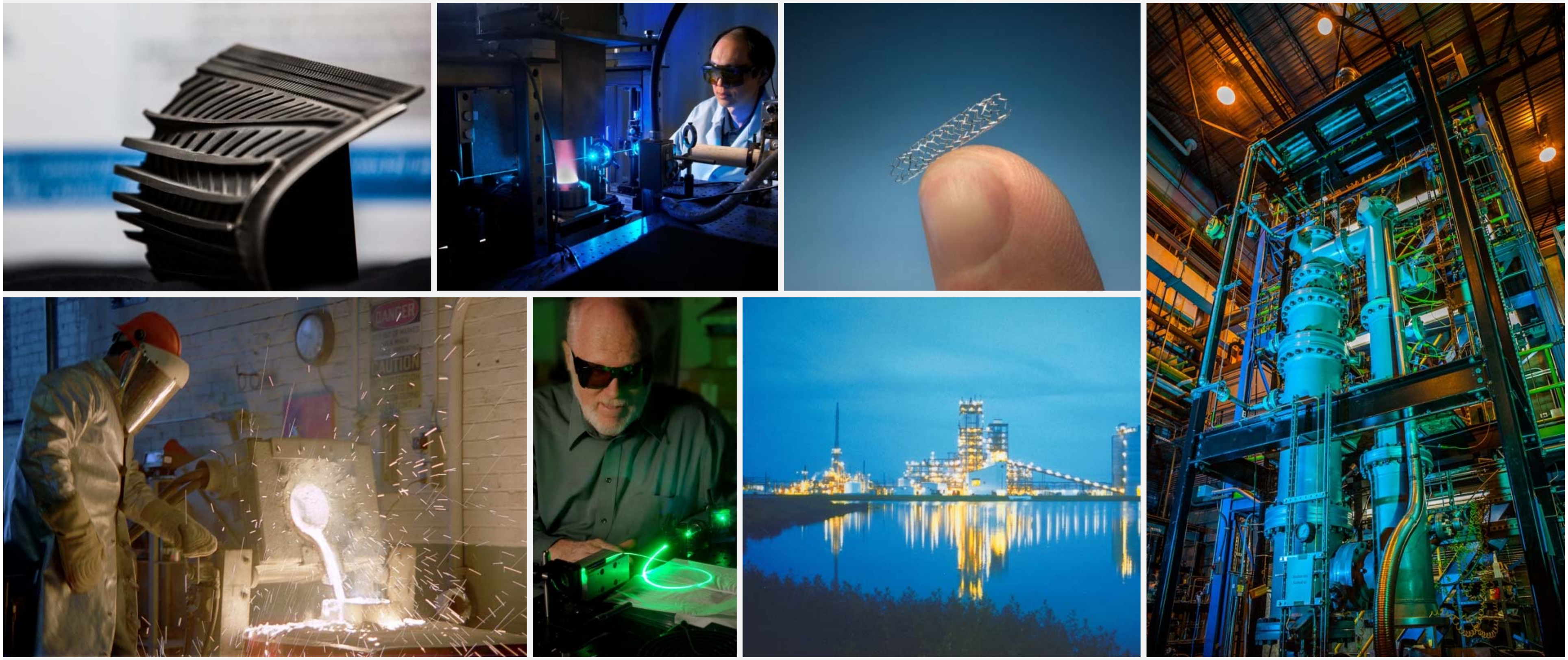
Driving Innovation ♦ Delivering Results



Advanced Controls and Cyber-Physical Systems

Hybrid Performance Project (HYPER)

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2016 Crosscutting Research & Rare Earth Elements Portfolios Review

April 19, 2016

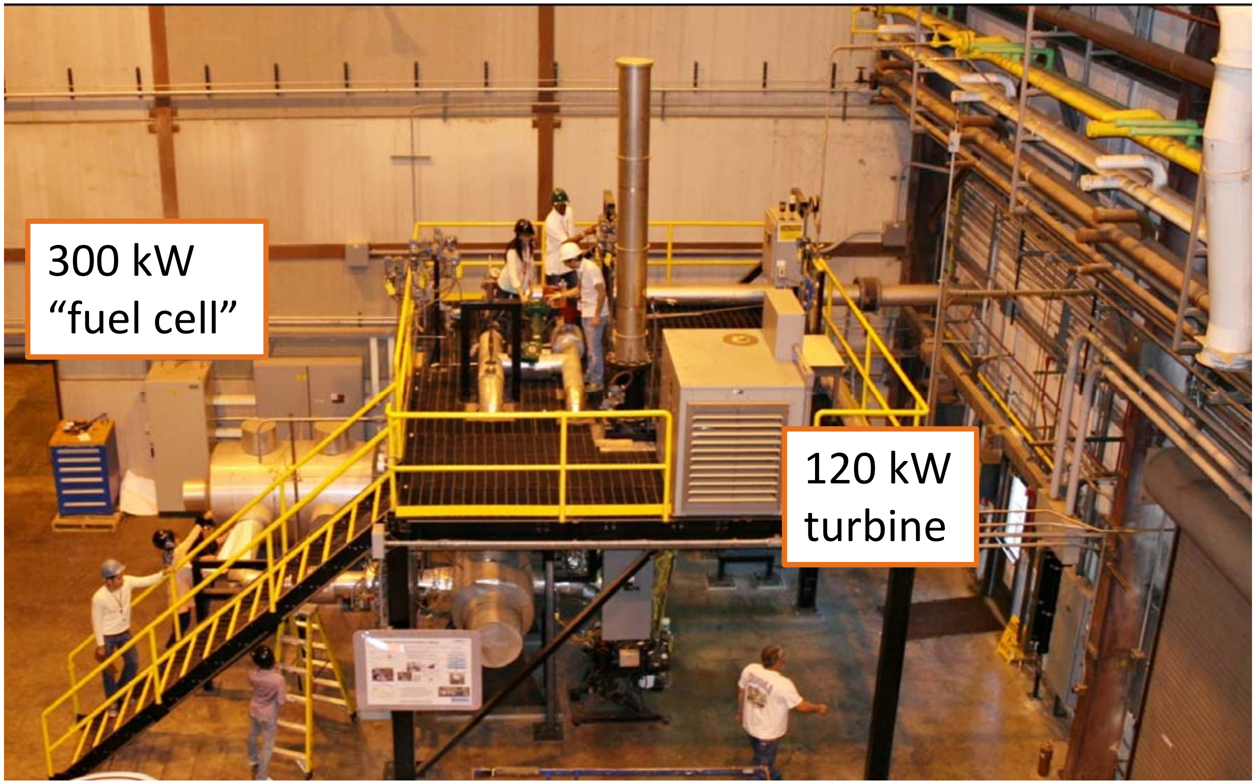
U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

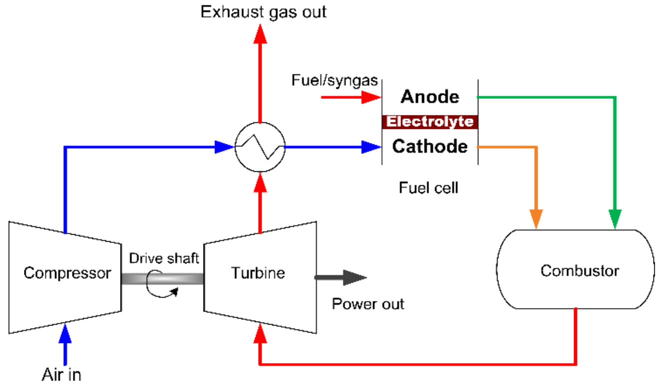
Introduction

1. Hybrid Performance (HYPER)
2. Cyber Physical Systems
3. Advanced Control Research

Hybrid Performance Project: HYPER

- Public Domain Facility
- Model and Process Validation
- DOE Program Support
- Coal Syngas Systems
- Integration Issues
- Quantifying Transient Effects
- Component Impact
- Controls Development
- Operating Envelope



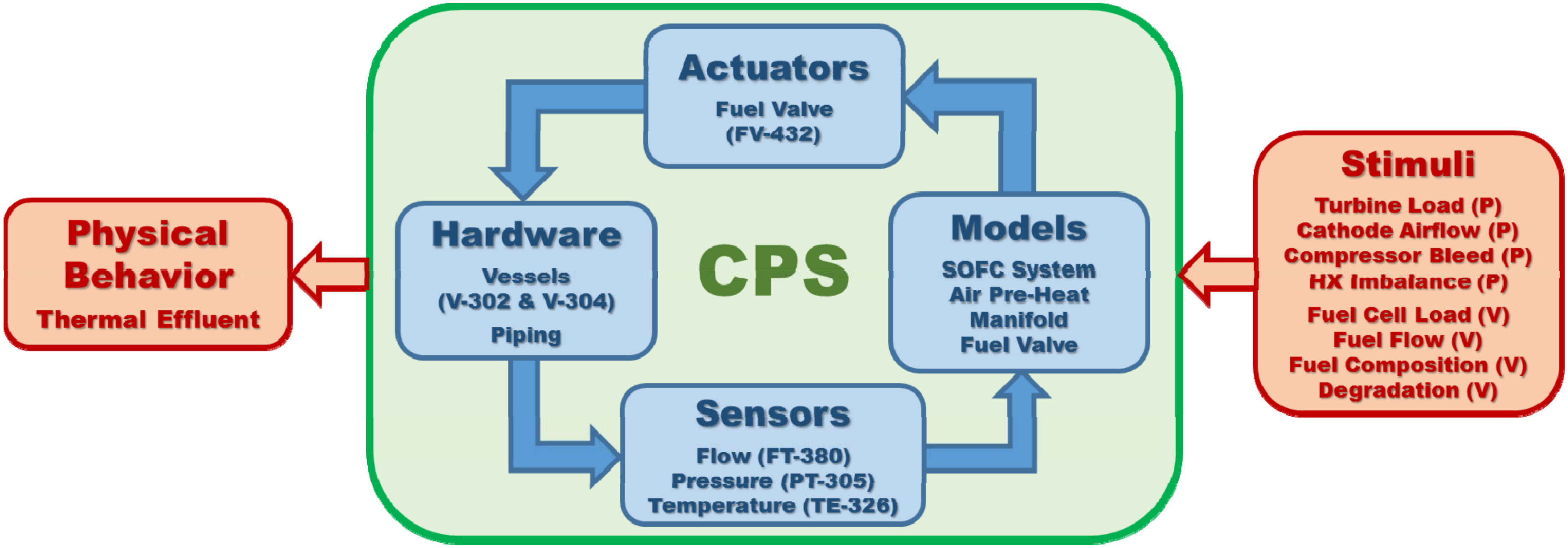


Cyber-physical simulations (hardware in the loop) using 1D distributed fuel cell model data; exhibits real nonlinear power system dynamics.

Cyber Physical Systems for Research of Advanced Power Cycles

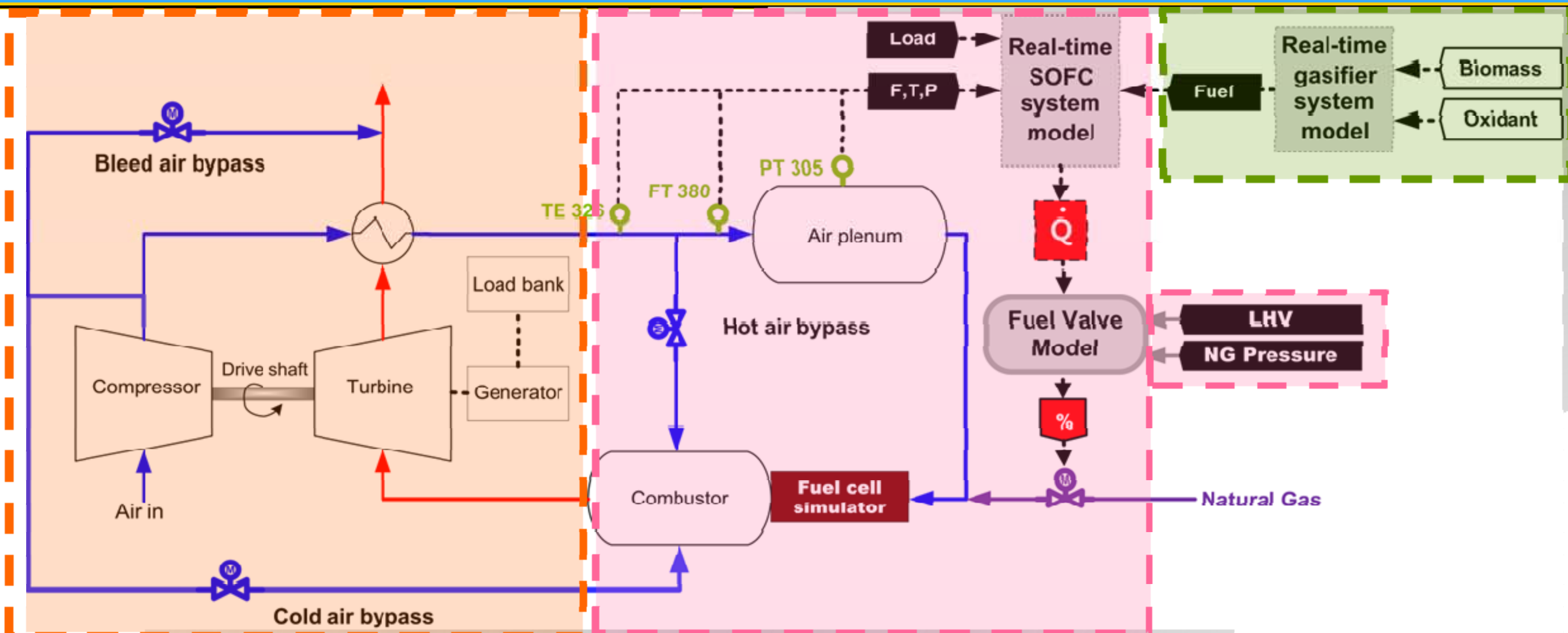
Cyber Physical Systems are used to replace physical systems that:

1. are irreplaceable,
2. are expensive,
3. not technically viable…yet.



NSF invested roughly $40 million in support of 37 CPS projects in 2015. Since 2008, NSF has invested more than [$250 million](#) to build the foundational knowledge underlying all cyber-physical systems.

Cyber Physical Approach in HYPER



FIDELITY

Hardware
- Turbine
- Exhaust gas recuperators
- Generators
- Novel sensors

Physical connections

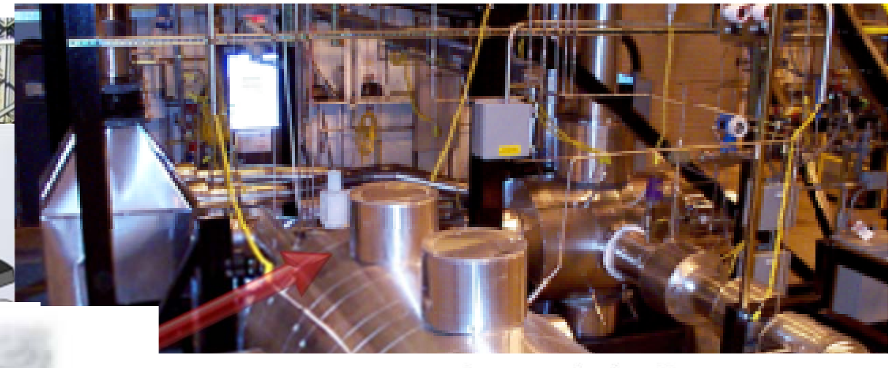
Cyber-physical components
- Solid oxide fuel cells

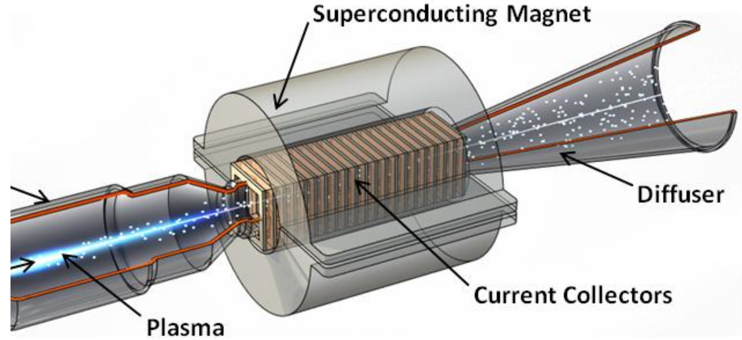
Virtual connections

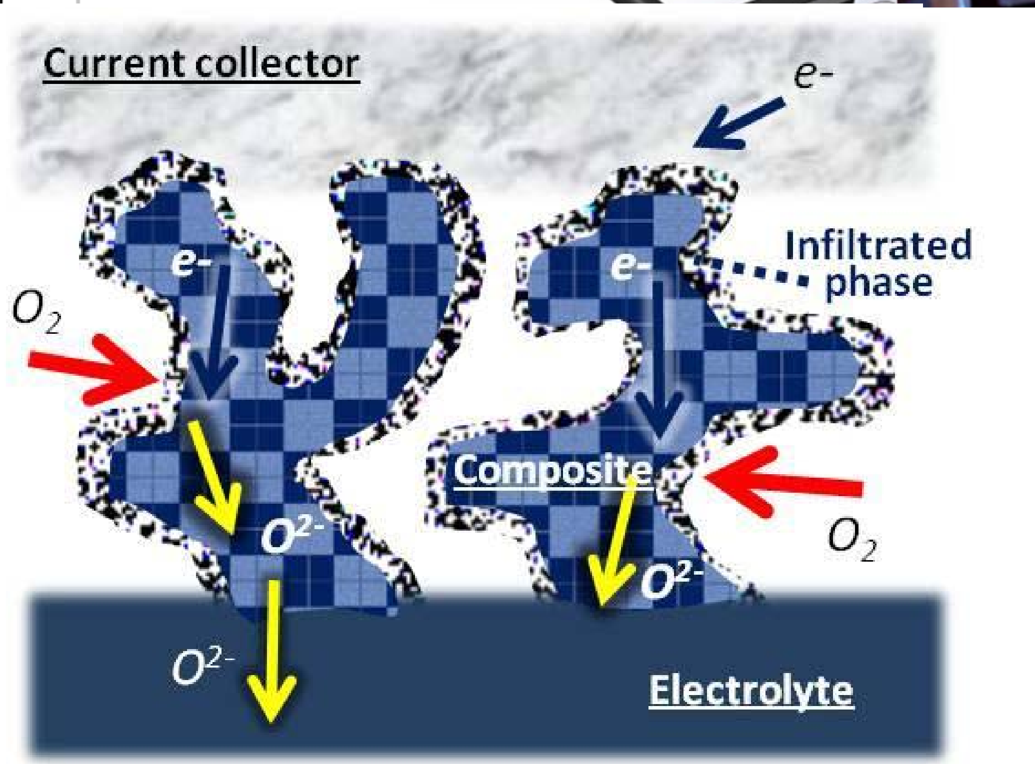
Virtual components
- Gasifier
- Syngas cleanup, etc...

FLEXIBILITY

Cyber Physical Approac







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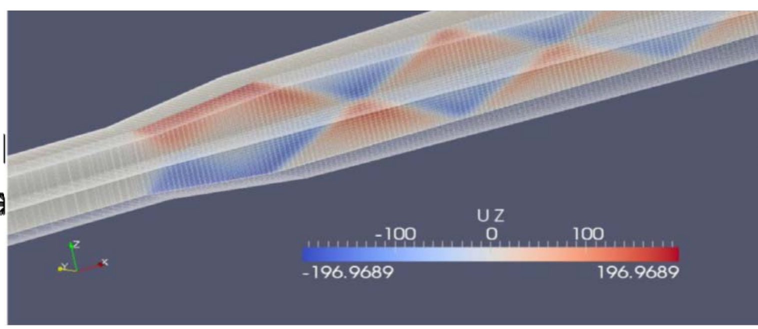

Geothermal
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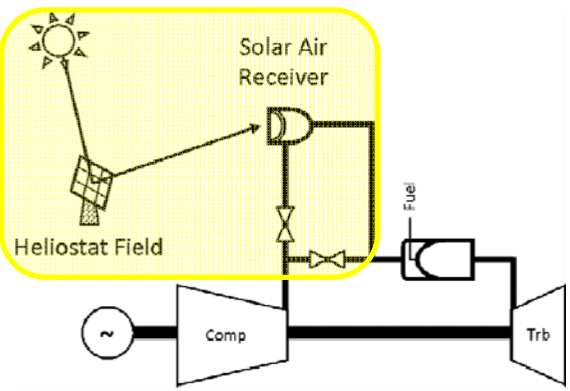
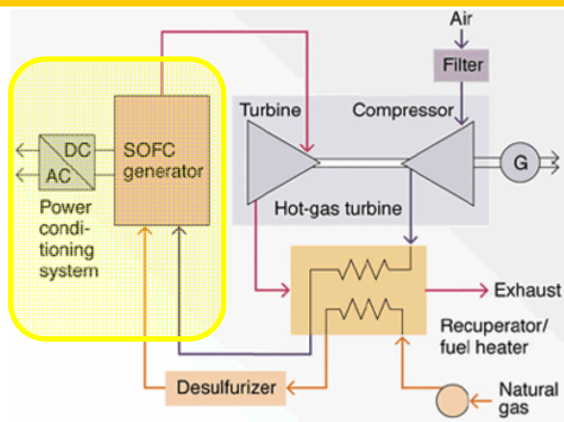
Development

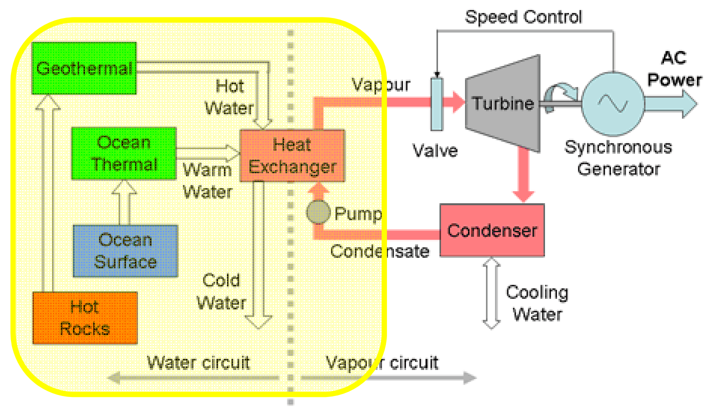
A Large Scale Cyber Physical Platform
leading energy system development



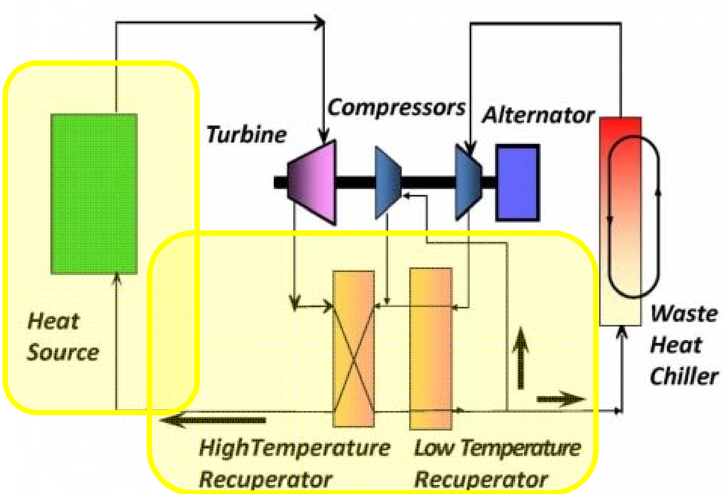
Hyper From Fuel Cells to Concentrated Solar Power



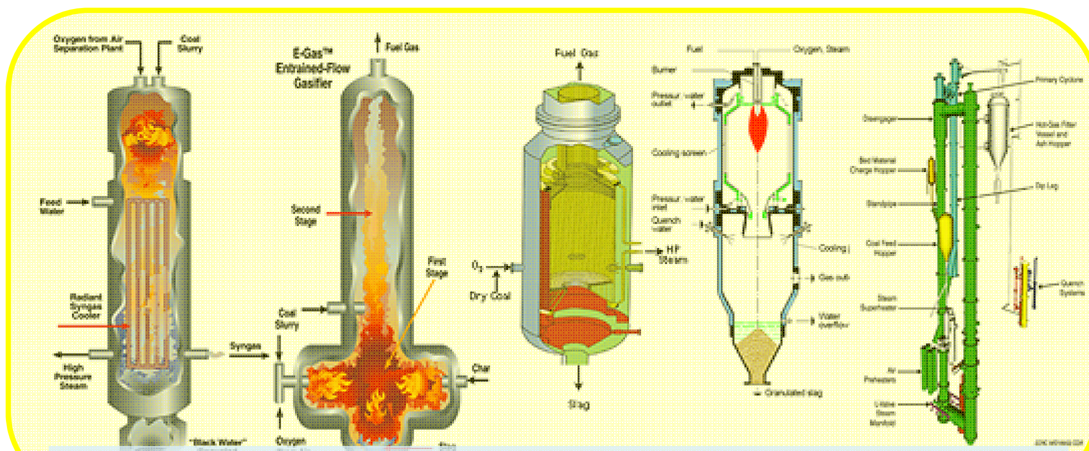
Replacing Components that Don't Exist…Yet



Geothermal Electric Power Hybrid



Supercritical CO_2 Cycles ***Taking Advantage of Reconfigurable CPS***



Testing CO_2 capture, materials, pre- and post-processing, controls with different gasification technologies

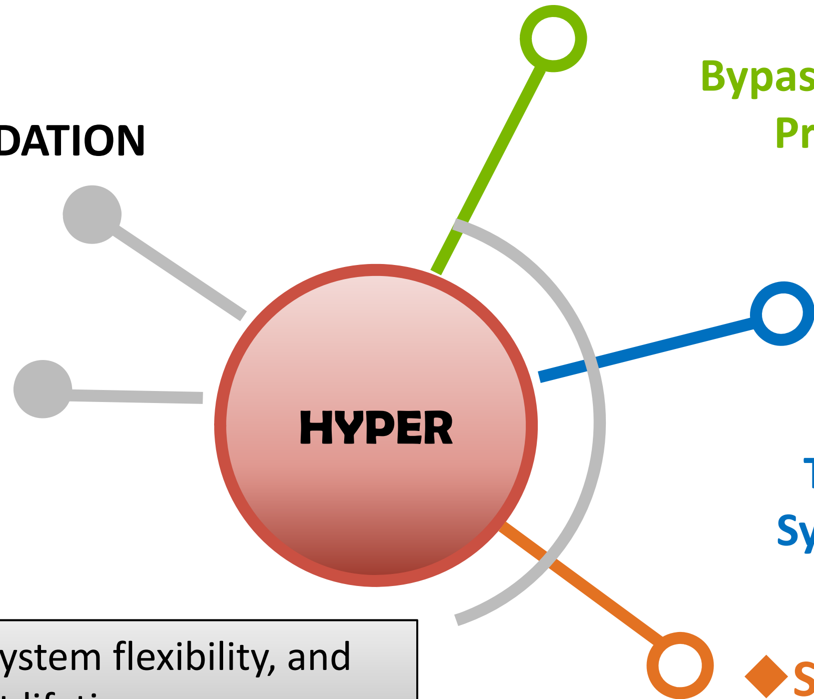
Gasification ***Converting Coal to Syngas without a Gasifier***

Hybrid Applications

Challenges in Controls Development

◆ **FUEL CELL DEGRADATION**

◆ **FUEL FLEXIBILITY**



Improving efficiency, system flexibility, and component lifetime

◆ **THERMAL MANAGEMENT**

Bypass valve (air flow)
Pre-combustor

◆ **STALL AND SURGE (SURGE MARGIN)**

Turbine speed
System pressure

◆ **SYSTEM NONLINEARITY**

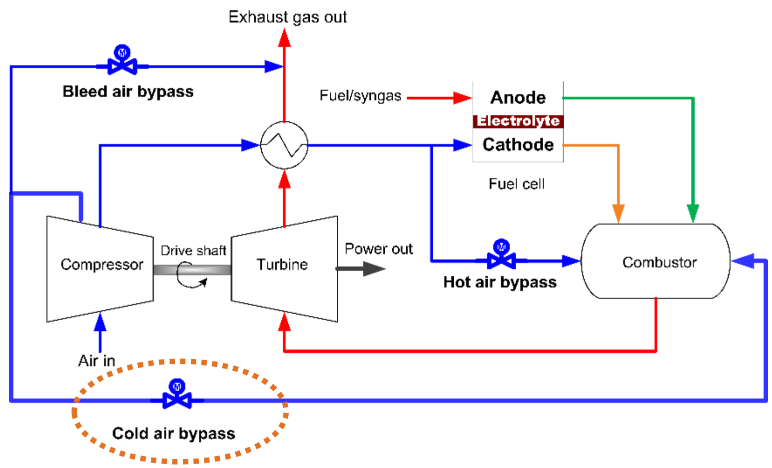
Advanced dynamic controls

Thermal Management in Hybrid Systems

Cold Air Bypass Valve

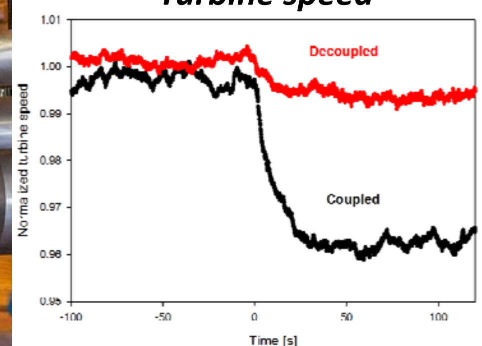
Thermal management using cold air bypass valve:

- Fuel cell thermal management
- System identification
  - With fuel cell (coupled mode)
  - Without fuel cell (decoupled mode)

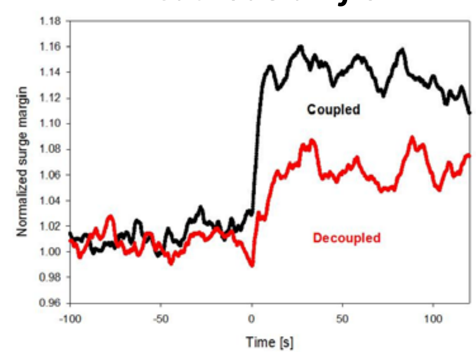


Garret Turbine in HYPER project

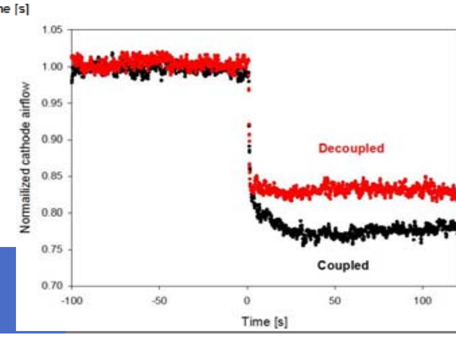
Turbine speed



Cathode air flow

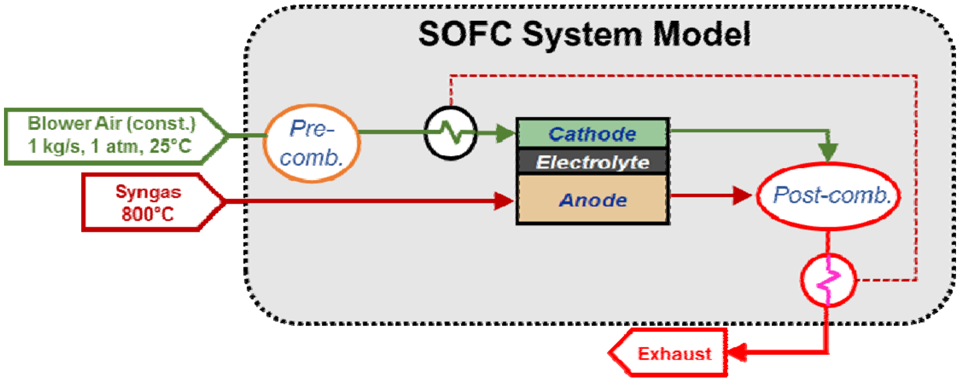


Surge margin



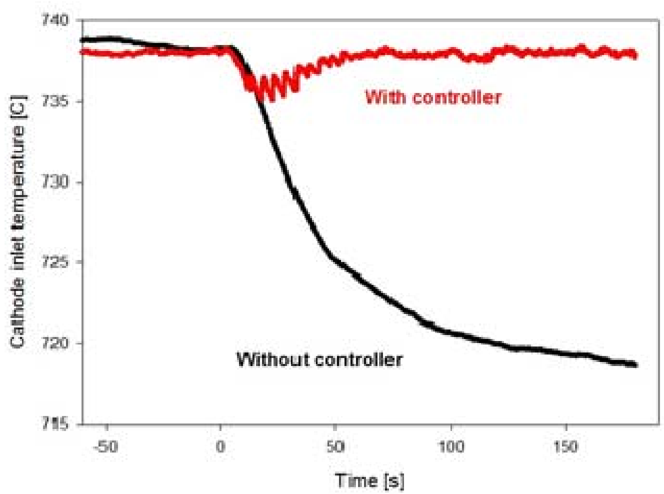
Thermal Management in Hybrid Systems

Pre-combustor



Direct temperature control for fuel cell hybrid systems:

- More flexibility for temperature distribution control
- Insignificant effects on hybrid efficiency

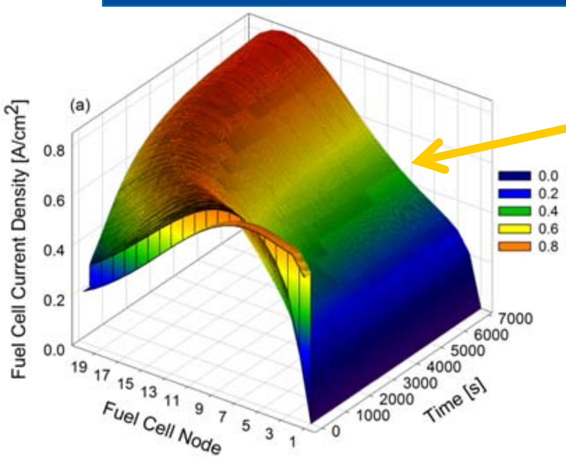


Fuel Flexibility in Hybrid Systems

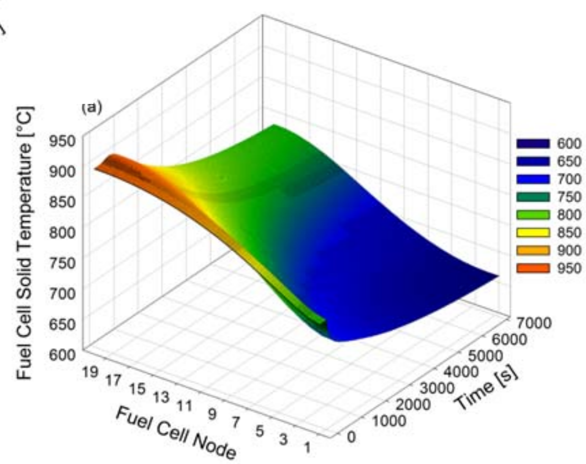
Syngas to Humidified Methane

Impacts of fuel composition transient in hybrid systems:

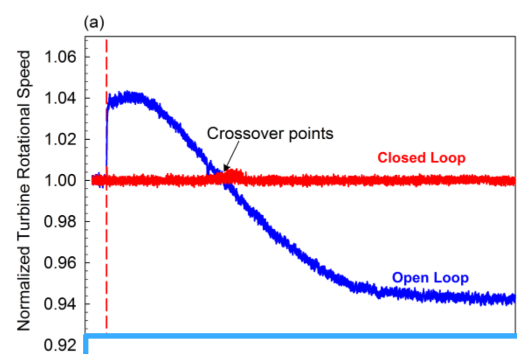
- Improves the use of fuel resources
- Load following
- Flexibility to meet fuel and energy prices, tax, and environmental policy



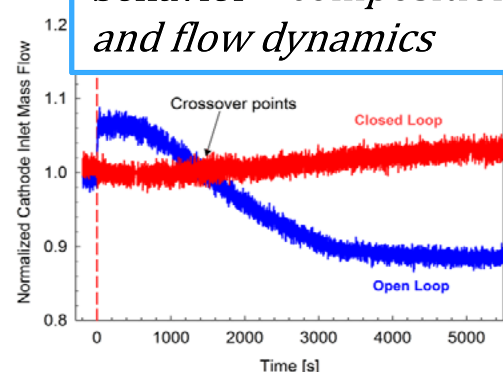
Current density transients *– provides opportunity for degradation control*



Temperature *– challenges for thermal management controls*

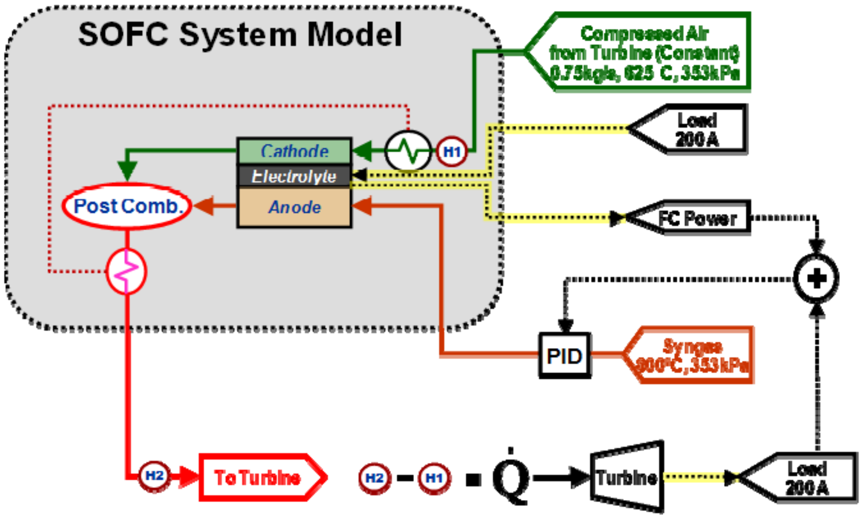


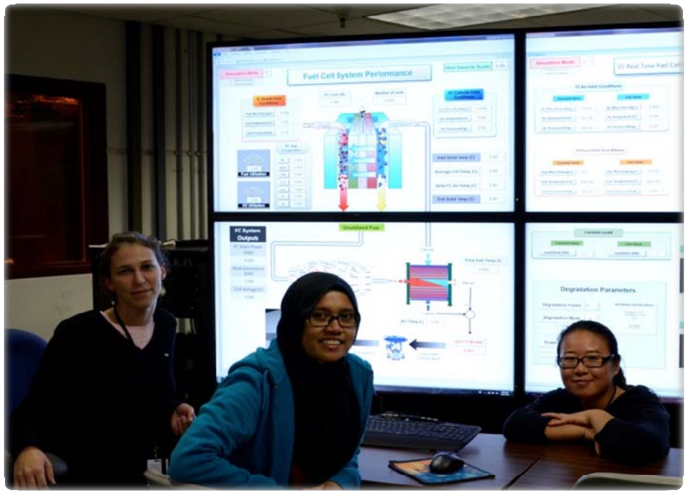
Nonlinear coupling behavior – *composition and flow dynamics*

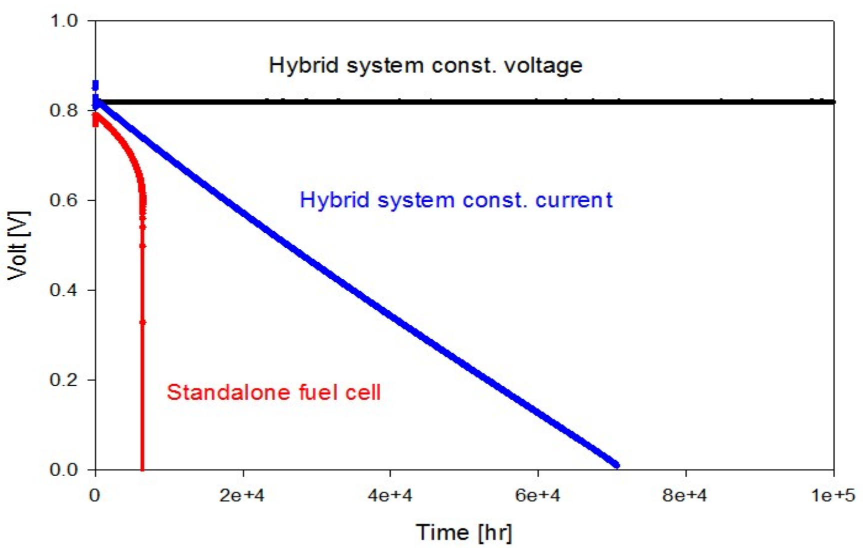


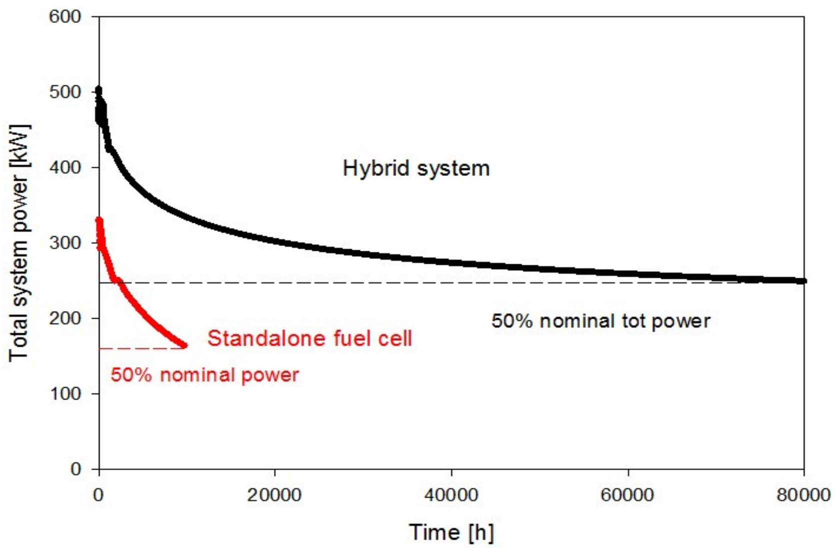
Control Strategies for Degradation

Lifetime Assessment









SOFC Degradation Uncertainties
Standalone vs Hybrid (Lifetime)

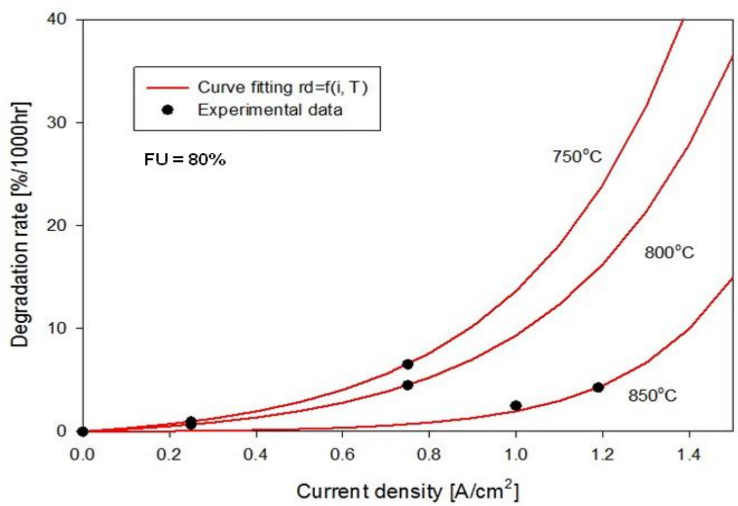
UNIVERSITY OF GENOA

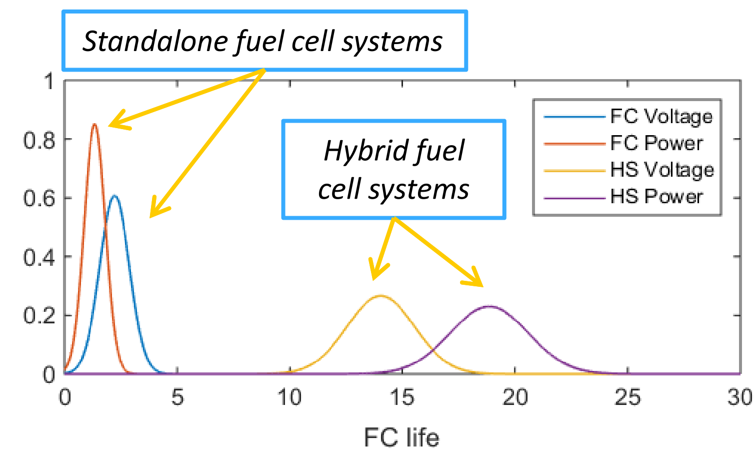
Lifetime of fuel cell systems under design uncertainties

- Limited experimental data in the empirical degradation model

Degradation rate model:

$$r_d = \frac{c_1 FU + c_2}{1+\exp(\frac{T - T_0}{d})}(e^{2.64i} - 1)$$



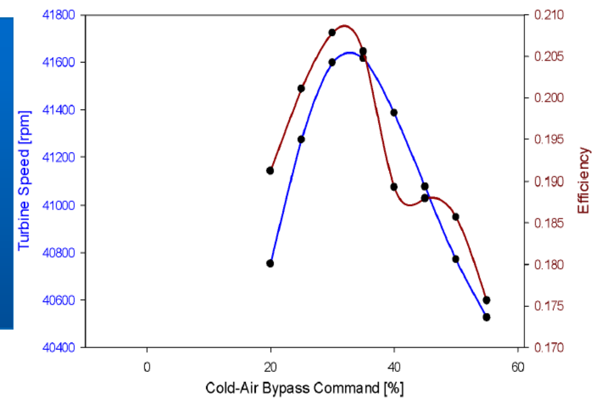


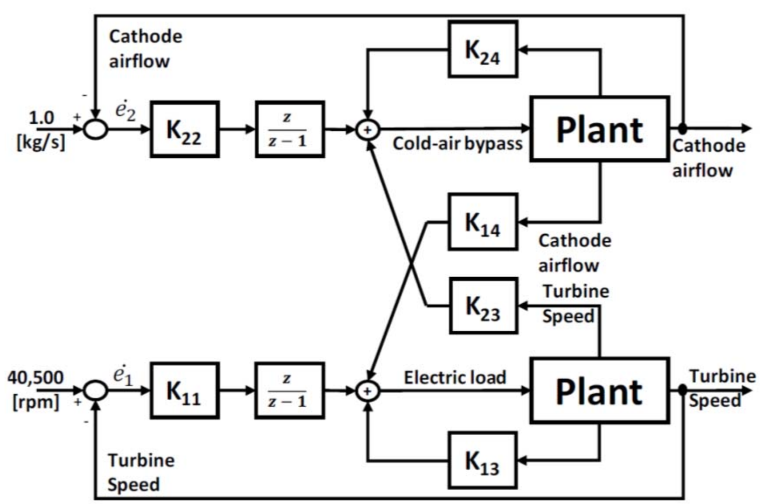
Standalone FC constant power: 1.3 ± 0.49 yrs
Standalone FC constant voltage: 2.2 ± 0.70 yrs
Hybrid system constant voltage and power: 18.9 ± 1.70 yrs
Hybrid system constant voltage: 14 ± 1.54 yrs

Advanced Control Methods for Hybrid Power Plants

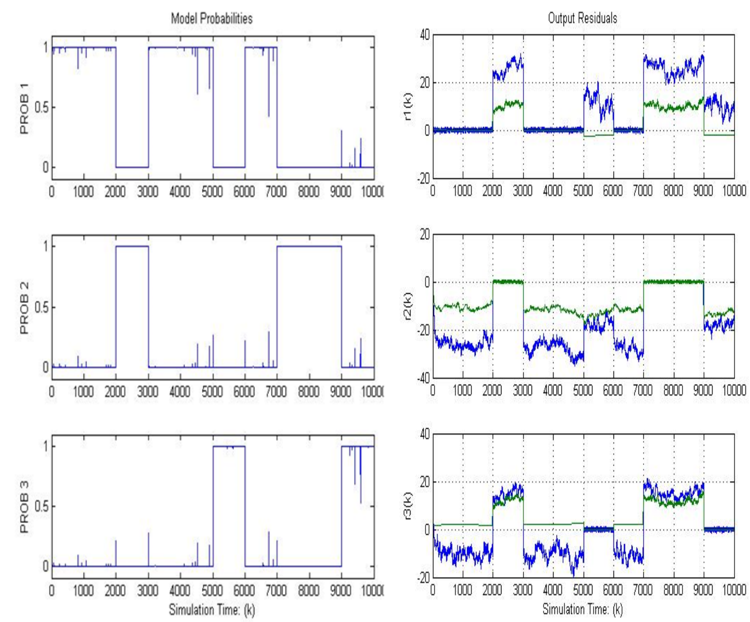
Collaborative research with Ames Laboratory and U.S Coast Guard Academy on highly unconventional controls for power plant applications

- Multi variable controls development (MISO, MIMO)
- Multiple model adaptive estimation





MIMO State Space Controls



Multiple Model Adaptive Estimation

Research Partnerships and Commercial Developers

Domestic Collaborations

Ames National Laboratory
Iowa State University
West Virginia University
Georgia Institute of Technology
University of California, Irvine
Oregon State University
Florida International University
+13 more…

Commercial Developers

GE Fuel Cells
Babcock and Wilcox
Woodward Industrial Controls
Delphi
Mitsubishi Heavy Industries
Solar Turbines
Micro Turbine Technology B.V.
+14 more…

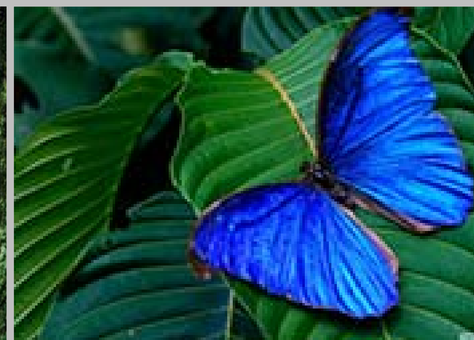
National Laboratories

International Collaborations

The German Aerospace Research Center (DLR)
The University of Genova
McMaster University
Chongqing University
University of Manchester
Technical University of Denmark
+11 more…

Co-authors: Farida Harun, Valentina Zaccaria, Larry Shadle, Dan Oryshchyn



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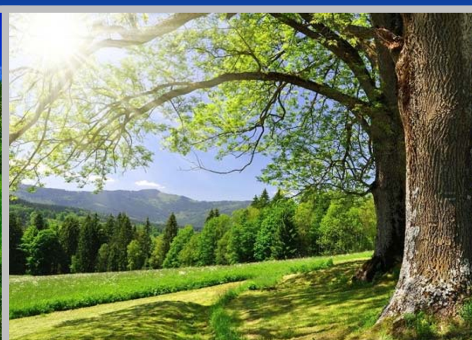

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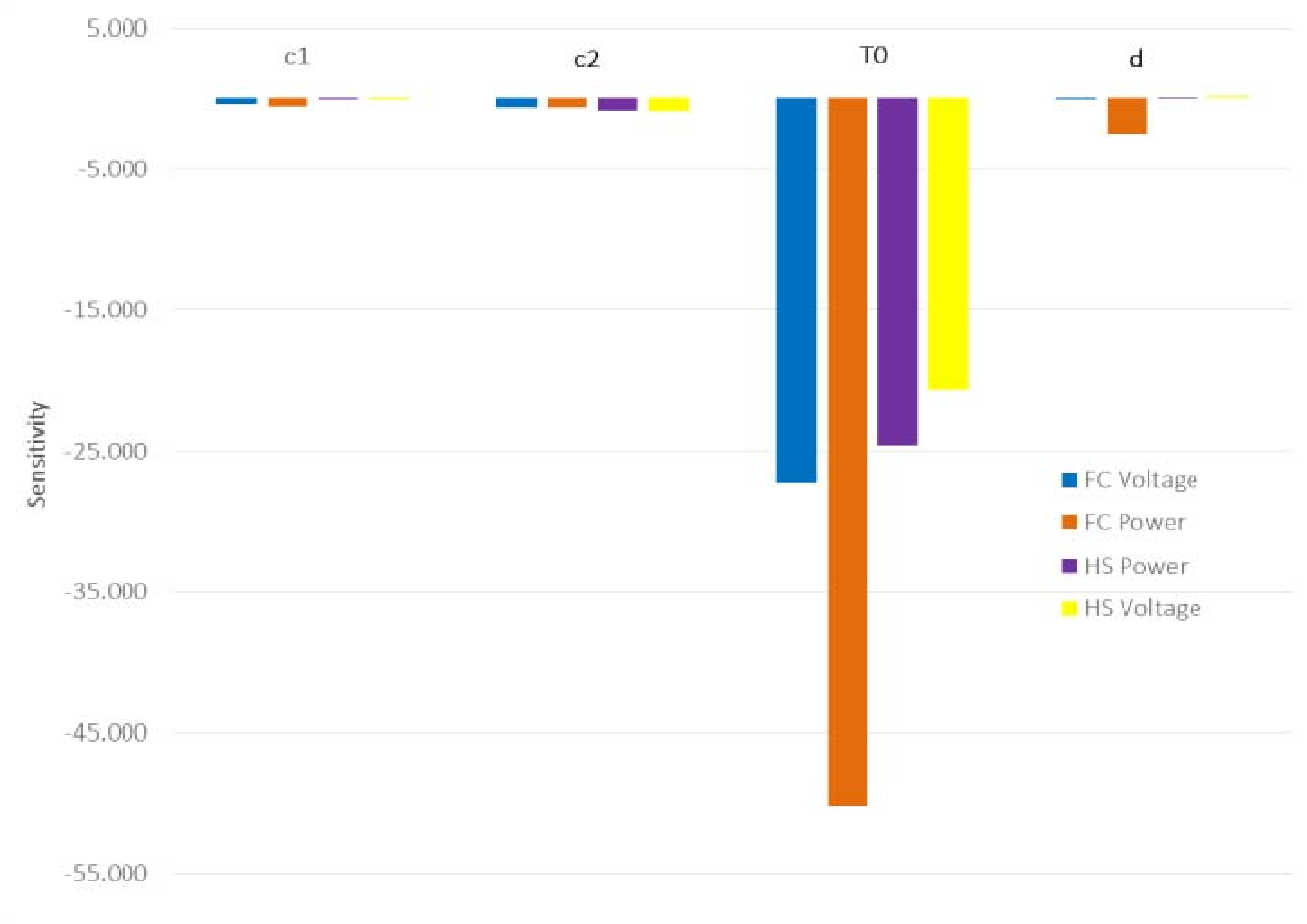
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Sensitivity
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FC Voltage
FC Power
HS Power
HS Voltage